Controls on High-Grade Au Ore-Shoots: Towards a New Paradigm

Jon Hronsky

BALI 2013: East Asia – Geology, Exploration Technologies and Mines
28 May 2013
Introduction

• Never more important for the gold industry to target high-grade!

• Need a *process-based* model for controls on ore-shoot distribution

• Requires revision of existing structural targeting paradigm

• A simple model proposed with important practical targeting implications
Ore-shoot Controls: How to Move from Empirical to Predictive?

Peters (1993)
• Seldom articulated

• Correctly recognises mineralised volumes as sites of anomalous ore-fluid flux

• Assumes:
  – these are localised more-dilatant or more permeable rock volumes embedded within a larger-scale, less focused fluid flow system
  – they are generated by active syn-ore deformation
  – therefore, their location can be predicted by knowledge of structural geometry and syn-ore stress field
  – they are an intrinsic property of their host structures
The Current Paradigm for Ore Fluid Focusing:
Localised volume of higher fluid flux embedded within a broader flow system
Problem with the Current Paradigm: Lack of consistent predictive relationship between structural geometry and ore accumulation.

Cracow Epithermal Gold Deposit

Mickelthwaite (2008)
1. Gold deposits restricted to transient fluid-exit conduits, associated with the episodic rupture of underlying over-pressured reservoirs

2. Primary control on Au deposition within conduits is fluid unmixing in response to pressure decrease

3. In some cases, localised zones of dilatancy within these conduits result in enhanced unmixing and locally higher grades

4. Rheological architecture – not prevailing stress field - is the key control on location of both conduits and local high-grade ore-shoots
Fluid Exit Conduits

- Rock volumes that have been conduits for large amounts of fluid flux, usually over multiple cyclic events
- Zones of *extreme* crustal permeability and localized intense fracturing
- Sourced from underlying overpressured reservoir zone
- Break their way up to the surface, taking the easiest path
- May re-use existing structures or fracture previously intact rock
- Fluid-pulse related stress changes large and overwhelm ambient stress field
Fluid Exit Conduits and Ore-forming SOC Systems

- Fluid (Energy) Source
- Fluid Reservoir
- Transient Exit Conduit
- Fluid Sink
- Thermal Halo-produced by entropy dumped into environment
- Threshold Barrier (need not be a physical seal)
- Episodic focused energy and mass flux
- Slow persistent fluid flux
Electric Charges Accumulate Slowly

Threshold Barrier: Resistive Air

Transient Rapid Breach of Threshold Barrier

Ground

The Lightning Analogy for Ore-Forming Systems
The Lightning Analogy for Ore-Forming Systems

Electric Charges Accumulate Slowly

Threshold Barrier: Resistive Air

Transient Rapid Breach of Threshold Barrier

Ground
Porphyry Cu Example

From Sillitoe (2010)

Fluid Exit Conduit

Fluid Reservoir
El Teniente:
A well documented example of multiple, superimposed focused fluid exit events all using the same plumbing
Examples of Fluid Exit Conduits

New Holland: (Henson, 2008)
Section view

Fitzroy Fault and Au distribution (gold blobs):
*Image from Gocad looking SW?*

*Strongly fault controlled*

**Kanowna Belle**
Example
*(Henson, 2008)*

*Image from: Carl Young*
Ernest Henry IOCG deposit: Pipe-like breccia zone
(Cleverley, 2008)
Propagating Fluid pressure pulse:
30 day after-shock swarm – some > M 5.0
– transient permeability $10^5 - 10^6 \times$ background

Main Shock Rupture Site
(M 5.6-6.0)

Overpressured Evaporite sequence
(known from deep drilling)

Modern Process Model
Fluids do not respond passively to structure: They create their own Pipes!

Modeled Changes in Coulomb Failure Stress post rupture – no correlation with aftershock swarm

Modeled Changes in Pore Fluid Pressure post rupture - good correlation with aftershock swarm

1997 Umbria-Marche EQ
Controls on Conduit Localisation

- Key control is rheological structure of rock mass above reservoir – how easy is it for the fluid pulse to fracture itself upwards?

- Fault and shear zones effectively just another rock type

- Certain geometric patterns consistently favourable – “Lightning Rod” analogy
Fluid-pressure driven conduit development commonly prefers pipe-like volumes of more competent rock rather than pre-existing structures. Structures are important because they establish the rock geometry.
Examples of Ore-hosting Fluid Conduits in Brittle Pipes

Source: David Groves (Miller, 2008)
Two End-member types of Ore-Fluid Conduit

- **Type 1**: pervasively fractured rock volumes – individual fractures tend to be extensional and randomly oriented
  - Porphyry-style stockworks; more extreme types manifest as breccia pipes
  - Metal grade broadly proportional to fracture density – more or less the same metal-depositing process prevails uniformly throughout the conduit volume

- **Type 2**: associated with shear failure of pre-existing planes of weakness
  - Heterogeneous ore deposition (local high grades) related to *locally enhanced dilation* and associated pressure drop
  - Shear component causes local dilation of structural heterogeneities
Example of a fluid conduit dominated by shear failure (Mother Lode – Goldfarb et al, 2005)

Example of an fluid conduit dominated by extension failure (ie stockwork) (Los Sulfatos– Irarrazaval et al, 2010)

Type 1

Type 2
What Controls Conduit Morphology?

- Relationship between Pore Fluid Factor \( \lambda_v = \frac{P_f}{\sigma_v} \) and Differential (Shear) Stress \( (\sigma_1 - \sigma_3) \)

- In practice, three main geological controls:
  - Fluid pressure \( (P_f) \)
  - Depth of formation \( (\sigma_v) \)
  - Anisotropy of the rock mass \( (\sigma_1 - \sigma_3) \)
Conduit Morphology-Summary Model

Type 1: Uniform grade distribution dominates

Type 2: Local High-Grade Shoots dominate

Massive Sequence

Layered Sequence

Increasing ($\sigma_1$-$\sigma_3$)
Pressure Reduction and Ore Deposition

- Only a certain section of the ore-fluid conduit has the potential to host mineralisation:
  - “The Primary Depositional Interval”

- Increasingly clear this primary depositional control relates to pressure reduction and fluid unmixing in most gold deposits

- Where present, local high-grade ore shoots also appear to relate to locally-enhanced pressure reduction
Primary Depositional Interval – Epithermal Gold

Primary Depositional Interval ("Boiling Zone")

Hishikari Epithermal deposit, Japan
(Faure et al, 2002; modified after Ibaraki and Suzuki, 1993).
Primary Depositional Interval – Porphyry Example
Butte Deposit:

Note correlation between base of mineralization and lower limit of brine inclusions
(ie evidence for phase separation as critical control on mineralization)
Orogenic Gold Example - Norseman: *Local* Quartz-Au association within conduit implies pressure is key process

Campbell (1990)
Modeling indicates that small-scale rupturing of dilatant zones will produce flash vaporisation (Weatherly & Henley, 2013)
UNIFIED MODEL - ORE SHOOT FORMATION

1. FIRST ORDER CONTROL
Fluid exit conduit
- Fluid driven rupture zone which nucleates in underlying reservoir and propagates upwards

2. SECOND ORDER CONTROL
Primary ore depositional interval
- Usually paleodepth and/or lithology related
- May be >2km vertically or restricted to a narrow interval (eg, just below paleosurface)

3. THIRD ORDER CONTROL
Localised higher grade volume (not always present)
- Usually related to localised dilatant zone or zone of favourable substrate development (eg higher fracture density)
Applying the Model: Mararoa Reef (Norseman) Case study

First Order control: Fluid exit conduit
-intersection of (more brittle) mafic stratigraphy and cross-cutting u/mafic dyke swarm

Second Order control:
Base of Primary Depositional Zone?

Third Order control:
Local Dilational Zone
-local deflection of conduit-hosting shear fracture, controlled by dyke intersections

Campbell (1990)
So what are the practical implications of all this?
Exploration needs to target first-order plunge controls
Need to recognise ore-hosting fluid conduits where they are barren (like the nickel explorers!)
Conduit-focused rather than Structure-focused Targeting Perspective
Inferred Ore Fluid Path

Figure 1. Schematic NW-SE long section through the Lepanto lithocap and its enargite-Au ore body, largely offset from the underlying Far Southeast porphyry deposit (Garcia, 1991); long dashes show the unconformity. Potassic biotite in the porphyry and alunite in the lithocap are contemporaneous at 1.4 Ma (Arribas et al., 1995). Drilling through the lithocap near the vertical shaft, i.e., where the residual quartz is thickest, would not intersect the causative intrusion, its porphyry Cu deposit, or even proximal alteration.

Lepanto-Far South East “Elbow Bend” Example

Hedenquist and Taran (2009)
Flat lode systems need steep feeders somewhere!

Sunrise Dam example: Baker et al (2010)
Conclusions

• A new predictive framework is proposed for understanding ore-shoot formation and localisation

• The key to successful application is:
  – Understanding and not confusing the different scales of control on mineralisation
  – A conduit-centric rather than structure-centric perspective
  – Understanding the rheological architecture of the ore environment
END