Sulphide microchemistry variations in West African gold deposits

Module 2.2

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36 Sponsors

11 Sponsors in kind (Geological Surveys)

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22 Research and Capacity Building Partners
14 deposits studied

(after Milési et al., 2004)

Baratoux et al., 2011
Orogenic gold deposits

→ Ebournean orogeny

Compressional/transpressional environments

Depth (km)

0

1

5

10

20

Orogenic Deposits

Hg

Hg-Sb

Epizonal Au-Sb

Mesozonal Au-As-Te

Hypozonal Au-As

Goldfarb et al., 2001

Le Mignot et al., in review, EGeol

Mali

SW Burkina

D6

D5

Au - breccia with Py, Ank
Tabakoroni, Komana, Kalana

Au -breccia with Py, Ank
Banfora west
Nassara ~2040Ma Re-Os

Au - common high As
Klaka ~2080Ma Re-Os
Inata ~2090Ma Re-Os

Au - Morila
Tarkwa-like units

Archean detrital zircons

Early Au
(Morila ~2135Ma U-Pb)

Early Au
early Klaka ~2160Ma Re-Os

Early Au

Periphery Cu (Dawra)
ca. 2250-2170Ma Re-Os

Tarkwa-like units

VM5 (inferred age Perkoo)

Le Mignot et al., in review, EGeol

Goldfarb et al., 2001

D4

D3

D2

D1 (?)
Emplacement conditions

determined from mineral parageneses

3 main types detected
Morila type 450 – 550° C

FeAs₂ + FeS + 1/2S₂

2FeAsS

Apy - Po - Löe

Evolution of arsenopyrite-bearing ore samples (Barroc Tectonic Zone)

Arsenopyrite + pyrrhotite (as inclusions) + invisible gold

Arsenopyrite + pyrite ± pyrrhotite + visible gold

Contour of At% arsenic in arsenopyrite

Stability range for arsenopyrite, pyrrhotite and invisible gold

Stability range for arsenopyrite, pyrite and visible gold

Alteration path representing transition from invisible to visible gold
Pampe type ~ 375°C

FeS₂ + As

FeAsS + 1/2S₂

Evolution of arsenopyrite-bearing ore samples (D2 shear zone and shear zone).

As isopy cracking in arsenopyrite and pyrite.

Stability range for arsenopyrite, pyrrhotite, and visible gold.

Stability range for arsenopyrite, pyrite, and visible gold.

Alteration path representing transition from invisible to visible gold.

Contours of % arsenic in arsenopyrite.

Nassara type <300°C

FeS₂

Py
OROGENIC GOLD DEPOSITS

Nassara type
D2, D3, D4, D5
telescoping events

Pampe type
D2, D3, D4

Morila type
D2?

450 – 550°C

~ 375°C

< 300°C
- Gaoua district
- Gaoua district

porphyry Cu mineralization

orogenic gold
Fluid inclusion evidence

Porphyry stage

**Solid-bearing H₂O** fluid inclusion with salts and a **chalcopyrite** crystal

- **High temperature** (>400°C)
- **High salinity** (>30 wt% NaCl eq)
- Orthomagmatic fluid

Orogenic stage

**H₂O and H₂O-CO₂** fluid inclusions

- **Low temperature** (<200°C)
- **Moderate salinity** (13-24 wt% NaCl eq)
- Hydrothermal fluid

**Gaoua district**
Porphyry systems elsewhere in the world

Farallon Negro (Argentina)

Santa Rita (NMex)

Morenci (Az)

Red Mtn (Az)

Grasburg (Indonesia)

Calabona (Italy)
...back to orogenic deposits!

Sulphide distribution
Gold intimately associated with pyrite (or apy)
Sulphide evolution

As distribution $\rightarrow$ several generation of py and apy
**Invisible gold**

Py rim = 8 ppm Au; 0.6 wt% As
Invisible gold

Reich et al., 2005

Buescham Au = 601 ppm

Wassa Au = 7.4 ppm

Tabakoroni Au = 2.59 ppm
Visible gold

- Ankerite
- Rutile
- PbS
- Au
- Apy2
- Py2
- Cpy
- Pb-Te
- Au-Te
- Albite
- Chlorite
- JM-10A-SF-C1a

Sulfosalt nanoparticles:
- Ni
- Bi
- Pb
- Cu
- As
- Te
- Sb
- Ag
- Background

Py2
- Au
- Cpy
- PbS
- Apy2
- Py3
- Bi-Te
- Au
Microprobe and LA-ICP-MS analyses of pyrite and chalcopyrite

- **Gaoua district**

[Graph showing elemental counts and compositions]

<table>
<thead>
<tr>
<th>Element</th>
<th>Pyrite 1</th>
<th>Pyrite 2</th>
<th>Pyrite 3</th>
<th>Pyrite 4</th>
<th>Pyrite 5</th>
<th>Pyrite 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni (ppm)</td>
<td>4.41</td>
<td>385.7</td>
<td>4.92</td>
<td>1.78</td>
<td>1.19</td>
<td>145.6</td>
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<tr>
<td>Cu (ppm)</td>
<td>0.2</td>
<td>0.6</td>
<td>0.21</td>
<td>0.22</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td>As (ppm)</td>
<td>4.9</td>
<td>0.287</td>
<td>9.42</td>
<td>5.88</td>
<td>11.28</td>
<td>17.8</td>
</tr>
<tr>
<td>Se (ppm)</td>
<td>38.26</td>
<td>100.62</td>
<td>35.81</td>
<td>33.54</td>
<td>52.25</td>
<td>71.49</td>
</tr>
<tr>
<td>Ag (ppm)</td>
<td>0.0057</td>
<td>0.0061</td>
<td>0.0079</td>
<td>0.0076</td>
<td>0.0074</td>
<td>0.0054</td>
</tr>
<tr>
<td>Sb (ppm)</td>
<td>0.203</td>
<td>&lt;0.073</td>
<td>0.063</td>
<td>&lt;0.062</td>
<td>0.164</td>
<td>&lt;0.056</td>
</tr>
<tr>
<td>Te (ppm)</td>
<td>0.11</td>
<td>0.204</td>
<td>0.037</td>
<td>0.0211</td>
<td>25</td>
<td>&lt;0.0039</td>
</tr>
<tr>
<td>Au (ppm)</td>
<td>0.00122</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>0.00365</td>
<td>0.00405</td>
<td>&lt;LOD</td>
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<tr>
<td>Pb (ppm)</td>
<td>0.00346</td>
<td>0.00371</td>
<td>0.00067</td>
<td>0.00127</td>
<td>&lt;0.00044</td>
<td>0.00055</td>
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<tr>
<td>Bi (ppm)</td>
<td>0.0077</td>
<td>0.00084</td>
<td>0.00026</td>
<td>0.00586</td>
<td>0.00013</td>
<td>0.00096</td>
</tr>
<tr>
<td>SAMPLE</td>
<td>S44-249-C1-2</td>
<td>S44-249-C2-1</td>
<td>S44-249-C3-1</td>
<td>S44-346-C1-2</td>
<td>S44-346-C3-1</td>
<td>S44-346-C2-1</td>
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<tr>
<td>-------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
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<tr>
<td>Ni (ppm)</td>
<td>25.70</td>
<td>2.36</td>
<td>1.63</td>
<td>3.89</td>
<td>2.49</td>
<td>2.22</td>
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<tr>
<td>Cu (ppm)</td>
<td>3491149</td>
<td>352197</td>
<td>351523</td>
<td>339379</td>
<td>342389</td>
<td>351170</td>
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<tr>
<td>As (ppm)</td>
<td>4.80</td>
<td>1.06</td>
<td>0.37</td>
<td>0.14</td>
<td>0.36</td>
<td>0.10</td>
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<tr>
<td>Se (ppm)</td>
<td>1719.73</td>
<td>182.98</td>
<td>152.79</td>
<td>219.94</td>
<td>176.49</td>
<td>183.99</td>
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<tr>
<td>Ag (ppm)</td>
<td>32.74</td>
<td>4.97</td>
<td>2.43</td>
<td>2.32</td>
<td>2.92</td>
<td>1.92</td>
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<tr>
<td>Sb (ppm)</td>
<td>528.10</td>
<td>164.60</td>
<td>23.42</td>
<td>75.16</td>
<td>108.21</td>
<td>40.72</td>
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<tr>
<td>Te (ppm)</td>
<td>3.54</td>
<td>1.46</td>
<td>0.24</td>
<td>0.15</td>
<td>0.23</td>
<td>0.13</td>
</tr>
<tr>
<td>Au (ppm)</td>
<td><strong>0.61</strong></td>
<td><strong>0.23</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.34</strong></td>
<td><strong>0.16</strong></td>
<td><strong>0.11</strong></td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>21.69</td>
<td>8.48</td>
<td>0.60</td>
<td>1.13</td>
<td>1.52</td>
<td>0.65</td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>10.95</td>
<td>2.56</td>
<td>0.29</td>
<td>0.49</td>
<td>0.61</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**Orogenic**

<table>
<thead>
<tr>
<th>sample</th>
<th>S19-267.5A-C4-1</th>
<th>S19-267.5A-C8-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni (ppm)</td>
<td>2.39</td>
<td>2.45</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>163.94</td>
<td>77.1</td>
</tr>
<tr>
<td>As (ppm)</td>
<td>6.93</td>
<td>11.69</td>
</tr>
<tr>
<td>Se (ppm)</td>
<td>34.84</td>
<td>36.11</td>
</tr>
<tr>
<td>Ag (ppm)</td>
<td>0.0472</td>
<td>0.139</td>
</tr>
<tr>
<td>Sb (ppm)</td>
<td>0.183</td>
<td>0.95</td>
</tr>
<tr>
<td>Te (ppm)</td>
<td>5.13</td>
<td>19.07</td>
</tr>
<tr>
<td><strong>Au (ppm)</strong></td>
<td><strong>0.334</strong></td>
<td><strong>2.22</strong></td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>0.0629</td>
<td>0.566</td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>0.696</td>
<td>4.47</td>
</tr>
</tbody>
</table>
Comparative trace chemistry of sulphides

**Pyrrhotite**
- Ni: 1320 ppm
- Co: 60 ppm
- Au = 0.008 ppm

**Chalcopyrite**
- Ni: 140 ppm
- Co: 140 ppm

**Arsenopyrite**
- Ni: 1560 ppm
- Se: 990 ppm
- Sb: 620 ppm
- Au = 43.25 ppm

**Pyrite**
- Co: 140 ppm
- As: 2285 ppm
- Au = 2.03 ppm
- Sb: 2285 ppm
- Se: 140 ppm

- Au = 0.15 ppm
Geochemical signature of mineralized vs barren zones – Footprinting?
PETROGRAPHIC RESULTS

MICROTHERMOMETRIC RESULTS

VEIN NETWORK

- CO\(_2\)(L)
- H\(_2\)O (L)

L\(_{\text{CO}_2}\)
V\(_{(\text{CO}_2)}\)
Pr-FI
Lt(aq.)
Qtz

Salinity (wt.% NaCl eq.)

T\(_{h}\) (total) °C

Pr-H\(_2\)O-CO\(_2\)-salt

0 100 200 300

0 2 4 6 8 10

l.p. at 6 km
l.p. at 4 km
h.p. at 6 km
h.p. at 4 km

brittle transition (quartz-ankerite)

2 FLUIDS immiscibility

CO\(_2\)-H\(_2\)O-NaCl critical curve

gEOthermal gradient of 40°C/km at l.p.

gEOthermal gradient of 40°C/km at h.p.
Model for the formation of the zoning and mineralization

Stage 1: Ductile
- Qtz-Ank-Ab lens
- Rt
- Py-core
- Pressure shadow
- As-Au-rich band
- As-Au-poor zone of rim

Stage 2: Brittle - ductile transition
- Brittle - ductile transition
- 1 fluid
- 2 fluids
- CO$_2$-H$_2$O-NaCl critical curve

CO$_2$(L+V)
H$_2$O (L+V)
Model for the formation of the zoning and mineralization

Stage 2: Brittle - ductile transition

As-Au-rich band
As-Au-poor zone of rim

Metabasaltic fragment
Qtz-Ank-Ab vein network

P (Kbar)

T (°C)

Brittle - ductile transition

Ductile 1 fluid

2 fluids

As-rich bands

Core

Rim
Model for the formation of the zoning and mineralization

Stage 2: Brittle - ductile transition

- As-Au-rich band
- As-Au-poor zone of rim
- Metabasaltic fragment
- Qtz-Ank-Ab vein network
- Py overgrowth
- MsL
- Ank PS1
- Ank PS2
- Chl L
- Pyrite

Diagram showing the brittle-ductile transition and the formation of zoning and mineralization with P-T diagrams and mineral phases (Qtz, Ank, MsL, etc.).
Elemental analysis of fluid inclusions

By Femtosecond Laser Ablation-Time of Flight-Inductively Coupled Plasma Spectrometry

Example of early D$_2$ aqueous fluid inclusions

1: albitized diorite dyke
2: sheared quartz
3: undeformed quartz

Inata deposit

20 µm
Elemental analysis of fluid inclusions

Selection of elements

- High Na → albitization
- No Ca, No K!

Fe, Cu, Pb, Bi, Sb, As

Ni, Co, Cr, Mn, Fe

Au, Ag
Elemental analysis of fluid inclusions

Selection of elements

- Fe, Cu, Pb, Bi, Sb, As
- Ni, Co, Cr, Mn

Au = 4.0 ppm
Experimental synthesis of Au-As bearing pyrite

How does Au - As intake into pyrite work?

(collaboration G. Pokrovski, GET, Toulouse)

Initial solution in equilibrium with native Au:

\[ S + \text{NaOH ou K}_2\text{S}_2\text{O}_3+\text{HCl} \pm \text{KCl} \pm \text{silicates} \]

Major species in solution:

\[ \text{H}_2\text{S}, \text{HSO}_4^-, \text{SO}_4^{2-}, \text{S}_3^- \]

\[ \text{Au(HS)}_2^-, \text{AuHS}, \text{‘Au-S}_3\text{’} \]

Injection of FeCl₂ or FeSO₄ solution

Coprecipitation of pyrite and gold

200-500°C, 500-1500 bar

Flexible-cell hydrothermal reactor

False-colour SEM BSE image
Thanks for the attention