A Systematic Framework for Targeting High-Grade Ore-Shoots in Gold Deposits

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Jan 2010
Introduction

- In most cases, the greatest leverage that a gold mine has to increase its profit margin is to increase its production grade.
- Given this, and the fact that most gold deposits contain a variable grade distribution, with localised higher-grade ore-shoots, it is surprising that the industry does not systematically seek to understand the controls on such ore-shoots and to systematically target them.
- This presentation attempts to provide the basis of a systematic framework for targeting high-grade ore-shoots within gold deposits.
- Most of these concepts will also be relevant to other hydrothermal ore deposits.
CONCEPTUAL BACKGROUND
Underpinning this framework are some recent developments in our understanding of the controls on the emplacement of ore-systems.

In particular, the concept of ore-shoots forming as transient fluid exit conduits from over-pressured reservoirs at depth is critical (ie as part of a self-organised critical system; Hronsky 2009)

This concept has several very important implications for how we think about ore-shoot emplacement.

Most significantly, it means that the current paradigm for structural targeting ore-shoots in hydrothermal ore systems is totally wrong.
A General Model for Ore-forming SOC Systems

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

- Primary focus of structural targeting for ore deposits
- Rock volumes that have been conduits for large amounts of time-integrated fluid flux usually over multiple cyclic events
- Represent zones of extreme crustal permeability
- Zones of localized intense fracturing
- Sourced from overpressured reservoir zone at depth (may be partly located within this zone)
Fluid Conduit Zones in Orogenic Gold deposits

(A: Mother Lode, California (Goldfarb et al. 2005) B,C: Bendigo (Cox, 2005)
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)
Ernest Henry IOCG deposit:
Pipe-like breccia zone
(Cleverley, 2008)
Ore-Fluid Focusing: The Current Paradigm

• The concept of ore-shoots as transient fluid exit conduits from over-pressured reservoirs at depth has very significant implications for how we think about the relationship between ore-shoots and the structural architecture that hosts them.
• The existing paradigm for the relationship between ore-shoots and host structures may be described as “structure-centric”. It focuses on the ore-hosting structure(s) and regards mineralisation as an intrinsic property of these structures.
• There are several implicit assumptions with this paradigm:
  – ore-fluid flow is focused within more dilatant parts of host structures
  – knowledge of structural geometry and the prevailing stress field can be used to predict these dilational sites
  – these ore-hosting dilational sites are surrounded by a rock-volume which is saturated in ore-fluid, readily available to be drawn through these segments (this particular implied assumption is rarely acknowledged!)
Fault Geometry and Ore-fluid Focusing: The Existing Paradigm

Source: Montpellier University Website
Problems with the Current Paradigm

- The current paradigm is based on the robust observation that ore-shoots are commonly associated with anomalously oriented segments of their host structure.
- The simplest explanation for this, formalised at least as early as the 1930’s with the development of the “Shear-Link” hypothesis at Norseman, seemed to be that these mineralised segments were more dilational.
- The primary problem with this hypothesis is that although there definitely is a relationship between heterogeneous host structure geometry and mineralisation, it is not consistent.
- Within the one host structure it is very common to find ore-shoots associated with segments interpreted to be both dilational and contractional.
- As a result, this paradigm has no conceptual predictive capability at the ore-shoot scale. In practice what is usually done is that an ore-hosting structural geometry is empirically defined and then analogue geometries are targeted elsewhere. This same basic methodology is applied even in sophisticated computer-based fluid flow modeling carried out by groups like the CSIRO.
But no consistent structural relationship between fault geometry and mineralisation!

Cracow Epithermal Gold Deposit

Mickelthwaite (2008)
Reason why the Current Paradigm is Wrong

- The SOC system- fluid exit conduit hypothesis explains why the current paradigm is wrong but also why ore-shoots tend to follow geometrical heterogeneities in host structures.
- In this model, the over-pressured reservoir at depth is breached when a seismic failure occurs which ruptures the seal to the reservoir. This rupture may actually be initiated by the progressive build up of fluid pressure within the reservoir.
- Following the initial rupture, fluids escape from the reservoir along the initial rupture plane but also generate their own after-shock sequence as this fluid pressure pulse seeks to escape upward; this is considered to be the basic process of ore-shoot emplacement.
- The fluid-pressure pulse will naturally seek to take the most efficient path to the surface and will therefore exploit any local structural heterogeneity it encounters – this explains the relationship between ore-shoots and pre-existing structures (and in particular where these are anomalously oriented).
- In some cases, the path of least resistance for the fluid pressure pulse may actually be to fracture an intact rock volume rather than to re-fracture an existing structure (eg Mt Charlotte style ore-bodies).
As will be shown below, the magnitude of the stress changes associated with this fluid pressure pulse are large and overwhelm the ambient stress field.

For this reason, the path of the ascending fluid-pressure pulse will have no particular affinity with more dilatant parts of host structures; it will instead focus where it is easiest to break the rock volume ahead of it and continue its upward path.
The 1997 Umbria-Marche Earthquake as a model

- The 1997 Umbria-Marche earthquake represents a particularly well-documented (Miller et al, 2004) modern example of the type of processes discussed above. It can be considered a model for the type of processes that form mesothermal gold deposits.

- Two ruptures of M 5.6-6.0 occurred near the top of an evaporite unit, at about 6km depth.

- This unit was known from deep (4.8km) petroleum drilling along strike to contain over-pressured CO₂ fluids. It was sealed on its top surface by a flat overthrust, with hydrostatic pressures above this.

- These initial ruptures were followed by a 30 day sequence of thousands of aftershocks, including some > M 5.0.

- Modeling indicates a strong correlation between the propagation of a fluid pressure pulse from this reservoir and the distribution of the after shock swarm.

- Aftershocks are most commonly modeled as a consequence of post main-shock stress redistribution. However, the modeled triggering amplitude of this fluid pressure pulse is 10-20 MPa, which is 2 orders of magnitude greater than the typical amplitude (0.1-0.2 MPa) of post-seismic stress changes. This implies that the effect of the fluid pressure pulse will overwhelm all other factors.

- The localised transient, post-seismic permeability associated with this fluid pulse has been modeled as 4 x 10⁻¹¹m²; 10⁵ to 10⁶ times > than background crustal permeability at that depth (6km).
Overpressured Evaporite sequence (known from deep drilling)

Propagating Fluid pressure pulse: (after-shock swarm)

Main Shock Rupture Site

1997 Umbria Marche EQ: Cross-section
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
CONDUIT GEOMETRIES AND NETWORKS
In the new paradigm, we now recognise fluid-flow conduits as the primary architectural element of ore-forming hydrothermal systems.

In other words, we have replaced the historical “structure-centric” framework with a “fluid-centric” framework.

Fluid conduits have a characteristic linear, pipe-like to ribbon-like geometry; they are essentially One-Dimensional features.

One-dimensional structural heterogeneities fundamentally must represent the intersection of two 2D curviplanar surfaces. The most common scenarios include the following:

- Structural intersections
- Structural deflections
- Fold hinge zones
- Intersections of structures and relatively brittle rock units
- Pipe-like volumes of relatively brittle rock, either related to primary emplacement geometry or later structural modification

A very important concept in the fluid-centric framework is that fluid conduits may be much more extensive features than the pre-existing structures which host them. A single fluid conduit may move between host structures as it propagates upward, depending on which pathway provides the path of least resistance to its propagation.
Conduit-focused rather than Structure-focused Targeting Perspective
• One of the more surprising things to emerge from this new paradigm is that fluid flow conduits may commonly follow quite torturous paths from source to sink, including right-angled bends in three dimensions.
• The existence of such right-angled bends, termed here “Elbow Joints” has obviously great importance for targeting in the near-mine environment (and perhaps at larger scales).
• Such bends are most likely to occur when a propagating fluid pressure pulse jumps from a steep to a flat structure (or vice-versa) as it moves upward, always seeking the path of least resistance. However, as the example on the next slide shows, they can also occur within a network of steep structures.
• Such “elbow bends” have been documented in modern seismogenic environments (Bonini, 2009) and in ore systems (Begg, 1996; Hedinquist, 2009)
Links between Mud-volcanoes and Deep Fluid flow inferred from Seismicity: Northern Appenines (Bonini, 2009)
Elbow Bend Example: Emperor Epithermal Au deposit, Fiji

Ore-Fluid Flow

Cross-Section (Begg, 1996)
Figure 7.7a. Prince Flatmake summary plan of ore grade distribution.

- Intersection Trace of the HW Shear
- Flat-plunging Fluid flow pipe
- Steep-plunging ore-shoot associated with loci of steep fluid flow pipe

Plan-section (Begg, 1996)
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 (Garca, 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)
Mapping Conduits when they are not Orebodies

- Although this model predicts that fluid-flow conduits will be vertically (and/or laterally) continuous features, this does not mean that they will necessarily be continuously mineralised along their entire length.
- As will be discussed further below, whether or not significant levels of gold are deposited along the conduit may depend on many other factors apart from fluid flux.
- To apply this targeting framework fully, we need to develop the geological skills to identify fluid conduits where these are not coincident with economic orebodies.
- This is directly analogous to the approach that Ni geologists at Kambalda and elsewhere have used for more than 30 years – they are routinely able to define high-magnesian komatiite channels in the absence of NiS mineralization.
- Expect that conduit zones outside ore bodies will be:
  - Zones of intense, relatively-barren, veining
  - Pipe-like volumes of anomalous (but sub-economic) gold
- May be able to image conduits in 3D datasets using Leap-Frog at a low cut-off grade?
Copying the Komatiite NiS Approach:
Find the Conduit then Find the Ore-shoot
The Implications of a Connected System

• This model predicts that the ore-forming fluid conduits must form a continuous network from source (the underlying over-pressured reservoir) to sink (where the fluids disperse, either at the surface or into some permeable sub-surface layer)

• The implication of this is an important constraint on conduit geometry relevant to near-mine exploration:
  – conduits should not terminate at depth (except within the source region)
  – Conduits may merge and bifurcate along the vertical extent of the system
  – The same amount of fluid must have flowed through any horizontal cross-section of a generally vertically-oriented fluid flow system
Need to think of our ore-systems as a connected network from source to sink.
TWO MAIN TYPES OF ORE-SHOOT:
AN EMPIRICAL CLASSIFICATION
Two Types of Ore-Shoots

- Depending on how the site of gold deposition relates geometrically to the fluid conduit zone, there are two fundamentally different types of ore-shoots:
  - Type A:
    - Gold along entire length of fluid conduit
  - Type B:
    - Gold strongly localised where fluid conduit intersects favourable depositional zone
- There are very important exploration implications in being able to characterise our ore-shoots in this way.
Characteristics of Type A Ore-Shoots

- Ribbon or pipe-like geometries
- Very extensive down-plunge extent
- Relatively-minor down plunge grade variation
- Gold deposition driven by:
  - gradients in T or P between source and sink (most likely?)
  - Near-simultaneous tapping and mixing of multiple heterogeneous over-pressured reservoirs
Section view

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

Kanowna Belle: Example of Type A Ore-shoot
(Henson, 2008)

Image from: Carl Young
Characteristics of Type B Ore-Shoots

- Relatively equant, “blob-like” geometries
- Represent the intersection of three curviplanar surfaces (cf Type A ore-shoots which represent only two)
- Limited vertical (plunge) persistence
- Require intersection of conduit with favourable depositional zone
- May be very high-grade
  - Are most very high-grade ore-shoots Type B??
Examples of Type B Ore-shoots

An example of Type B ore-shoot control; Cross-section through the Honko and Sanjin ore bodies at Hishikari, Japan (Faure et al, 2002; modified after Ibaraki and Suzuki, 1993). The bonanza veins are depicted as thick black lines; they have a limited vertical extent and are closely associated with the unconformity between the underlying Shimanto sediments and the overlying Hishikari Andesites.
Ultra High-grade Oroya Shoot

Oroya Shoot, Golden Mile, Kalgoorlie
An example of a Type B shoot associated with base of BFB?
PROCESS CONTROLS ON VARIABLE GOLD GRADE
What controls Gold Grade in conduits?

- Although we expect our high-grade ore-shoots to be restricted to the rock-volumes of our fluid conduits, we do not expect all the rock-volume of our fluid conduits to have high-grade.
- It is very important for us to consider the geological processes which lead to locally higher Au grades in a rock volume.
- It is noted that much recent research of Au deposition mechanisms has tended to focus almost entirely on those processes which might reduce Au solubility in the transporting fluid.
- However, to obtain high-Au grades in a rock volume, it is necessary to also physically deposit that Au in the rock volume. The processes which control this physically deposition may be unrelated to those processes which reduce Au solubility in the carrier fluid.
- The following slide attempts to elucidate from first principles the fundamental processes that might contribute to an increased Au grade in a rock volume.
A review of the possible processes involved in ore-shoot formation, their possible interactions and their underlying controls has been summarised in the following slide (“Influence Diagram for Ore-Shoot Formation”).

This review indicates that multiple process factors (both physical and chemical) may interact in a positively reinforcing way to generate ore-shoots.

However, the most important conclusion is that only three main independent geological elements are likely to control the complex factors which contribute to higher gold grades:

- Vertical level in the system
- Host-rock lithology
- Proximity to the core of the Fluid Conduit
Factors which locally enhance gold deposition

- Enhanced mineral substrate for gold deposition
  - Host rock type (including pre-ore alteration)
  - Carbon Oxides Sulphides
  - More competent rocks

- Enhanced surface area/unit volume (fracturing/ brecciation)
  - Fracturing enhanced near surface

- Total ore fluid flux
  - Greater $P_f$-driven fracturing

- Greater gradient in Au solubility
  - Likely higher $P_f$ gradient in conduit

- Vertical level in conduit system
  - Unmixing and mixing zones

Proximity to core of ore-fluid conduit

INFLUENCE DIAGRAM FOR ORE-SHOOT FORMATION (SINGLE EVENT)
A major theme that has emerged from this study is the importance of rapid fluid pressure changes in an ascending ore-fluid in driving gold precipitation.

Brown (1986) demonstrated that artificially-induced boiling of geothermal fluids could lead to very significant Au deposition (thin sulphide scales up to 7 wt% Au formed in pipes) from fluids that were strongly undersaturated in Au.

Subsequently, in studies of epithermal deposits, the concept that high-grade “bonanza” zones relate to the boiling zone has become well established.

However, there has seemed to be an implicit assumption that these processes were unlikely to be important in those deposits formed at deeper levels in the crust.

A number of recent studies however have strongly implicated the importance of rapid pressure change and mineralization at such deeper levels.

It is important to realise that in complex CO₂-H₂O fluids (which seem to characterise the deeper levels of porphyry and orogenic gold systems) successive stages of progressive fluid unmixing might occur.
Rapid Pressure Change and Mineralization at Deeper Crustal Levels

- There have been several recent significant studies relevant to this topic:
  - Rusk et al (2008) demonstrated that mineralization at the Butte deposit was clearly related to the onset of phase-separation in an ascending fluid plume. A particularly significant aspect of this study is that it unequivocally demonstrated the critical role of fluid-unmixing processes in a scenario with similar fluids to orogenic Au deposits (CO$_2$-H$_2$O) and at similar vertical depths (6-9 km).
  - Landtwing et al (in press) have demonstrated a similar process occurred at the giant Bingham deposit; they were also able to demonstrate that Au deposition was enhanced in the zone of strongest fluid upflow and phase separation.
  - Marukami et al (2009) have demonstrated a strong relationship between emplacement pressure and Au content in Porphyry deposits, which they relate to the role of fluid unmixing in response to rapid decreases in pressure.
  - Oliver et al (2009) have reported fluid inclusion evidence for dramatic syn-emplacement pressure drops (400 MPa to <150MPa) associated with emplacement of IOCG breccias in the Cloncurry District. Breccia emplacement initiated at about 10km paleo-depth.
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)
Barren Deep Core:
Single Phase Parental Fluids

Au-Cu Centre:
Low density vapour – very saline brine

Peripheral Cu Zone:
Denser vapour – less saline brine

Deep Periphery:
Single Phase Parental Fluids

Bingham Canyon – Zonation in Cu/Au and Grade and Relationship to Ore Fluid Physical Evolution
(Landtwing et al, In Press)
Landtwing et al Model for Cu/Au Zonation at Bingham:

Enhanced expansion of magmatic vapour in the core of the system, leading to greater Au deposition
Cryptocrystalline Quartz as an Indicator of Rapid Boiling

- We would expect that any quartz deposited from rapidly boiling fluids would be cryptocrystalline in form (i.e. because of its rapid deposition).
- Both Begg (1996) and Wurst (2004) have documented a close association between very high-grade Au mineralization and dark-coloured cryptocrystalline quartz at the Emperor and Mt Muro epithermal deposits, respectively. In the case of Emperor, there was also a telluride association.
- In both these cases, classic epithermal cockade and crustiform-style vein textures were also present, both associated only with lower-grade mineralization.
- Clout (1989) has also documented an association between dark-coloured cryptocrystalline quartz and the highest grade (“Green Leader”) Au-Te alteration assemblage recognised on the Golden Mile.
- This suggests that the very highest grade parts of the giant Golden Mile deposit (which were restricted to the uppermost parts of the system) represent boiling zones.
Boiling Zone-Related Ore-shoot Controls at Mt Muro Epithermal Deposit  (Wurst, 2004)

Competent units in the host sequence has provided a locus for brecciation, pressure release and constriction of the main upflow zone, leading to subsequent boiling and high grade gold precipitation.
High-Grade “Green-Leader” Au-Telluride Ore-shoot

Interpreted main fluid flow conduits

Low-grade “spent-fluid” zone

Base of Boiling Zone?

Long Section No.3 West Lode, Lake View Mine, Golden Mile, Kalgoorlie

Clout (1989)
The Relationship between Boiling Zones and Lithological Layering

• The location of boiling zones in epithermal ore systems has traditionally been considered to only relate to paleo-depth (although susceptible to some variation as the regional water table moves up and down)

• This study however has suggested an empirical relationship between the location of boiling zones and lithological layering:
  – Hishikari deposits occur close to the unconformity between underlying sediments and overlying andesites
  – At Mt Muro, the high-grade boiling zone deposits are closely associated with a more coherent basaltic-andesite layer (Andy Wurst, pers. Comm.)
  – In the Lake View #3 West Lode on the Golden Mile (see previous slide) an inferred boiling zone is associated with the boundary between Unit 8 and Unit 9 of the Golden Mile Dolerite (GMD). Elsewhere in the Golden Mile, similar very high-grade Au-Te assemblages are associated with the boundary between the GMD and overlying Black Flag Beds

• If this relationship turns out to be common, it suggests that the rapid pressure drops associated with boiling in epithermal systems are not simply a function of paleodepth but also depend on the dynamic processes of fluid emplacement and related fracturing of the rock mass.
The role of Surface Energy Effects and the Substrate

• To make a high-grade ore-shoot Au particles must be physically deposited within the host rock volume
• We have abundant evidence that this process of physical Au deposition is not simply a function of the Au saturation state of the carrier fluid.
• The following observations are commonly made in Au deposits (particularly the orogenic style):
  – In detail Au grains are often closely associated with the boundaries of gangue sulphide grains
  – It is common for Au grains to be located at either the wall-rock margins of host quartz veins (particularly where these margins cut sulphide grains) or associated with thin laminae of wall-rock selvedges within the vein; in contrast, it has been known since the 19th century that “buck” quartz veins are typically barren.
  – High-grade Au is commonly associated with carbon-rich lithological units
  – Fine-scale (mm-cm) variability in Au grade may occur associated with selective sulphide replacement of a magnetite bearing BIF
• All of the above observations are consistent with the conclusion that local, surface-energy related effects are important controls on gold deposition.
• Given that Au is likely present at only low concentrations in the host fluid, it is perhaps not surprising that locally favourable surface kinetics are required for deposition.
BIF-hosted Gold Deposit:
Note fine scale pyrite replacement of magnetite and associated Au deposition
(photo from David Groves)
Adsorption: An Important Process

- Adsorption is defined as the process by which a liquid solute accumulates on the surface of a solid.
- It is a surface energy effect; the atoms on the surface of any solid experience a bond deficiency because they are not wholly surrounded by other atoms. Thus it is energetically favourable for them to bind with whatever happens to be available (ie in the adjacent fluid).
- The exact nature of the bonding depends on the details of the species involved but it would be reasonably to expect metallic elements such as Au to be favourably attracted to sulphide grains.
- We have two very good “real-world” examples of the potential importance of adsorption in Au deposition.
- The most important metallurgical process in the modern gold industry is CIP. This process relies on the adsorption of Au, from an under-saturated solution, onto carbon and achieves gold loadings of up to 2 500ppm.
- Significantly, the best type of carbon to use has the highest surface area/mass ratio (and it turns out that coconut husks are the best source for this type of material).
- Another good example is the Champagne Pool in New Zealand. Here strongly Au under-saturated geothermal fluids are depositing up to several hundred ppm Au via adsorption onto As-Sb-Sulphide colloids.
- These two examples prove the role of sulphides and carbon as important Au-adsorpers and demonstrate that Au deposition does not actually need a Au saturated fluid!
Champagne Pool
Taupo Region, NZ

Several 100 ppm Au adsorbed on to amorphous orange As-Sb-S colloids from highly Au under-saturated fluids (Renders & Seward, 1989)
There are some important implications of the adsorption concept for the formation of gold ore-shoots:

- Au deposition may occur at favourable sites without the requirement for a prior chemical process to saturate the fluid in Au.
- Certain minerals (particularly sulphides and carbonaceous material, and perhaps oxides) are likely to be far more important in adsorbing Au than others. Therefore, rock types rich in these components may be favourably mineralised.
- Everything else being equal, the amount of gold deposited by adsorption processes in a volume of rock will be proportional to the amount of exposed surface area within that rock volume.
  - Therefore, zones with high ratios of fracture density per unit volume are likely to be more favourably mineralised.
  - This effect may be part of the reason for higher Au grades in more intensely fractured and brecciated rock volumes.
What about Fluid Mixing?

- Fluid mixing has recently been commonly invoked as an important depositional process because of its potential to produce very strong gradients in fluid chemical parameters, likely leading to bulk metal deposition.
- If fluid mixing is to be invoked however, the proposed scenario must satisfy a basic physical constraint; the two fluids must be able to mix in **broadly equivalent mass proportions**.
- This physical constraint is clearly met when ore-fluids discharge into their sink zones; either the hydrosphere or some permeable sub-surface aquifer.
- Perhaps the best examples are VMS deposits, where the ore-fluids discharge onto the sea-floor.
- Henty and Eskay Creek are Au-rich examples of this scenario.
- Realistic fluid mixing scenarios within the conduit network are more difficult to imagine however.
- Two scenarios might work:
  - Local intersection with an upper overpressured reservoir with different fluid composition (possibly Black shale related-Oroya Shoot scenario?)
  - At initiation the fluid conduit taps and mixes two reservoirs which had somehow remained separate prior to rupture.
Discharge Zones: The Optimal Site for Fluid Mixing

Discharge into a Surface Sink

Discharge into a Sub-surface Sink
PRACTICAL METHODOLOGIES
Applying These Concepts

- The purpose of this section of the presentation is to propose a systematic methodology for applying these concepts to increase exploration success in the near-mine environment for high-grade gold ore-shoots.
- It is noted that in many gold mines little effort is made to explicitly delineate the high-grade ore-shoots that occur within a broader minable envelope.
- Therefore, the starting point for a focus on targeting high-grade needs to be a rigorous empirical definition of the currently known high-grade ore-shoots and their geological controls.
Where are the conduits on this map? Which way are they plunging? Where do they intersect favourable units?
Recommended Practical Methodology

1. Complete 3D modeling (eg using software like LeapFrog) of all deposits at a series of higher COGs to determine presence, nature and geometry of high-grade ore-shoots.

2. Apply a systematic ore-shoot nomenclature to each deposit that attempts to identify each distinct conduit zone. Nomenclature should be numeric in form and leave space for new intervening discoveries (eg ORSHT10, ORSHT20 etc). The purpose of this is to focus attention on the connectivity and continuity of these conduit zones.

3. To the extent possible, produce an interpretation of the likely conduit network – any gaps represent targets.

4. Identify and classify all ore-shoot terminations at depth using the framework presented in this report. Develop follow-up exploration strategies as appropriate.

5. Apply the Ore-shoot Classification Decision Tree presented in this report to classify all identified ore-shoots and to match them to their optimum targeting strategy.
EVALUATING ORE SHOOT TERMINATIONS AT DEPTH

1. LIMIT OF FAVOURABLE DEPOSITIONAL HORIZON

2. LATE FAULT OFFSET

3. MERGER WITH ANOTHER CONDUIT

4. ELBOW JOINT

5. ECONOMIC ARTIFACT

6. BASE OF FUNDAMENTAL DEPOSITIONAL PROCESS
<table>
<thead>
<tr>
<th>Ore-Shoot Type</th>
<th>Optimum Targeting Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>Systematically follow down-plunge; focus strongly and understanding nature of any terminations with depth (be aware of post-ore disruption, elbow bends and economic artifacts) and the potential for continuations. Understand the 1-D structural heterogeneity that has localised the ore-shoot and target repetitions under cover elsewhere.</td>
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<tr>
<td><strong>B1a</strong></td>
<td>Identify proxies for critical paleo-depth level (eg structural/stratigraphic level). Major sub-horizontal stratigraphic boundaries may be particularly important. Target inferred conduit positions in these intervals. Target down-thrown areas for blind deposits. Be aware of post-ore disruption and paleo-water table fluctuations in epithermal environment.</td>
</tr>
<tr>
<td><strong>B1b</strong></td>
<td>Define stratigraphic surface which represents discharge zone (eg paleo-seafloor; may be marked by lateral exhalite); target the intersections of other potential conduits zone and this paleo-surface.</td>
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<tr>
<td><strong>B2a</strong></td>
<td>Map the conduit network in 3D, including non-mineralised segments. Target other intersections of the identified favourable host lithology with this network. Be aware of alternative ore-shoot localising scenarios along the extent of the conduit network (eg localised rheological contrast).</td>
</tr>
<tr>
<td><strong>B2b</strong></td>
<td>Map the conduit network in 3D, including non-mineralised segments. Target other intersections of the identified favourable host lithology with this network. Consider and target other lithological geometries that may have same rheological properties as the known ore-shoot hosting scenario. Be aware of alternative ore-shoot localising scenarios along the extent of the conduit network (eg enhanced adsorption controls).</td>
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Example of Targeting the Paleo-Boiling Zone Level in an Epithermal System: Pachuca – Real del Monte District

Simmons et al (2005)