Formation of high grade ore shoots driven by gold remobilisation from auriferous arsenopyrite in the giant Obuasi gold deposit, Ghana

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(Fou-ge-roose 😊)

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Collaborators (in random order):
Louise Fisher, Andy Tomkins, Angela Halfpenny, Yuan Mei, Matt Kilburn, Laure Martin, John Cliff, Paul Guagliardo, Mary Gee…
Talk Outline

I. The different mechanisms for remobilisation

II. Introduction

III. Structural evolution and oreshoot controls

IV. Timing of mineralisation and alteration
   1. Sulphide ores mineralisation/alteration
   2. Quartz vein ore mineralisation/alteration

V. Arsenopyrite textures and remobilisation

VI. Summary: Structural evolution, ore shoot control, timing of mineralisation and alteration
I. Gold remobilisation
A contentious issue

Three mechanisms linked to trace element mobility:

1) Partial melting of the sulphide ore

High grade, but also greenschist facies metamorphic mineral deposits in the presence of low-melting-point chalcophile elements (LMCE - Bi). The melts can scavenge metals such as gold.

2) Intragrain diffusion

Three sub-mechanisms: Volume diffusion, high diffusivity pathway diffusion and dislocation-impurity pair (DIP) diffusion. Migration of elements (and dislocations) in minerals. Crystallographic zonation is usually at least partially erased and becomes diffuse.

3) Fluid-mediated replacement

Dissolution-reprecipitation of a metastable phase in a reactive fluid. The daughter phase can be the same as the parent (with a different composition) or different phases.
II. Introduction

Obuasi general overview

Obuasi, an amazing ore body:
- Industrial mining from 1897 to 2014
- Largest gold deposit in West Africa
- 62 Moz of gold (past production + resources)
- Exceptionally high grade mineralisation on 8 km along strike
- Mined down to 1.5 km with active exploration below this depth
- More than 20 individual ore shoots and 15 satellite deposits

Two distinct style of mineralisation:
- Sub-microscopic gold contained within arsenopyrite
- Visible gold in micro-factures of large quartz veins
II - Introduction

Northern Ghana geology and locations of major gold deposits (modified from Allibone et al., 2002).
II - Introduction

- Hosted in the Kumasi basin close to the contact with the Ashanti belt
- Junction between Akropong and Ashanti faults
- Three mineralised trends share the same strike
  - Binsere trend
  - Main trend
  - Gyabunsu trend
III - Structural evolution and oreshoot controls
III - Structure evolution
Dominant S2 and stretching

- Dominant foliation, strikes NE and dips steeply SE to NW
- F2 folds plunge toward NE, but SW also occur
  → post-F2 modification (refolding)
- S2 is very consistent across the district (steeper dips in Anyankyerem and Sibi pits)
- Major faults parallel with S2
III - Structure evolution
Dominant S2 and stretching

- Intense stretching during D2 in each trend
- Boudinage creating sub-vertical boudin necks across the district but girdle of orientation at Obuasi
- Strain shadows around sulphides and hard minerals (carbonates)
- Quartz lodes affected by boudinage
III - Structure evolution

Overprinting S3

- Low angle crenulation cleavage, strikes E-W and dips 20-45° to the NW
- F3 folds plunge 30 to 45° toward the NE
### III - Structure evolution

<table>
<thead>
<tr>
<th><strong>DEFORMATION</strong></th>
<th><strong>REPRESENTATIVE STRUCTURES</strong></th>
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<tbody>
<tr>
<td>D1</td>
<td>-</td>
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<tr>
<td>S1 rare bedding parallel shearing</td>
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<tr>
<td><strong>Similar to D1</strong>&lt;sub&gt;AI&lt;/sub&gt;</td>
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<tr>
<td>D2, NW-SE shortening</td>
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<tr>
<td>Steeply dipping NE striking S2&lt;sub&gt;Ob&lt;/sub&gt;</td>
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<tr>
<td>F2 tight to isoclinal folding,</td>
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<tr>
<td>Sub-horizontal stretching (boudinage, BN=boudin neck)</td>
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<td><strong>Similar to D1</strong>&lt;sub&gt;BI&lt;/sub&gt; and D2&lt;sub&gt;AI&lt;/sub&gt;</td>
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<td>Gently dipping E to NE S3&lt;sub&gt;Ob&lt;/sub&gt;</td>
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<tr>
<td>Asymmetric F3 folds</td>
<td></td>
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<tr>
<td>F3 = 30 → 45</td>
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<tr>
<td>Folding of the Ashanti fault</td>
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<tr>
<td><strong>Similar to D2</strong>&lt;sub&gt;BI&lt;/sub&gt; and D4&lt;sub&gt;AI&lt;/sub&gt;</td>
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</tbody>
</table>
III - Structural evolution and oreshoot controls
• Two distinct groups of ore shoots
  – **Group 1.** $F_{3_{Ob}}$ fold hinge controlled shoots.
  – **Group 2.** Fault intersections and bifurcations.
• Dominant ore shoot group plunges moderately to the NE at 20 to 40º
→ F3 fold hinges concentrating high grade mineralisation
Ashanti fissure and Obuasi fissure are both deeply charged and contain anastomosing fault splays. These splays enhance permeability and fluid circulation. The Main reef is also present and intersects with the fissures.
IV - Timing of mineralisation

1. Sulphide ores mineralisation/alteration
2. Quartz vein ores mineralisation/alteration
IV.1 - Sulphide ores

- Increasing importance of the sulphide ores relative to historical production
- Mainly arsenopyrites disseminated in metasediments
- Treated onsite with bio plant
IV.1 - Sulphide ores

- Strain shadows around gold-bearing arsenopyrites
- Strain shadow parallel to S2 crenulated by S3

Arsenopyrite mineralisation formed during syn-D2

D2\textsubscript{ob} compressional event
Development of the strain shadows

D3\textsubscript{ob} compressional event
Folding of the strain shadows
IV.1 - Carbonate “spotting”
IV.1 - Carbonate “spotting”

- Carbonates as a proximal to intermediate alteration halo
- Porphyroblasts of *ankerite* and *siderite* aligned with S2 with strain shadow around then (i.e. Same as gold-bearing arsenopyrite)
IV.1 - Carbonate “spotting”

- Geochemical database from Mazzucchelli study (1997)
- Drill core through ore zone
- Signature of carbonates
  - Abundance of minerals increase toward the mineralisation
  - Drop of abundance in the mineralised zone
- 25-50 metres wide
IV.2 - Quartz vein ores

- Laminated thick quartz veins (up to 11m)
- Free milling gold and high grades
IV.2 - Quartz vein ores

- Free milling gold and high grades
- Preferentially in quartz with smoky and milky textures
- In the fractures of the quartz veins
The quartz vein is **boudinaged (during D2)**, folded and overprinted by S3.

The lode is folded during D3 with higher grades in the fold hinge of the quartz vein (visible gold).

Late fractures overprints the lode.

Sulphide distribution remains unchanged either side of the fold hinge.

Visible gold mineralisation during D3.
IV.2 - Quartz vein ores

- The gold is distributed along fracture planes crosscutting the quartz veins
- Gold particles are flaky with irregular sizes filling the porosity created by the fracturing
- Associated with muscovite, graphite and accessory minerals (galena, chalcopyrite, sphalerite, bournonite, boulangerite, and aurostibine)
IV.2 - Quartz vein ores

- High-resolution X-ray computed tomography: 3D distribution of the gold particles in an high grade sample
- All the gold is distributed along the fracture network overprinting the quartz vein
IV.2 - D3 alteration

Overprinting Chlorite

- Large sized (200-300 microns) chlorite porphyroblasts overprint the S3 cleavage
- Proximal alteration halo of the visible gold mineralisation
- Not a lot of fluid!
### IV - Summary

**Structural evolution and gold timing**

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<th>Representative Structures</th>
<th>Mineralization</th>
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<tr>
<td>S1 rare bedding parallel shearing</td>
<td>-</td>
<td>First stage mineralization Disseminated gold-bearing sulphides (Apy, Py)</td>
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<tr>
<td>Similar to D1$_{Al}$</td>
<td></td>
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<tr>
<td><strong>D2, NW-SE shortening</strong></td>
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<td>Second stage mineralization Native gold in quartz veins (Au, Gn, Ccp, Sp, Brn, Ast...)</td>
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<tr>
<td>Steeply dipping NE striking S2$_{ob}$</td>
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<tr>
<td>Similar to D1$<em>{Bi}$ and D2$</em>{Al}$</td>
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V - Arsenopyrite textures and remobilisation
• Apy(I) = idiomorphic arsenopyrite with gold-poor core and gold-rich rim (up to 1000 ppm).
• Non-stoichiometric composition, enriched in S, depleted in As

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>As</th>
<th>Au</th>
<th>Fe</th>
<th>Total</th>
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<tbody>
<tr>
<td>Core</td>
<td>23.309</td>
<td>41.894</td>
<td>BDL</td>
<td>35.859</td>
<td>101.06</td>
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<tr>
<td>Core</td>
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<td>43.740</td>
<td>BDL</td>
<td>35.190</td>
<td>100.92</td>
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<tr>
<td>Rim</td>
<td>22.047</td>
<td>43.860</td>
<td>0.06</td>
<td>35.063</td>
<td>101.03</td>
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<tr>
<td>Rim</td>
<td>22.319</td>
<td>43.901</td>
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<tr>
<td>Rim</td>
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<td>44.718</td>
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<td>34.979</td>
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<tr>
<td>Rim</td>
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<td>44.320</td>
<td>0.06</td>
<td>34.831</td>
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<tr>
<td>Alteration zone</td>
<td>20.072</td>
<td>45.444</td>
<td>BDL</td>
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<td>Alteration zone</td>
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<td>46.059</td>
<td>BDL</td>
<td>34.730</td>
<td>101.54</td>
</tr>
</tbody>
</table>
V – Arsenopyrite textures

- **Apy(II)** = domain cutting across Apy(I), penetrating in from microfractures and grain boundaries. Compositions close to stochiometric with higher As and lower S concentrations than Apy(I).

- **Py(III)** = xenomorphic pyrite surrounding and infilling Apy fractures. Contains native gold particles up to 10 μm.
V – Arsenopyrite textures
Microchemistry

- Apy(I) = Fine sub-micron oscillatory zoning
- Apy(II) = Ni-rich with (almost) no gold
- Sharp contact between Apy(I) and Apy(II)
- Py(III) = Ni-rich
V – Arsenopyrite textures
Microchemistry
V – Arsenopyrite textures
Microchemistry

• Sharp contact between Apy(I) and Apy(II)
• Apy(II) is a more stoichiometric arsenopyrite composition than Apy(I)
• Apy(II) penetrates from microfractures and grain boundaries
  ➢ Dissolution-reprecipitation reaction (fluid assisted replacement)

• During the reaction from Apy(I) to Apy(II):
  – Incorporation of Ni ➔ Ni transported as Cl complexes (NiCl$_2$(aq))
  – Release of S ➔ Increase of sulfur fugacity in the fluid
  – Release of Au ➔ Gold complexes with S to form Au(HS)$_2^-$

$$\text{FeAsS(Au)}_{\text{high } S} + \text{NiCl}_2(\text{aq}) + 2\text{H}_2\text{O}(\text{aq}) + \text{e}^- \rightarrow \text{FeAsS(Ni)}_{\text{low } S} + \text{Au(HS)}_2^-(\text{aq}) + 2\text{HCl}(\text{aq}) + \text{O}_2$$
V – Arsenopyrite textures
Geochemical modelling

[Graph showing element composition in fluid (mg/kg) and minerals (grams).]
V – Arsenopyrite textures

Timing of remobilisation

Crystal plasticity and geochemical modification

Gold remobilisation during D3
V – Arsenopyrite textures
Nanoscale elemental distribution

- Atom probe tomography
- Newly commissioned Geoscience atom probe at Curtin
- Position-sensitive time of flight mass spectroscopy
- 3D imaging and chemical composition at the atomic scale (around 0.1-0.3nm resolution)
V – Arsenopyrite textures
Nanoscale elemental distribution

Au distribution in Apy(I)

Ni distribution in Apy(II)
VI - Summary: Structural evolution, gold timing and remobilisation
D2 - Classic Orogenic Gold System (over printed)

Laminated veins in the shear zone

Boudinaged quartz vein

Arsenopyrite mineralization

Distal carbonate alteration

D2_{ob} - Subhorizontal stretching: Boudinage and strain shadows

Breccia

Gold-bearing arsenopyrites

Increasing percentage of arsenopyrite

Increasing percentage of carbonate
**D3 - Visible gold 2nd overprints**

- **Visible gold mineralization**
- **Gold overprinting the quartz vein**
- **Overprinting chlorite**
- **Gold remobilization and Nickel-rich pyrite**
D3 – Gold remobilisation and formation of high grade ore shoots
Thanks!