Preservation as a Predictive Concept in Regional Gold Exploration

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New Approaches in Regional to Mine-Scale Targeting of Gold Systems
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Introduction

• Preservation – Critical Issue in Targeting

• Can we be Predictive? – Yes!
Key General Observations

• General association between gold deposits and terranes with preserved supracrustal rocks of host cycle

• Secular distribution of some deposit types (eg Porphyries) well explained by progressive erosion but not others (eg Orogenic Gold deposits)
Secular deposit distribution and preservation:

A progressive erosion model (dashed lines) explains observed distribution of Epithermal and Porphyry deposits well but not Orogenic deposits (Kesler & Wilkinson, 2006)
A New Concept: The Gold Depositional Window

• Analogous to the “Petroleum window” in oil exploration, which must be preserved for a basin to be prospective
• Several important recent studies strongly implicate fluid depressurisation and unmixing as the fundamental gold depositional process
• Usually acts to deposit gold only in the upper 10km or less of the crust (more CO₂ – eg in Orogenic gold systems – allows somewhat deeper deposition)
• Terranes eroded deeper than 10-15km will be barren, irrespective of original endowment.
• Explains strong empirical relationship between supracrustal preservation and gold endowment.
Depth Control on Gold Grade in Porphyry Deposits

Murakami et al (2009)
Section through the Butte Deposit:
(~3km of vertical exposure after restoration of Continental Fault offset)
Note correlation between base of mineralization and lower limit of brine inclusions
(ie evidence for phase separation as critical control on mineralization)

Rusk et al (2008)
Au-Cu Centre: Low density vapour – very saline brine

Bingham Canyon:
Controls on Cu/Au deposition related to unmixing of an ascending ore fluid
(Landtwing et al, 2009)

Peripheral Cu Zone: Denser vapour – less saline brine
Orogenic Gold Deposits

- Above studies focus on Porphyry-style deposits but strong evidence for similar controls in Orogenic gold deposits:
  - Ubiquitous evidence for phase separation associated with ore deposition
  - Localised Gold-Quartz association
  - Deposits which “die out” at depth (eg Kalgoorlie, Norseman, Lancefield)
Norseman: 
Local Quartz-Au association within conduit implies pressure is key process

Campbell (1990)
Mararoa Reef (Norseman) Case study: Ore “Dies-Out” at about 1Km depth

Campbell (1990)
Schematic Section - Continental Crust
(Cawood et al, 2013)

Base of Gold Depositional Window - Porphyry Style deposits

Base of Gold Depositional Window - Orogenic Gold deposits (more CO₂-rich fluids)
Gold Deposits and Accretionary Orogens

- Almost all Au deposits and the majority of Cu deposits are associated with long-lived accretionary orogens.

- This probably reflects that they are the loci of long-lived and complex subduction and therefore optimum sites for the recycling of water and metals into the upper crust.

- Any predictive targeting for gold deposits (including related to the role of Preservation) needs to understand their context within Accretionary Orogens.
What are Accretionary Orogens?

- A complex convergent margin zone, developed along the margin of a continent
- Comprises an interacting complex of:
  - micro-continents (all derived locally from the adjacent major continent),
  - arcs (mostly built on micro-continental slivers)
  - back-arc rifts.
- Commonly long-lived (> 200 Ma) and form at the margin of major, Pacific-size oceans.
- Rifted micro-continents typically progressively re-accreted to the major continent over the life of the orogen
- Finally terminated by a major collision with an “exotic” continental block
Schematic Summary: Accretionary Orogen

Major Continent
(behaves as craton during Orogenic Cycle)

Major Long-Lived Ocean
(eg Pacific)

Accretionary Orogen
Schematic Summary: Collisional Orogen
This is a special type of orogenic event with great significance for gold metallogeny. Most major epochs of orogenic gold deposit formation occur association with this geodynamic context.

Schematic Summary:
Collisional Orogen terminating an Accretionary Orogen
Accretionary Orogens: Two Alternating States

Most of the Time

The Most Important Time

Source: Cawood et al (2009)
Retreating Accretionary Orogen: Japan Example

Leahy et al (2005)
Advancing Accretionary Orogen: Andean Example
“Fossilized” Ancient Accretionary Orogen: Altaides Example

Leahy et al (2005)
Granite-Greenstone Terranes

- Distinctive type of fossilised orogenic terrane

- Characteristic pattern:
  - anastomosing, curvilinear, volcanic-dominated supracrustal belts ("greenstone belts"), separating ovoid granite-gneiss domains, which comprise the bulk of the terrane

- Commonly well endowed with orogenic gold and VMS deposits

- Most common in Archean terranes but many Paleoproterozoic examples and some at least as young as the Late Neoproterozoic
Granite-gneiss domain:
Exhumed mid-crustal (10-20km) layer (core-complex)
Slightly younger than adjacent greenstone

Greenstone Belt:
Preserved volcanic-rich supracrustals in inverted rift zone

No exhumed Granulites – High T/Low P Metamorphism

Schematic Structural Architecture of a Generic Granite-Greenstone Terrane
Schematic Section - Continental Crust

(Cawood et al, 2013)

Max. Depth of Exhumation in Granite-Greenstone Terranes
Tectonic Interpretation of Granite-Greenstone Terranes

• Final products of cratonisation and subsequent erosion of complex accretionary orogens, where these developed over large-scale mantle thermal anomalies.

• Effect of mantle thermal anomaly:
  – Rifts more likely to be filled with volcanics
  – Widespread mid-crustal melting and emplacement of mantle-derived batholiths means little preservation of original basement in upper-mid crust
  – High-T mid-crust makes orogen weak and susceptible to extensional collapse, basement exhumation and the formation of core-complex style geometries (juxtaposing more deeply-eroded batholiths and supracrystal greenstone belts)

• Net result = better preservation of inverted rift zones!
Geodynamic Settings of Au Deposits in Accretionary Orogens

- Gold (-Cu) deposits are associated with particularly anomalous geodynamic settings within Accretionary Orogens.

- These include either the final terminal stage of such orogens or particularly anomalous periods of re-organisation during their evolution.

- Four major distinct tectonomagmatic associations can be recognised, each with a different geodynamic context.

- This framework is considered the best way to classify Au (-Cu) deposits at the regional targeting scale.
<table>
<thead>
<tr>
<th>Major Tectono-magmatic Setting</th>
<th>Deposit Types</th>
<th>Specific Favourable Geodynamic Regimes</th>
<th>Comments</th>
<th>Major Examples</th>
</tr>
</thead>
</table>
| 1. Active Subduction-Related Arc Magmatism | Porphyry and related deposits (e.g., High-Sulfidation Epithermal Au deposits) | • Transient anomalous compression  
• Transition from flat-slab compression to extensional slab roll back | Diversity of deposits depending on proximal – distal spatial relationship with magmatic centre | Tampakan, Bingham Canyon, Carlin? Grasberg |
| 2. Superimposed Rifting | Alkaline Intrusion Low-Sulfidation Epithermal Au; Bimodal Rift-Associated Low-Sulfidation Epithermal Au; VMS and VMS-epithermal hybrids | • Incipient extension associated with slab roll-back, either in the arc or back-arc position  
• Local extension within a collisional setting | Deposit type strongly dependent on degree of extension/water depth at time of mineralisation | Ladolam, Lihir, Cripple Creek, Porgera, Henty, Eskay Creek |
| 3. Inversion of Retro-Arc Pericontinental Rifts | IRG and Orogenic Au deposits | • Terminal stage of collisional inversion  
• Minor post-orogenic extension | Significant crustal magmatic contribution in this setting (a petrogenetically fertile environment) dominates mantle-derived component | Donlin Creek, Kalgoorlie, Muruntau, Ashanti, Bendigo |
| 4. Superimposed Impingement of a Hot Mantle Upwelling | Olympic Dam-type IOCG deposits  
Sleeper-style Low-Sulfidation Epithermal deposits | • Initial stages of hotspot impact on crust | Mineralisation may occur >100s my after cessation of active local subduction | Olympic Dam, Sleeper |

First-Order Classification: Accretionary Orogen Cu-Au Metallogeny  
(Hronsky et al., 2012)
Setting 1

Setting 2: Syn-Rifting (arc/back-arc)

Setting 3: Syn-Inversion (more CO₂)

Setting 4: Superimposed mantle upwelling
1. Granulite Facies terranes will only be prospective if overprinted by a late tectonothermal event

2. Each major Au deposit tectonomagmatic setting has a predictable preservational potential (at the end of its host orogenic cycle)

3. For those deposits with a high probability of surviving their host orogenic cycle (eg Orogenic Gold) long-term preservation depends on avoiding subsequent, overprinting orogenic cycles

4. Competing preservational processes may explain the Mesoproterozoic endowment gap for Orogenic Gold deposits rather than fundamental lack of endowment at this time

5. Deposits with a low probability of surviving their host orogenic cycle (eg Porphyries) will only be preserved in areas of anomalous subsidence. Interestingly, this is more likely for giant systems.
<table>
<thead>
<tr>
<th>Metallogenic Association</th>
<th>Typical Deposit Types</th>
<th>Emplacement Environment</th>
<th>Long Term Preservational Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Porphyry-suite deposits</td>
<td>Topographical positive Constructional Arcs</td>
<td>Low – typically very high denudation rates (up to 1km per Ma)</td>
</tr>
<tr>
<td>2</td>
<td>Rift associated Epithermal, VMS</td>
<td>Topographically negative Rifted Arcs; shallow rifts for Epithermal, deep submarine rifts for VMS</td>
<td>Low for Epithermals in shallow rifts; Moderate for VMS in deeper rifts (syn-cycle reworking and erosional possible)</td>
</tr>
<tr>
<td>3</td>
<td>Orogenic Au</td>
<td>Inverted Pericontinental Rift zones right at cratonisation</td>
<td>High – late orogenic timing means limited syn-cycle erosion, particularly in hot orogens</td>
</tr>
<tr>
<td>4</td>
<td>Olympic Dam style IOCG Sleeper style Epithermal</td>
<td>Intracontinental rifts or anorogenic sites</td>
<td>High if emplaced post-cratonisation Moderate if emplaced during the orogenic cycle</td>
</tr>
</tbody>
</table>

**Summary of the Preservational Potential of Major Au(Cu) deposit types that form in Accretionary Orogens**

Metallogenic Association framework derived from Hronsky et al (2012); Note that all deposits are susceptible to removal by subsequent unrelated orogenic cycles
Orogenic Au Endowment correlates with periods of Supercontinent Assembly but why the Mesoproterozoic Gap?
Proposed model of competing preservational processes to explain observed secular distribution of Association 3 (Orogenic) gold deposits.
Preservational Potential of Porphyry Deposits

- Porphyry deposits form in geological environments undergoing strong uplift - high probability of erosion relatively soon after formation.

- Therefore, most Porphyry’s are Cenozoic.

- Significantly, older deposits tend to occur as isolated giants (eg Oyu Tolgoi, Cadia) whereas younger deposits typically occur in belts of multiple deposits.

- Older deposits require anomalous post-ore subsidence for their preservation.

- Because localised subsidence may be controlled by the same type of major structural intersection that controls ore localisation, this may be more likely at the sites of giant deposits.
Number of known Porphyry deposits decreases dramatically with age.

Recent porphyry (i.e. <65 Ma) deposits have more chance of being preserved and are more common.

Preservation potential decreases with time due to erosion and crustal recycling.

Ancient porphyry (i.e. >65 Ma) deposits have less chance of being preserved and are rarer.

Wurst (2010)

After Cooke et al. 2005
Preservation of Older Porphyries requires overprinting extension soon after ore formation

- Boyongon (Pliocene covered by younger actively extending basin)
- Pebble (Mid Cretaceous porphyry covered by L. Cretaceous basin)
- Red Chris (L. Triassic porphyry at margin of E. Jurassic basin)
- Oyu Tolgoi (L. Devonian porphyry covered by older Devonian and E. Carboniferous basin)
- Cadia East (Ordovician porphyry covered by Silurian basin)
Model: Selective Preservation of Giant Porphyry Complexes

Formation

Anomalous Subsidence at First-Order Structural Intersection

Erosional Removal of all deposits except Giant
END