**Journey to the Dark Side: a Search for the “DNA” of mineral systems**

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**Slides 1-3:**

This talk charts progress in conceptual thinking from a “Classical View” of ore deposits models and processes to a mineral system perspective, over the course of a career studying mineral deposits/resources (some 4 plus decades),

The mineral systems methodology aims to document the whole system, not just the site of mineral deposition. In the purist form the mineral system perspective aims to identify a limited number of parameters (geological, physical and chemical) that allow the system to be described independent of scale and commodity.

These parameters might be thought of as the “DNA” of mineral systems. Ideally, they should be quantifiable.

The background to the first slide is an image of the hydrogen halo around the earth; extending out some 65,000 kms. It is the largest geochemical halo that I am aware off associated with the Earth. A reminder that in thinking about Earth systems, one needs to think across all scale up to Earth scale.

The track of the presentation covers

* The classical phase: mineral deposit studies
	+ - beginnings at Uni of Tas with Mike Solomon and lecturing at ANU
* Development of mineral systems thinking
	+ - CSIRO and working with the exploration industry
* Mapping systems: a work in progress
	+ - Gradient mapping in Archean Au system
* Brief comments on the Earth-scale drivers of systems

And the take home messages:

* The mineral systems are bigger than we ever imagined
* The mantle and its volatiles are not far away
* The challenge: testable scale – integrated/4D models – to Earth Scale & independent of commodity

**Slides 4-5:** The beginnings with Mike Solomon

I worked with Mike Solomon as a postdoc from ~1975 to 1980.

Solomon had a strong desire to understand the processes of deposit formation and I worked with him on the problem of sulfide formation on the seafloor. He was keen on analogue experiments and was experimenting with buoyant plumes on the seafloor and I did the numerical modelling of the precipitation mechanisms. Our paper on "The formation of massive sulfide deposits on the sea floor" was published just weeks before the first discovery of the black smokers. The experience validated the process of building robust concepts from the geological and geochemical data sets.

**Slide 6:** 1981-1994: My Classical Phase: Lecturing in Economic Geology at ANU

A great time with a bunch of students & post docs studying ore deposits – mostly of the Lachlan Fold Belt. In many ways I simply followed in the footsteps of Solomon. He sent his students (mostly) to the west coast of Tasmania to study the deposits and I sent mine (mostly) into NSW to study the Pb-Zn, Cu, Au, Sn-W deposits of the Lachlan Fold Belt.

In the next few slides I comment on some of the important influences of the time.

**Slide 7:** Thermodynamics as a tool for understanding processes. In particular, I was interested in calculating fluid chemistry (temperature, redox, pH etc) from the mineralogy. Quantification provides a way to discipline thinking. Provides the freedom to think what you will!! You don’t have to be constrained by existing paradigms.

**Slide 8-9:** The business of doubt and being driven by the data not the model.

There is/was outside Canberra a volcanic-hosted Cu-Pb-Zn deposit (the open cut is now a dump for Sydney rubbish) which given my training with Solomon I accepted as having formed on the seafloor; an interpretation that goes back to Dick Stanton. Towards the end of my time at the ANU I was invited by the chief geologist, Mark Bouffler, along with Dick Glen from the NSW Geol Surv., to inspect a recently exposed section of lens A towards the bottom of the mine. I recall saying as we drove out of the mine I couldn’t believe what I had just seen so we returned to map it. What we had seen was the bedding (So; layered chert) that is notoriously difficult to find in altered /deformed volcanics. The main mineralized lenses were subparallel with cleavage not bedding. The main sulfide masses were syn-tectonic in timing not syn-sedimentary.

**Slide 10:** CSIRO, industry engagement and development of mineral systems thinking

These days living in Perth I get to enjoy the Western Australian Symphony Orchestra in the Perth Concert Hall – reputedly with the best acoustics in Australia. The principal conductor Asher Fisch says of Wagner Asher Fisch on Wagner (1813-1883)

“Wagner revolutionised every parameter of music” creating a new dynamic, impressionistic form to better convey …… ………………stories in music.

Arguably, some 150 years after Wagner wrote the Ring Cycle and ~ 130 years after Van Gough was painting sunflowers and ~ 70 years after Crick and Watson worked out the structure of DNA and revolutionised biology, in the Earth Sciences we are just beginning the effort to find a more holistic way to describe mineral deposits and the systems that created them.

Interestingly the drive to develop mineral systems concepts and application, in the Australian context, emerged at the interface between industry and academe, driven by the need to improve exploration practice. In leaving the university system and joining the CSIRO, I joined a conversation about how to describe a mineral system and was introduced to the 5 questions. My first recollection of the 5 questions was a fax from Bruce Hobbs (May 97) to Greg Hall and myself stating “Attached for your information are Bruce’s five questions”.

It was the late Tom Loutit, at the time with GA, who drove the 5 questions with respect of mineral systems in sedimentary basins, aided and abetted by Leslie Wyborn.

 These days looking back through Solomons Book (Geology and Origin of Australia’s Mineral Deposits, published in 1984) with its highly structured framework …..lode gold deposits, Sn-W deposits, volcanic-hosted massive sulfides ………… it has a “Beethoven” feel of working within classical forms of ore deposit descriptions. The minerals system approach offered a more free flowing, holistic “Wagnarian” approach.

**Slides 11-12:** Why 5 questions? I asked Tom Loutit , but I was never sure he understood the question.

Turns out many folks ask five questions or something very similar.

Toyota Industries developed the 5 Ws technique in the 1930s to resolve production problems.

Accordingly:

…any understanding/system/concept/model … is only complete if it answers these questions

These days, the Five Ws ….effectively a philosophical device to get to a deeper meaning….are attributed to an ancient Greek: [Aristotle](https://en.wikipedia.org/wiki/Aristotle).

**Slide 13:** The “answers” to the 5Qs as they evolved in the latter days of the AGCRC and through the pmdCRC (2002-2008) aimed to provide the data/knowledge to predict where next. The answers would work across scale. The answers would provide the data to allow quantitative modelling of systems.

The first 2 questions are really framework – they define the space/time framework in which the system operated.

The next question (which I have promoted in the order from the original listing) is about the chemistry of fluids in the system; whatever the nature of those fluids.

The reason for the promotion is that I’ve come to appreciate it is not possible to map pathways, let alone define sources, without a robust understanding of the chemistry of the fluids in the system.

**Slide 14:**

A fundamental concept that plays into mapping the chemistry of the system is that of gradients. Any fluid or energy flow will produce gradients. The rate of mineralization is not just dependent on the parameters controlling metal solubility (T, redox, pH, salinity) but on their spatial gradients.

The two-fold challenge of the chemistry is to understand the important parameters and to map their gradients. In theory, the gradient information will allow vectoring across scale in the system to locate the metal.

**Slide 15:** The MERIWA/MRIWA projects (~2002 to 2020) focused on the practical tasks of mapping gradients in Archean Au systems at deposit/camp scale and understanding why the deposit is *there* (rather than somewhere else). The ultimate goal was to provide explorers with tools for navigating camps to detect the deposits. It remains a work in progress!

**Slide 16:** Often it is easier to appreciate gradients at the camp-scale rather than at the scale of the deposit or hand specimen. In the St Ives Camp, Kambalda, oxidized assemblages (magnetite proxy) are associated with gravity lows and the gold deposits are spatially related to these features.

**Slide 17:** The gradients can be appreciated in other data sets such as the δ34Spy: red (negative; oxidized conditions) blue (positive; reduced conditions) and in the short-wave infrared (SWIR 2250nm wavelength). The overall interpretation is that the gold deposits occur across a gradient from oxidized/alkaline conditions to reduced/acidic conditions. Importantly the redox/gradient is much more extensive than the gold occurrence, so the redox boundary provides a mappable surface on which the gold will be located. The question becomes what parameter (s) are controlling the precis location of the deposits. The answer lies partly with the architectural constraints on fluid flow and partly with fluid chemistry. In addition to redox and pH gradients gold occurrences are related to the gradients in water activity: transitions from domains of low water activity/conc (anhydrous fluids) to domains of high water activity (aqueous fluids). Domains of low water activity appear much more spatially restricted.

**Slide 18-20:**

This phase of the research was undertaken at the industry/academe interface using on-sight researchers – the Embedded Researcher Initiative. Made possible at the time through collaboration between St Ives and Placer Dome. Significantly, the redox-gradient research was stimulated by industry colleagues and the first extensive survey of sulfur isotopes through the Eastern Goldfields was undertaken by Paul Kitto and Scott Halley. And when the money ran out we celebrated with a “Dinner in the Desert”.

**Slide 21-22:**

Until ~2010 we were applying standard technologies to map geochemistry/alteration (multi-element analyses, pXRD, SWIR technologies). Trying to map gradients with these technologies is “looking through the glass darkly”. To achieve a robust layer of chemistry we had to do better. Doing better meant undertaking “industrial scale” quantitative SEM mapping of minerals. The advantages were mapping of all the major & minor minerals with greater certainty re: identification, composition and abundance. To do this I put together a new team and Adam Bath led the charge on undertaking “industrial scale” quantitative SEM mapping of minerals in Archean Au systems.

**Slide 23:**

In the Kundana Camp (west of Kalgoorlie) we mapped over 30km of strike length, mostly scanning air-core chips and diamond core proximal to known deposits. One outcome was a camp-scale zoning in the Na-Ca feldspars with the more calcic feldspar proximal to the Au deposits. This pattern is attributed to higher temperatures in productive parts of the system. Interestingly there is a trail of the calcic feldspar well south of known mineralization.

**Slides 24-26:**

I want to come back to the Victory Defiance section and the question of “why is the gold there!!”

As noted earlier there is not a unique correlation of gold with a redox gradient; the gradient is spatially more extensive than the Au.

With Adam Bath I worked in detail on the East Repulse deposit that is part of the Vicory-Defiance complex. The simplified geology is shown in the inset (slide 24) and note the repeat of the ultramafic rocks in the section. The East Repulse lode sits just beneath the upper ultramafic unit and Repulse Thrust (not shown). Slide 25 shows the domains of CO2±CH4-rich fluids for CD7042 as defined by assemblages of jimthompsonite±talc±actinolite±calcite± dolomite. The jimthompsonite formed from highly CO2-rich fluids (XCO2>~0.9). The high CO2 domain lies within and below the upper ultramafic unit and the best gold zone in the hole occurs on the lower margin of the zone.

It is inferred the upper upper ultramafic unit ± Repulse Thrust acted as an aquitard in the system with the CO2-rich fluid “ponding” beneath. Gold deposition was controlled by a water activity gradient on the lower margin of this zone in association with redox/pH gradients.

Slide 26 shows a jimthompsonite±talc±calcite± dolomite assemblage overprinting a quartz-albite vein within biotite-chlorite-albite-calcite altered Mg-rich basalt.

**Slide 27:**

This slide illustrates an example of converting mineral maps into gradient maps for targeting purposes. This was a greenfields study of an area ~10\*10km, mostly using aircore chips.

The study identified corridors of higher temperature alteration (> 400 °C), redox gradients in neutral to acidic conditions and redox gradients at neutral to alkaline conditions. Redox gradients in higher temperature setting at alkaline conditions were considered most favourable for gold deposition.

**Slide 28:** Earth-scale systems

The late Archean Au deposits/provinces represent one of the great Au-depositing epochs of Earth history. Roughly speaking Au epochs have occurred every ~0.5 to 1 billion years and last several hundred million years. Metal provinces typically have length-scales of 100s to 1000s km across the Earth’s surface. The Mid-Proterozoic multi-metal system extends across the continent. The scale of the Au systems, as well as other metal system, both in time and space suggest some “Earth-scale” process.

**Slide 29:** System driven by mantle volatiles

It is possible to think of late Archean Au systems as volato-thermally driven chemical engines with roots deep in the mantle.

The aqueous fluids are crustal, but the chemical drivers of the system are anhydrous volatiles from the mantle. Oxidized volatiles from the upper mantle; reduced volatiles from the lower mantle.

**Slide 30:** The ultimate driver

The ultimate driver of these metal systems that are active every 0.5 billion years or so: an electron flux from the core.

Reaction with OH and carbon/sulfur species in the lower/upper mantle leads to a volatile flux. The metallogenic outcomes of the mantle volatiles reacting with crustal fluids is strongly controlled by crust/mantle architecture.