The Mineral System Concept: Key to Predictive Exploration Targeting

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Mineral systems are complex dynamic systems exhibiting self-organised critical (SOC) behaviour.

Critical elements of mineral systems are whole lithosphere architecture, transient geodynamic triggers, fertility, and preservation of primary depositional zone.

In application of the mineral system concept, SCALE of decision must be matched to scale of relevant geological process.
The Problem

2.7-2.6 Ga Ni and Au in the Yilgarn WA
How to predict location and geometry of new high quality mineral districts – camps – oreshoots?

Craton / district scale

Deposit scale

Camp scale

Oreshoot scale

St. Ives Au
(Miller et al. 2010)

New Holland Au
(Henson, 2008)
Deposit Models

Our current view of deposit ‘footprints’

after Sillitoe (2012)
A New View on Footprints

In exploration for new high quality mineral districts under cover, it is the largest scale footprint of the deposits that is relevant to our targeting models.

These large scale footprints differ substantially from the local expressions captured by traditional analogue models.
An Example of a Large Scale Footprint

After Harper & Borrok (2007)

Understanding large scale mineralisation footprints quickly narrows the search space for large mineral districts
We Need Non-Traditional Datasets to See Large Footprints

Need to understand the entire system

Magnetotelluric Section through Olympic Dam

Modified after Hayward, 2004; Magnetotelluric section provided R. Gill, Uni. Adel; “hotter” colours are more conductive
Mineral Systems Science

Mineral deposits = expressions of multiscale earth processes focussing energy and mass transfer at a range of scales

Process based, rather than analogue based

Substantial predictive power compared to traditional approaches based on analogue deposit models

Examples: Yeelirrie Calcrete U, Olympic Dam Cu-U-Au, Nebo Babel NiS
Mineral Systems - Some Constraints

Take elements at low concentration from large volumes of rock to high concentration in small volumes of rock.

Only plausible mechanism is through advective mass flux - needs a fluid (fluid/magma).

Ore deposits therefore are foci of large scale advective mass and energy flux.

Fluid needs to be low viscosity, available in large quantities over short timeframes, highly organised (focussed in space and time).

Mineral systems are dynamic complex systems.
Understanding Dynamic Complex Systems

Structure and Pattern in Earth Systems
e.g. Power-law size frequency distributions (scale invariant) in Earth Systems

Example: Gutenberg-Richter earthquake scaling.

Example: Fault size populations

Example: Superior craton, greenstone-hosted lode gold

Malamud & Turcotte 2006

Needham et al., 1996

Robert et al., 2005
The tendency of complex systems to order around a critical point is termed self-organised criticality (SOC; Bak et al 1987)

Key drivers of SOC behaviour are:

- Energy is added slowly over long timeframes
- A barrier (threshold barrier) to energy flux is present that stops dissipation into the energy sink, forming extreme energy gradients
- Energy is released over very short timeframes in dramatic pulses termed ‘avalanches’

These systems will remain SOC systems as long as the energy flow is maintained, and the threshold barrier is intact.
Understanding Dynamic Complex Systems

Ore formation as a product of self-organising critical systems

McCuaig and Hronsky, 2014
Critical Elements of Mineral Systems

Fertility

Favourable Whole-lithosphere Architecture

Favourable (Transient) Geodynamics

Preservation (of primary depositional zone)

Ore Genesis
Critical Elements of Mineral Systems

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Ore Genesis
Whole Lithosphere Architecture

A Multiscale Fluid (incl Magma) Delivery System

McCuaig and Hronsky, 2013
Whole Lithosphere Architecture

Isotopic maps as ‘paleogeophysics’ to image paleoarchitecture

Time slices can provide insights into spatial distribution of multiple mineral systems through time → PREDICTIVE TOOL

NiS (red), Fe (blue), Au (gold) deposit distributions

NiS deposits (stars) and komatiite Mg# (red) at 2.9Ga

Craton margin, 2.7 Ga

Craton margin, 2.9-2.8 Ga
Antamina, Peru

After McCuaig 2003 (courtesy of Antamina); Love et al., 2004
Vertical Accretive Growth History – Antamina

McCuaig and Hronsky, (2014)
Antamina VLR fault equivalent (NE-strike, subvertical) along strike to NE of the mine.

Classic example of upper crustal brittle fractures overlying a fundamental, vertically accretive lithospheric flaw at depth.
Vertical Accretive Growth History
Fundamental Lithospheric Flaws

McCuaig and Hronsky (2014)
Common Characteristics of Large Scale Ore-Controlling Structures

Strike-extensive.

Depth-extensive (often lithospheric mantle) with relatively steep dips (as imaged in geophysics).

Commonly juxtapose distinctly different basement domains (as imaged by isotopes and magma chemistry).

Multiply-reactivated (commonly with variable senses of movement) with a very long history.

Vertically-accretive growth histories.

These are not the obvious structures at or above the level of mineralisation – an important message for targeting.
Anastomosing Near-Surface Pattern overlying Fundamental Structure at depth

Sierra Foothills Gold Province, California. From Bierlein et al (2008)
Cryptic Near-Surface Pattern Overlying Fundamental Structure at depth

Carlin and Battle Mountain–Eureka trends not obvious in surface geology
Cryptic Near-Surface Pattern Overlying Fundamental Structure at depth

Bouguer data processes to image deep architecture – trends much clearer!
Critical Elements of Mineral Systems

- Fertility
- Favourable Whole-lithosphere Architecture
- Favourable (Transient) Geodynamics

Preservation (of primary depositional zone) + Geodynamics
In recent years increasing availability of high-resolution geochronology and better understanding of global geodynamics is increasingly indicating that major ore-forming events occur in narrow time windows, often over broad areas. These critical time horizons must reflect unusual regional-scale geodynamic settings that are favourable for mineralisation. These favourable settings must be transient, lasting for only short periods of geological time.
Focused system with little lateral dispersion

Main ore events are transient in a larger magmatic/hydrothermal event

Translucent focused ore-forming flux

Temporal Evolution of System
Transient Geodynamic Triggers

Eocene Magmatic events in SW USA

Bingham, Carlin and Cripple Creek all form associated with this event

Very different deposit styles, same geodynamic trigger?

Tosdal (2009)

After Dickinson (2002); Christiansen and Yeats (1992)
Transient Geodynamic Triggers

All these major deposits formed at 440 Ma
(as did North Kazakhstan Gold Province)
Favourable Transient Geodynamic Events

Empirically we recognise three common scenarios:

Incipient Extension (VMS, Akalic LSE Au, LSE Au, NiS)

Transient Compression (Porphyry Suite deposits, Mafic Intrusion NiS)

Switches in Far-Field Stress (All?)
Favourable Transient Geodynamic Events

During these events:

- Active permeability creation is stopped, or
- Vertical permeability is clamped
- Energy and fluid input to the system continues
- Extreme energy and fluid pressure gradients are formed
- The system self-organizes to form ore as long as the geodynamic threshold barrier remains intact.
Threshold Barrier
Incipient Extension
e.g. VMS-epithermal

McCuaig and Hronsky 2014
Threshold Barrier
Transient Anomalous Compression

e.g. porphyry

McCuaig and Hronsky 2014
Threshold Barrier
Stress Switches
e.g. orogenic gold

Goldfarb et al., 2005
Critical Elements of Mineral Systems

Fertility

Favourable Whole-lithosphere Architecture

Favourable (Transient) Geodynamics

Preservation (of primary depositional zone)

Ore Genesis
Fertility

A geological region or time period systematically better-endowed than otherwise equivalent geological environments

4 components

- Secular Earth Evolution
- Lithosphere fertility (e.g. Au)
- Geodynamic context (e.g. magmatic-hydrothermal Cu)
- Paleolatitude (Zn-Pb, U, Fe, others?)
Fertility
Secular Earth Evolution

Cooling of earth through time
  e.g. komatiite-hosted NiS

Evolution of biosphere-atmosphere-hydrosphere
  Controls availability or mobility of metals
  E.g. U, sediment hosted Pb-Zn

Evolution of lithosphere and geodynamic cycles
  E.g. Orogenic Au at terminal stages of supercontinent assembly
Retreating arc

Advancing arc

Small volume melts trapped in mantle lithosphere

Au transferred to crust by subsequent tectonic and thermal trigger

Hronsky et al., 2012
3 periods of subduction

potential enrichment of mantle lithosphere pre-Mesozoic Au in North China Craton

allows gold introduction into previously metamorphosed terrane
Implications of lithosphere enrichment
Fertility - Geodynamic Context

Andean Cu since the cretaceous - anomalously compressive margin

Which made the western margin compressional

This pushed South America hard to the west

Spreading Rate on the MAR increased rapidly in Cretaceous
Nested scales of Threshold barriers

Transient extreme anomalous compression causes ore
Paleolatitude Control

Observed in basin-hosted deposits

Probably relates to availability of evaporites to provide salinity for ore-transporting fluids

Arid environments restricted to between about 20 and 40 degrees from equator

e.g. SEDEX, Hypogene BIF upgrade, uranium

Leach et al (2010)
Links Between Mineral Systems

One advantage of the Mineral Systems Method is that it enables us to recognise common underlying controls that link apparently different deposit types.

This enables us to focus our targeting on those common underlying controls.

It also helps us be more predictive about the deposit types we might find in a particular environment.

A good example is the Alexander Triassic Metallogenic Belt of Alaska-British Columbia.
Alexander Triassic Metallogenic Belt

Northern Part of Belt:
Deep-water Seds and Basalt, No Felsic Volcs

Southern Part of Belt:
Felsic Volcs overlie Shallow Water Carbonates

Classic Stratiform VHMS deposits

VHMS – Epithermal Hybrid Deposits

Epithermal Style Base Metal Veins

Modified from Taylor et al (2008)
Schematic Regional Longitudinal Section of the Alexander Metallogenic Belt
Mineral Systems

Challenge in practical application is in keeping scale of decision matched to scale of relevant mineral system process:

At all scales, processes at site of deposition get heavy weighting, despite their lower relevance to regional targeting decisions. Bias is to data rich areas at expense of data poor areas.
## Scale Dependence of Critical Elements for Orogenic Au

<table>
<thead>
<tr>
<th>SCALE</th>
<th>FERTILITY</th>
<th>FAVOURABLE GEODYNAMICS</th>
<th>FAVOURABLE ARCHITECTURE</th>
<th>DEPOSITIONAL PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ORE-SHOT</strong></td>
<td>NA at this scale</td>
<td>NA at this scale</td>
<td>Localised dilatant zone in host structure</td>
<td>2nd order - pressure drops; 3rd order - favourable substrate (chemical vs)</td>
</tr>
<tr>
<td><strong>DEPOSIT</strong></td>
<td></td>
<td>Period of low active tectonic strain, e.g. stress switch causing transient neutral stress state causing fluid system to self-organise. Areas of greatest uplift favoured (provides stress switch and high rates of energy and mass transfer)</td>
<td>Major heterogeneity (eg, cross-structure intersection) along trend of inverted rift axial (or rift-marginal) fault with associated physical seal (e.g., an informal culmination or unconformity)</td>
<td></td>
</tr>
<tr>
<td><strong>CAMP</strong></td>
<td></td>
<td></td>
<td></td>
<td>1st order - upper 10 km of crust AT THE TIME OF MINERALISING EVENT where fluid pressure (+T, X) gradients are greatest</td>
</tr>
<tr>
<td><strong>PROVINCE</strong></td>
<td>Discrete Au-enriched upper Lithospheric domain, particularly near its margins Potentially mantle lithosphere enriched by small volume partial melts prior to termination of orogeny</td>
<td>Terminal phase of syn-orogenic event (e.g., the transition to incipient extension associated with the termination of collision and focus of subduction retreat westward)</td>
<td>Inverted retroarc rift; preferably developed at acrotrental margin, or margin of deep mantle lithosphere core. Long lived 'vertically-accretive' structure</td>
<td></td>
</tr>
<tr>
<td><strong>CONTINENTAL</strong></td>
<td>Currently unclear but the occurrence of the Western US Gold Superprovince suggests that some control at this scale exists.</td>
<td>A major collisional orogenic event within the history of an evolving accretional orogen; the major collision that actually terminates a long-lived (&gt;200Ma) accretionary orogen is most prospective and usually associated with a peak of super-continental formation</td>
<td>Major &quot;ODI&quot;-scale type sub-continental scale lineament (representing long-lived zone of transverse dislocation within accretionary orogen), Long lived 'vertically-accretive' structure</td>
<td>1st order - upper 10-12 km of crust preserved through multiple orogenic cycles</td>
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# Scale Dependence of Critical Elements for Orogenic Au

## Critical Elements

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<th>Favourable Architecture</th>
<th>Depositional Process</th>
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<td><strong>Ore-Shoot</strong></td>
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<tr>
<td><strong>Camp</strong></td>
<td></td>
<td></td>
<td>1st order - Upper 10km of crust preserved at time of mineralisation</td>
</tr>
<tr>
<td><strong>Province</strong></td>
<td></td>
<td></td>
<td>Upper 10Km of crust preserved at time of mineralisation</td>
</tr>
<tr>
<td><strong>Continental</strong></td>
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<td></td>
<td>Upper 10Km of crust preserved at time of mineralisation</td>
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- **Localised dilation**
- **Pipelike volumes of competent rock**
- **Pressure drops**
- **Favourable substrate**

- **Enriched lithosphere**
- **Stress transition at terminal phase of major accretionary orogen**
- **Inverted pericratonic rift**
- **Long lived lineaments transverse to orogen**

Need mappable proxies at relevant scale for application to exploration.
Takeaway Messages

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