Mineral Systems and Exploration Targeting

T. Campbell McCuaig - Centre for Exploration Targeting
We will cover

• Mineral Systems as an organising framework to understand ore formation
• Translation of mineral systems to targeting systems
• Heuristics and Human behaviour
INTRODUCTION TO
MINERAL SYSTEM SCIENCE:
Why understand mineral systems?

• Point of this module is to give broader perspective on mineral deposits than usually addressed.

• In particular, emphasise links between different mineral systems that are often overlooked in ore deposit courses.

• The first key point is the difference between Mineral Deposit Models thinking and Mineral Systems thinking.
Deposit models

• Built from deposit-scale observations
  – Scale at which we can more readily study them

• Focus on ‘type’ deposits
  – Carlin style Au
  – Kambalda style NiS
  – Bushveld style PGE
  – Witswatersrand style Au
  – Kuroko style VHMS
  – Olympic Dam style IOCG
Ni mineralisation associated with ultramafic rocks (komatiites)
Deposit models

- More comprehensive syntheses encompass multiple deposit styles
  - High Sulphidation versus low sulphidation epithermal
  - Epithermal-Porphyry transition
  - Continuum model for Orogenic Au
  - Unconformity uranium
  - SEDEX-MVT

- Good summaries of variations between deposit styles
- Can be excellent summaries of deposit scale processes
Epithermal Au

Corbett 2004
Porphyry to Epithermal Cu-Au Deposit Model

Corbett 2004
Archaean Orogenic Gold Deposit Model - Crustal Continuum for Au

Timing late tectonic = ca. 2640-2630 Ma in Yilgarn

Fluid Sources metamorphic-dominated

Groves et al., 1993
From Kyser (2008) in ioGlobal Uranium Short Course notes
Yilgarn komatiite-hosted Nickel Camps
Deposit models - limitations

• Often focus on one aspect of system, not holistic
• Often too many ‘variations on a theme’ for practical application
  – IRG
  – Porphyry model variants
  – Uranium – 14 models, 22 submodels
• Struggle to be predictive
  – Where predictive = local scale
  – Finds analogues of what you have already found
• Show that giant deposits and small showings often have similar fluids and deposit scale features (Groves, 2009)
  – E.g. fertile magmas hard to differentiate from infertile on deposit scale (Cooke et al, 2009)
Uranium Deposit Models

Published U deposit classification schemes are invaluable for communication of scientific concepts, reference and learning. But they comprise a large number of U deposit types and sub-types, which translates into a large number of geological variables. Working with too many variables is impractical for a continent-wide prospectivity analysis because of potential introduction of bias and reduction of efficiency. Many geological variables are only evident at the deposit-scale, whereas at larger scales many types of U deposits illustrate fundamental similarities in terms of source, transport and depositional processes.

IAEA Classification Scheme

- Breccia complex
- Unconformity-related
- Sandstone
- Surficial
- Metasomatite
- Metamorphite
- Volcanic
- Intrusive
- Vein-hosted
- Quartz-pebble conglomerate
- Collapse breccia pipe
- Phosphorite
- Lignite
- Black shale

Sub-types
- Proterozoic
- Phanerozoic
- Fracture-bound
- Clay-bound
- Strata-bound
- Tabular
- Roll-type
- Basal channel
- Precambrian sandstone
- Peat and bog
- Duricrust
- Karst cavern
- Pedogenic and structure fill
- Alaskite
- Carbonatite
- Pegmatite
- Granite, monzonite
- Peralkaline syenite
- Spatially related to granites
- In metamorphic or sedimentary rocks
- Perigranitic veins
- Intragranitic veins

14 principal U deposit types
22 sub-types

Tree based on NEA / IAEA (2005) classification scheme

Kreuzer et al., 2010
Deposit models struggle to be predictive

• We have a much better (albeit very incomplete) understanding of the processes controlling mineralisation than 40 years ago

• So our targeting must be more effective, yes?  
  – No
  – Find new deposits in brownfields, but struggle to find new ore systems in greenfields terranes

• DEPOSIT MODELS ARE AT WRONG SCALE for large scale greenfields exploration decisions!
We must see beyond Deposit-Scale Complexity

Sillitoe (2010)
Predictive Power comes from the Larger Scale

Sillitoe (2010)
Deposit model versus Mineral System approaches

- Deposit models – based on finding geological characteristics interpreted to be favourable for mineralisation in known deposits
  - E.g. Differentiated dolerite in Yilgarn

- Mineral Systems – based on finding evidence for interpreted critical mineralising processes
  - E.g. Olympic Dam
Dolerite model good, but…

- Excludes major deposits - would not find Wallaby (~7 Moz Au), Sunrise Dam (~10 Moz Au) and Kanowna Belle (~5 Moz Au) + many others
- Terrane Specific - would not be as successful in other Archaean Cratons

Robert et al., 2005
Olympic Dam – a mineral system approach

WMC model focused on:

- Underlying oxidized and altered basalts that would release Cu (Source)
- Major lineaments that could have tapped copper-bearing fluids (Pathway)
- Magnetic and gravity highs potentially indicative of alteration and metal accumulation (Physical throttle)
- Reduced sedimentary rock packages (Chemical Scrubber)
Uranium Systems Models

<table>
<thead>
<tr>
<th>12 models</th>
<th>6 models</th>
<th>4 models</th>
<th>New U systems models</th>
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<tbody>
<tr>
<td>IAEA Classification</td>
<td>“Manual” Analysis</td>
<td>“Automated” Analysis</td>
<td>Grouped based on similar genetic processes, environments of ore formation and mappable ingredients</td>
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<tr>
<td>surficial</td>
<td>surficial</td>
<td>surficial</td>
<td>Serve the purpose of exploration targeting (practical rather than explicitly scientific scheme)</td>
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<tr>
<td>unconformity-related</td>
<td>unconformity-related</td>
<td>unconformity-related</td>
<td>Are simple, flexible but internally consistent structures that emphasize the source and transport criteria, which are the key parameters for area selection at the regional to continent scale</td>
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<tr>
<td>sandstone-hosted</td>
<td>sedimentary</td>
<td>sedimentary</td>
<td>Satisfy a fundamental principle of conceptual targeting: mineral deposits are part of much more extensive systems of energy and mass flux, and hence targeting must be carried out at global through to regional scales (Hronsky, 2004; Hronsky and Groves, 2008)</td>
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<td>lignite</td>
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<tr>
<td>collapse breccia pipe</td>
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= Not considered in this study

Kreuzer et al., 2010
Mineral Systems – WHY?

• Conceptual organising framework
  – Much more powerful than predecessor - traditional Deposit Models

• Required to open up new mineral districts
  – Captures variations of thought process with scale
  – Allows for the undiscovered deposit styles
Mineral Systems Science: Conceptual Basis

• Based on the premise that:
  – Ore deposits (particularly large deposits) represent the foci of large-scale systems of mass and energy flux
  – the only way to predict their location or their metal endowment is to understand the entire system

• These systems comprise a scale-dependant hierarchy of processes:
  – the largest observable scale of process is usually continental-scale
Conceptual Mineral System

Knox-Robinson and Wyborn, 1997
Classic Mineral Systems Framework

Focus must be on understanding the geological PROCESSES as opposed to CHARACTERISTICS

Critical Success Factors

- Mass trapping
- Mass scrubbing

Source - Release - Migration - Trap - Seal

Source(s) - Migration - Throttle - Scrubber

McCuaig et al (2009)
Different styles of mineral systems

• Mass Trapping
  – Petroleum
  – Mineral Sands

• Mass Scrubbing
  – Mass addition
    • Hydrothermal Au, Cu, Pb-Zn, U, Fe
    • Magmatic NiS
  – Mass removal
    • Bauxite
    • BIF-hosted Fe
Physical considerations can change our perspective

- Ore formation requires concentrating metal, initially in low abundances in large volumes of rock, into small volumes of rock at high abundances

- Only plausible mechanism: large-scale advective fluid flux

- Necessary physical processes for ore formation provide fundamental constraints on what can be a viable Mineral System
Basic Physics of Ore Formation

- Fluid Sink
- Concentrated Metal Deposit
- Diffuse Metal Source Region
- Advective Fluid flux (= Energy Flow)
The Evolution of Perspective in Economic Geology

Early 1900s
- Ore specimen-centric
- Host Rock-centric
- Structure and chemistry-centric

21st Century
- Fluid flux and physics-centric

Increasing Scale of Observation

Context:
- Increasing Scale of Observation
A PHYSICAL PROCESS BASED MINERAL SYSTEM MODEL - FLUID CENTRIC

Can develop proxies for every component because they all map to a physical rock volume!
Goals of Mineral System Science

- Define key process components of Mineral Systems (at all scales)
- Map these components to physical rock volumes (essential for predictive targeting)
- Define the key *generic, unifying* process elements that govern ore-formation:
- Develop frameworks for evaluating the relative endowment potential of systems
Ore Genesis as the Focus of a Scale-Hierarchical Mass Concentratative System
We must see beyond Deposit-Scale Complexity

Sillitoe (2010)
Predictive power comes from larger scale

Deposit Scale

Camp Scale

After Sillitoe (2010)
But What About Chemical Processes?

- Much more diverse, complex and difficult to predict than fundamental physical processes
- Metal-bearing fluids in the upper crust encounter steep physical and chemical gradients - many potential depositional mechanisms, even within very similar mineral systems
- Explains why most metallogeny in upper 10km of crust
- Some proposed chemical mechanisms violate physical constraints (eg fluid mixing in the mesothermal environment)
- However, chemical processes still important and define type of mineral system and precise location of ore formation
Mapping Chemical Processes to the Physical Mineral Systems Model

- Key is defining a set of generic elements that represent important chemical processes but can also be related to rock volumes.
- These rock volumes are by definition a subset of those in the Physical Mineral Systems Model.
- Four critical elements:
  - 1. Pre-fertilisation of the fluid source region
  - 2. Metal/Other Critical Solute source regions
  - 3. Fluid Fractionation Site
  - 4. Metal Depositional Site
- If proxies for the rock volumes relating to these four elements can be defined, it will possible to significantly refine the generic Physical Mineral Systems Model.
1. Pre-Fertilised Fluid Source Region (eg enriched upper mantle)

2. Metal and/or Critical Solute (eg Cl, S) source region

3. Fluid Fractionation Site (eg magma > hydrothermal fluid; silicate magma > sulphide magma) – likely to overlap Fluid Reservoir

4. Ore Depositional Site – either in conduit or at discharge site

Ore Genesis as the Focus of a Scale-Hierarchical Mass Concentrative System

1. Map architecture
2. Then map chemistry onto architecture

McCuaig and Hronsky, 2013