OROGENIC GOLD MINERAL SYSTEM

Greg Hall

Golden Phoenix International

With acknowledgements to Scott Halley, John Walshe, Bruce Hobbs, Graham Begg, Ned Stolz, Janet Tunjicja, Karen Connors, Vic Wall, Chris Heinrich and many others including Goldfields, Barrick Gold Corporation, Centamin, Nyota, Chalice Gold Mines

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Giant Gold Deposit Database

Deposits greater than 150t contained gold

<table>
<thead>
<tr>
<th>CLASS</th>
<th>Number</th>
<th>Gold t</th>
<th>%</th>
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<td>Orogenic</td>
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<td>25,643</td>
<td>28.0</td>
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<td>Porphyry / Epithermal</td>
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<td>14,241</td>
<td>15.6</td>
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<tr>
<td>Carlin</td>
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<td>1,525</td>
<td>1.7</td>
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<td>91,435</td>
<td>100.0</td>
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Source: Placer Dome Exploration Database
**Giant Gold Deposit Database**

Deposits greater than 150t contained gold

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<tr>
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<th>Gold t</th>
<th>%</th>
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<tbody>
<tr>
<td>OROGENIC</td>
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<td>Intrusive Related</td>
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<td>TOTAL</td>
<td>55</td>
<td>25,643</td>
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<td>EPITHERMAL</td>
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</table>

Source: Placer Dome Exploration Database
THE OROGENIC GOLD MINERALISING SYSTEM

GEODYNAMICS
ARCHITECTURE
FLUID SOURCES
FLUID PATHWAYS AND DRIVERS
DEPOSITION MECHANISMS

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THE OROGENIC GOLD MINERALISING SYSTEM

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Au & Cu-Au Deposit Genesis

MAIN SETTINGS

– Inverted Peri-cratonic (± backarc) Basins
  • West Lachlan, Yilgarn, Abitibi, Tintina Belt, Birrimian, Arabian Nubian Shield, Lake Victoria, Tianshan

– Magmatic Arcs with history of disrupted subduction (e.g. collision & polarity flip; flat slabs)
  • SW Pacific Cu-Au porphyries and epithermal Au; East China

– Combination of the above
  • Great Basin/Carlin Trend

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Metasomatized (Ancient?) Mantle

- Common to most of these settings is the presence of continental lithospheric mantle (SCLM), either as the substrate to pericratonic margins or as microcontinental blocks
- Alkaline mantle-derived melts are an important ingredient in gold-rich magmatic systems (Loucks & Ballard, 2003) and possibly also in Orogenic Au systems
- Metasomatism of lithospheric mantle by subduction-related magmas/fluids creates the source region for these melts

Ancient lithospheric mantle domains accumulate this metasomatism throughout their history – a metal source region waiting to be tapped!

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Backarc/Peri-cratonic: VMS & CD base metal, Ni sulphide

VMS Base Metal:
- Melting of metasomatised CLM (metal source)
- Most favored if spreading ridge migrates into CLM
- Moderate preservation potential if peri-cratonic basin narrow

Graham Begg, 2011
Orogenic Au:
- Flanked by metasomatised CLM (metal source)
- Closure and suturing leads to selective melting of source
- Reduced sediments are a good host rock
- High deposit preservation potential

Late orogenic gold in inverted peri-cratonic basin

Erosional loss of Porphyry + Epithermal deposits

Graham Begg, 2011
Kalgoorlie Geochronology

Thol. Basalt +/- UM volcanism
Komatiite
TTG volcaniclastic (Black Flag)
Bimodal (Teutonic)
dolerite
Coarse clastic
D2

High-Ca Granite
Mafic Granite
Low-Ca Granite

VMS
Ni
De
De

Au
Laverton Geochronology

2820 2800 2780 2760 2740 2720 2700 2680 2660 2640

Thol. Basalt +/− UM volcanism
Calc-alk andesite
Komatiite/Thol. Basalt
Volcaniclastic
Caarse clastic
High-Ca Granite
Low-Ca Granite
Mafic Granite
Syenite

Ni Au Ni Au
WINDARRA ADMIRAL HILL AGNEW GRANNY SMITH, SUNRISE, WALLABY

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OROGENIC GOLD Geodynamics

• Gold is always immediately post-metamorphic peak for large deposits or later for smaller deposits
• Gold is always after collision and deformation
• Regional magmatism shows evidence of mantle contamination
• Giant gold deposits are located above collision boundaries
• Gold deposits formed at depth are never refractory. Gold deposits formed at shallower depths often are refractory (not enough heat in the wall rocks to anneal sulphides or recrystallise “preg-robbing” hydrothermal carbon after formation)
OROGENIC GOLD Geodynamics

• Arabian Nubian Shield is a composite terrain of largely oceanic crust micro-continents that amalgamate in the Pan African Orogeny
• There is no pre-existing continental basement only new crust hence VMS deposits can form
• The formation of this mafic crust created depleted sub-continental lithospheric mantle
• The coalition of these fragments is driven by oceanic plate subduction which metasomatises the depleted sub-continental lithospheric mantle
• The Arabian Nubian Shield is highly prospective for large VMS, Nickel and Gold deposits
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OROGENIC GOLD Architecture

• Major gold deposits are located in giant antiforms in the hangingwall of suture zones of cratonic fragments
• The suture zone extends to the crust mantle boundary
• Major gold deposits are located above this suture zone where that zone is intersected by a major deep fault at high angle to the suture zone
• Major gold deposits are located immediately within or adjacent to a late sedimentary basin or cover sequence
SEISMIC CROSS SECTION KALGOORLIE 100moz

KALGOORLIE TERRANE

KURNALPI TERRANE

IDA FAULT

Bullabulling Shear

Dunsville Syncline

Kunanalling Shear

Kurrawang Syncline

Mt Pleasant Anticline

BARDOC Deformation Zone

Scottia-Kanowna Anticline

Mt Monger Fault

Emu Fault

Avoca Fault

(does not outcrop in this section because it is intruded by the Arcoona Granites)

Arcoona Granite

Depth (km)

10km

V/H = 1

10

5

Upper basalt

Undivided basalt

Komatiite

Lower basalt

Early granite

Felsic gneiss

Basal felsic schist

Late granite

Felsic volcanic rocks

Felsic volcanic unit

Greenstone sequence (in Bardoc Shear Zone)

CDP

7200

9200

11200

13200

15200

17200

Two-way time (s)

0

5

10

15

20

MID CRUST ANOMALY

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Seismic Line NY2 at LAVERTON Yilgarn Province

• Greenstone Belt extends to between 5 and 13km
• Quiet Zone probably comprises homogeneous and weakly foliated granites
• Thick zone of probably basement gneiss. Cuts are interpreted as faults and shears, mainly as thrusts
• Master fault extends to the mantle
• Host 7mozs on section

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Seismic Section at Red Lake Canada
Host to 40 mozs

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“Observe” the magma chamber in the geophysical image

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Non-reflective zone; intrusive complex that produces the gravity-low.

Seismic section courtesy of Ned Stolz, Gold Fields, St Ives
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OROGENIC GOLD Architecture

• Arabian Nubian Shield is comprised of numerous terrains whose boundaries strike largely north south
• The northern ANS (Egypt) shows metamorphic core complexes and late sedimentary basins (molasse)
• The southern ANS (Ethiopia, Eritrea) shows deeper levels of erosion with larger plutons and lacks late sedimentary basins
• Sukari (14mozs) is located on a crustal suture at intersection of Najd Fault System and is adjacent to a molasse basin located in the footwall of a suture zone
OROGENIC GOLD Architecture

Fig. 1 General geology and location of gold deposits of the central Eastern Desert. Note concentration of metal occurrences close to major faults. Location of the Najd Fault System (NFS) is marked in the inset.
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OROGENIC GOLD Fluid Sources

• Ultimate source of gold and much of the sulphur is depleted sub-continental lithospheric mantle (SCLM)
• Fractionated deep source crustal magmas (syenites to I type granite) act as fluid carriers. Intrusive porphyries and lamprophyres often occur at the site of gold deposits. Seismic reflection and gravity data show magma bodies at depth.
• Fluids are oxidised and precipitate anhydrite
• Locally mantle fluid arrives direct at the deposition site and creates very high grade veins. Fluid inclusions in these gold veins are CO2-SO2 mixtures devoid of water. Celestite (Sr carbonate) in these veins shows a pure mantle isotopic signature.
• Gold is carried as a thio-sulphate complex
Enriched trend

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Significant Au and pyrite content in porphyries that are not notably altered;)
 Fluid is in equilibrium with the porphyry.
*Some of the St Ives porphyries are inherently enriched in Au and S*
3D Model of the Beta Porphyry
1 billion tonnes
mean gold grade = 0.37 g/t
~ 12 million ounces

Footwall porphyries commonly have 100mt to 1,000mt of porphyry @ 0.05 to 0.5 g/t Au, e.g. Victory, Revenge, New Celebration, Binduli, Mt Pleasant, Kundana, Granny Smith, Lancefield, Mt Morgans, Agnew, etc

All gold-rich porphyries have the same enriched trace element signature!!!
Compare Beta Porphyry + Santa Anna T with all mafics.
FI 7, Beta Porphyry

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Santa Anna Trondjhemite
OROGENIC GOLD Fluid Sources

• Late basins hold water and black shale. Methane is generated during gold deposit formation
• This reduced fluid is convected into the orogenic gold system during gold deposit formation
• The mixing of these two fluids causes precipitation of gold from thio-sulphate complexes by reduction of sulphate to sulphide
• Locally this fluid mixing precipitates hydrothermal carbon by the reaction

$$\text{CO}_2 + \text{CH}_4 \rightarrow 2\text{C} + 2\text{H}_2\text{O}$$
OROGENIC GOLD Fluid Sources

• Arabian Nubian Shield is host to late fractionated acid intrusive rocks that stitch along crustal sutures
  • Sukari (14mozs) is hosted by a highly fractionated intrusive rock
  • Zara (1mozs) is hosted by a fractionated intrusive rock
  • Host rock at Sukari contains black shales
  • Late sedimentary basins near Sukari occur in the footwall of the suture fault. This basin was far more extensive than the currently preserved remnants

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OROGENIC GOLD Fluid Pathways and Drivers

• The architecture of the system above the mantle tapping fault promotes fluid mixing
• The architecture involves antiforms existing beneath seals (usually regressive sedimentary sequences or sometimes thrusts)
• Gold deposits occur in areas of intersecting faults that were active during sedimentation of the host sequence and act as valves (not pumps)
• These faults access reservoirs of fluids with different redox potential
• Intersecting faults beneath a seal define an ore system

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St Ives Goldfield
Keys to size and grade??

• Fluid mixing

• An architecture promotes fluid mixing
“Observe” redox gradient in mineral zonations

- Oxidized
  - Hematite
  - Magnetite*
  - Pyrite
  - Arsenopyrite
  - Pyrrhotite*
  - Loellingite

- Reduced

*Magnetic minerals detected in aeromagnetic surveys
“Observe” the magma chamber in the geophysical image

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St Ives: Alteration in sediments

- Playa Fault
- Conqueror Fault
- Revenge
- North Orchin
- Victory Defiance

- Magnetite
- Pyrite
- Pyrrhotite
Gravity image of the Victory-Defiance Revenge Districts

Red – magnetite

Pink – magnetite/pyrite

Gamma West Fault

Mount Blanc Fault

Playa Fault

Revenge

North Orchin

Victory Defiance

After Ned Stolz
Karen Connors

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Interplay of fluids-architecture

Revenge through Victory-Defiance

After Ned Stolz & Janet Tunjicja
OROGENIC GOLD Fluid Pathways and Drivers

• Arabian Nubian Shield hosts numerous inversion structures
• The molasse basin near Sukari is preserved in the footwall of a major fault. The preservation of the highest part of the sedimentary stratigraphy in the footwall of a major fault is a classic indicator of basin inversion.
• Sukari porphyry is hosted in a postive flower structure at a bend in the major suture
• Uplift and erosion of the hangingwall of the porphyry complex during magma emplacement will promote rapid fluid release in deep magma chambers that are exsolving these fluids
OROGENIC GOLD Fluid Pathways and Drivers

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OROGENIC GOLD Deposition Mechanisms

• The architecture is host to a reduced host rock equilibrated fluid preserved beneath a seal

• The arrival of oxidised magmatic fluid into the reduced host rock fluid causes precipitation of gold from thio-sulphate complexes by reduction of sulphate to sulphide

• Locally this fluid mixing produces hydrothermal precipitated carbon by the reaction

\[ \text{CO}_2 + \text{CH}_4 \rightarrow 2\text{C} + 2\text{H}_2\text{O} \]
OROGENIC GOLD Deposition Mechanisms
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Pathways of $CO_2 - SO_2$ fluids

$\delta^{18}O$ Integrated Section

13 - 20 > ~ 20 $\%_{oo}$

0 500m

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OROGENIC GOLD Deposition Mechanisms

High T anhydrous-oxidized fluid (-3 to -5)

Approximate upper limit of anhydrite

SO₂ - CO₂

δ³⁴Spry Integrated Section

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OROGENIC GOLD Deposition Mechanisms

\[ 3\text{CH}_4 + 4\text{SO}_2 = 3\text{CO}_2 + 2\text{H}_2\text{O} + 4\text{H}_2\text{S} \]

CD5653: Carbonaceous Kapai in switch from oxidized to reduced zone in flat structure

Detectable zone of reduction above East Repulse

East Repulse

SO\textsubscript{2} - CO\textsubscript{2}

Integrated Section

\[ \delta^{13}\text{C} \]

Mantle CO\textsubscript{2}

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All Pyrite grains at KB are zoned; In the ore zone, $\delta^{34}S$ values in pyrite cores are negative (oxidised fluid), Distal to ore, $\delta^{34}S$ values in pyrite cores are strongly positive, $\delta^{34}S$ values in all clean rims are $\sim +2$ per mil Pyrite growth at KB records a history of reduced fluids overprinting an oxidised fluid system.

Spatial and temporal evolution from oxidised and alkaline to acid and reduced!!

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OROGENIC GOLD Deposition Mechanisms

• Arabian Nubian Shield is host to major gold deposits. The gold deposits in the southern ANS (Tula Kapi, Zara) are free-milling. A giant gold deposit of the northern ANS (Sukari) requires fine grinding to 10 micron to liberate the gold
• Sukari shows at least two magma pulses and a alteration evolution from early biotite magnetite, through hematite to late albite-sericite-pyrite
• Sukari shows anhydrite at depth
• Sukari shows hydrothermal carbon in the footwall to high grade gold zones
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