The Source and timing of Gold in Orogenic Gold Deposits;
A Case Study from the Giant Sukhoi Log Sediment-Hosted Deposit in Siberia

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CODES UTAS

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We are in for a Revolution in Gold Ore Genesis Theory

At Last we have a Technique to Place Gold into the Paragenesis of Orogenic Gold Deposits
The Technique?

*Laser Ablation-Q-ICPMS*

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
The Technique?

*Laser Ablation-Q-ICPMS*

Py2 = 0.34 ppm Au
Py1 = 9.8 ppm Au
Py1 = 7.41 ppm Au
Py1 = 6.55 ppm Au
Py3 = 0.05 ppm Au
Py3 = 0.05 ppm Au

200 microns
INTRODUCTION
• Project Sponsors
  – Barrick, Newcrest, Newmont, Perseverance, St Barbara

Photo: Dark arsenian pyrite (<933 ppm Au) rims earlier formed diagenetic or hydrothermal pyrite nodule, Roberts Mtn Fmn, Gold Quarry, Northern Carlin Trend, Nevada
AMIRA P923: STUDY AREAS

Three world-class sediment-hosted gold districts hosting deposits of contrasting style

- Carlin District, NE Nevada (50 %)
  - Periphery and host-rocks to Post-Betze-Screamer deposit (>38.6 Moz), Gold Quarry (~24 Moz)

- Central Victoria – NE Tasmania (25 %)
  - Fosterville (>1 Moz), Bendigo (>34 Moz), Tarnagulla (0.56 Moz), Lefroy (~0.23 Moz, historical)

- Lena Goldfield, Siberia (25 %)
  - Sukhoi Log (>46 Moz)
Challenge to Current Beliefs
Related to Orogenic Gold Deposits

Belief 1: “Gold is coming from some deep source or from crustal granites”

NO………

Gold is Already Present in the Sedimentary Basin
Belief 2: “Graphitic Sediments are Good Trap Rocks for Gold”

Yes, But……..

*Graphitic sediments are Ideal Source Rocks for Au & As*  
*plus Se, Te, V, Zn, Mo, Ni, PGE…….*
Belief 3: “Gold is introduced Late; i.e. Syn-tectonic or Post-tectonic”

NO………

Gold is Introduced Early; i.e. Pre-tectonic and Moved Around Late During Tectonism
Multi-stage Origin of Pyrite and Gold in the Giant Sukhoi Log Deposit, Lena Goldfield, Russia

Ross Large, Valeriy Maslennikov, Sarah Gilbert, Rob Scott, Leonid Danyushevsky and Zhaoshan Chang
Major Gold Deposits around Siberian Craton
Regional Geology

PATOM GROUP – NEOPROTEROZOIC
- Carbonaceous shale, siltstone and limestone – Bodaibo Subgroup
- Carbonaceous shale, siltstone, sandstone and carbonates – Kadalikan Subgroup
- Conglomerate, quartzite and slate – Ballagan Subgroup

MESOPROTEROZOIC
- Volcanic and sedimentary rocks – Medvezhi Formation of Teplogo Subgroup
- Undifferentiated Palaeoproterozoic to Mesoproterozoic granites
- Undifferentiated Neoproterozoic to Palaeozoic granites

- Primary disseminated Au deposits
- Primary vein Au deposits
Sukhoi Log: Resource

- Sukhoi Log is a giant low grade sediment-hosted gold deposit
- Open Pit resource: 384 Mt @ 2.6 g/t Au
Geological plan and Cross Section

Figure 3. Partly schematic plan and cross section through the Sukhoi Log deposit (modified from Woods and Popov, unpubl.).
Exploration Grid - Sukhoi Log
Sukhoi Log Ridge
Sukhoi Log Core Shed
Core Layout
Quartz-pyrite veins
Bedding Parallel & Folded
Previous Models

- Orogenic deposit: gold introduced and concentrated during metamorphism (Goldfarb, et al., 2005)
- Intrusion related gold deposit (Distler et al., 2004)
- Syngenetic gold deposit with remobilisation into anticlinal core during metamorphism (Buryak, 1982; Kribek, 1991)
- Three suggested sources of gold: metamorphic fluids, magmatic fluids, exhalation into seawater
- Recent detrital zircon dating in our lab by Sebastian Mefre shows the host sediments have a maximum age of ~600 Ma
- The main metamorphic event has been dated at 520 Ma (Laverov et al., 2000), and emplacement age of local granitoids is around 360 Ma (Rundquist et al., 1992)
Aims of this phase of the Research

- To determine the sulfide paragenesis at Sukhoi Log
- To determine the gold and trace element contents and associations for the various stages of pyrite
- Was gold introduced during sedimentation & diagenesis, or later during metamorphism and/or granite intrusion, or at several times?
Pyrite History

Sedimentary-diagenetic

Metamorphic in sst

Hydrothermal overgrowth

Metamorphic in shale
Pyrite 1

- Fine grained stratiform py
- Three types -
  - micron sized pyrite clusters
  - Framboidal pyrite
  - "sooty" pyrite
- Interpretation: syn-sed. to early diagenetic
Microtexture of the stratiform Py1; Clusters of fine 1-2 micron py
• Py1 is rich in a wide range of trace elements
• Gold content varies from 0.44 to 12.10 ppm; mean = 3.32 ppm Au
• Arsenic varies 180 to 14,000 ppm; mean = 1900 ppm As
• Elements which show a positive correlation with Au in Py1; Cu, Ag, Pb, As, Sb, Te
Py1 Chemistry

Laser analysis: Fe09A17

Fe standard
288 ppm Pb
170 ppm Co
650 ppm As
84 ppm Sb
175 ppm Ni
5 ppm Bi
6 ppm Ag
0.75 ppm Au
Py2 euhedra overgrow and replace Py1
Pyrite 2

- Clear py euhedra
- Overgrows and surrounds py 1
- Interpretation: early diagenetic; may involve recrystallization of pyrite 1
Py1 overgrown by Py2 overgrown by arsenopyrite
Py2 Chemistry

- Py2 is depleted in most trace elements compared to Py1; Au, Ag, Cu, Pb, Te, Zn, Sb
- As, Ni and Se remain at similar levels to Py1
- Gold content varies from 0.02 to 13.00 ppm; mean = 1.02 ppm Au
- Arsenic varies 2 to 18,550 ppm; mean = 4260 ppm As
Pyrite 3

- Inclusion rich
- Irregular outlines
- Fluffy or porous texture
- No obvious structural fabric
- Aligned along bedding
- Confined to sandstone layers
- Interpretation: diagenetic or metamorphic??
Pyrite 3

c59|210
Pyrite 3

- inclusions of po, cpy, sp and silicates
- no aligned internal fabric
Pyrite 3: internal fabric revealed after etching indicates Py3 most likely has a late diagenetic to early metamorphic timing overprinting a weak D1 sandstone fabric
Py3 in Sample 156/135.5

- Cpy
- Framboidal Py1 in Py2
- Py2 in Py3
- Framboidal Py1
- Py2 clusters
- Sphalerite
- Cpy
- Weak fabric
Pyrite 3, also has Au inclusions
Although Py3&4 may contain microscopic gold grains, the pyrite itself is depleted in gold compared to Py1&2.

Gold exhibits two populations: a low gold and high gold population.

Over 80% of Py3 is the low gold population which varies from 0.05 to 2.2 ppm; mean = 0.16 ppm Au

The minor high gold population varies from 4 to 82 ppm gold, with a mean of 30 ppm Au

Arsenic varies 7 to 31,000 ppm; mean = 2900 ppm As
Py1 is enriched in Au, Pb, Cu, V, Sb, but depleted in As & Ni cf Py3
Pyrite 4
Isolated large euhedra
Pyrite 4

- Large isolated euhedral pyrite in shale
- Quartz pressure shadows are common
- Internal fabric in Py4 shows the main cleavage(s)
- Abundant aligned micro-inclusions
- Interpretation: pyrite replaces all sediment components and inherits the structural fabric of sediments: Late metamorphic
Pyrite 4

Growth zoning

Internal deformation
Fabric revealed by acid etch
Py4 overprinting rock fabrics
Free Gold in Py3/4
Pyrite 4/ Pyrite 5
Py4 Chemistry

- Although Py3&4 may contain microscopic gold grains, the pyrite itself is depleted in gold compared to Py1&2
- Gold content of Py4 varies from 0.02 to 1.30 ppm; mean = 0.25 ppm Au
- Arsenic varies 400 to 5560 ppm; mean = 2270 ppm As
- Py4 is characterised by high Ti, up to 15,000 ppm (mean 1500 ppm). This relates to the abundant inclusions.
Pyrite 5
overgrows and may cut pyrite 4 (open space growth)

Po replaces Py1

Pyrrhotite is common in Py 4 assemblages
Pyrite is progressively depleted in gold from Py1 to Py5.

- **Py1** mean = 3.32 ppm Au
- **Py2** mean = 1.02 ppm Au
- **Py3** mean = 0.16 ppm Au
- **Py4** mean = 0.25 ppm Au
- **Py5** mean = 0.07 ppm Au
- **Po** mean = 0.002 ppm Au
# Pyrite and Gold Paragenesis

<table>
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<th>Pyrite</th>
<th>Sedimentation-diagenesis</th>
<th>Metamorphism</th>
<th>Post-peak metam.</th>
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<tbody>
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<td>gold dissolved in As-rich pyrite</td>
<td>Py1</td>
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<td>Py5</td>
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<tr>
<td>Au-Te-Pb-Bi-Ag association</td>
<td>Py2</td>
<td>Py4</td>
<td>Py6</td>
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<td>free gold</td>
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Pyrite and gold paragenesis involve various stages of geological processes, including sedimentation-diagenesis, metamorphism, and post-peak metamorphism. Each stage is characterized by the formation and distribution of different mineral assemblages, such as pyrite with gold, arsenopyrite, and various gold-arsenic associations. The diagram illustrates the temporal and spatial relationships between these processes and mineral deposits.
Pyrite in Py-Qtz Veins
Pyrite in py-qtz veins is zoned
Pyrite in py-qtz veins
Analysis of py3 core

Inclusions of galena with dissolved Bi-Ag-Au-Te
Galena Inclusions in Py3 Cores

- Bi, Ag, Au, Te are dissolved in the structure of the galena
  - 1.9 wt% Bi
  - 1.1 wt% Ag
  - 257 ppm Au
  - 423 ppm Te
Growth of py-Au-qtz veins

1) Early diagenetic pyrite and arsenopyrite growth along bedding

2) Late diagenetic py3 and early metamorphic py4 overgrowths

3) syn-tectonic py5 and quartz pressure shadow growth
Gold Events at Sukhoi Log

• The stratiform py1 represents the first (SEDEX) gold event (Au-As) from shallow basinal fluids
• The dageneitic cores to the bedding parallel veins represent the second gold event (Au-Ag-Pb-Te-Bi) from deeper basinal fluids
• On-going metamorphism led to remobilisation of free gold into later, more radiogenic, pyrite generations
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Bodaibo Basin: Reduced and Gold-rich

From Buryak (1982) and Yakubchek et al. (2005)
Key message: *Free gold in late pyrite does not mean the timing of gold is late, i.e. syn- or post-tectonic*

*Much gold is introduced early into sedimentary and volcanic basins, where it resides in arsenian pyrite*
Thank You