How a Systems Thinking Approach to Mineralising Geosystems is opening New Search Spaces for Ore Discovery

Timothy Craske*
Geowisdom Pty Ltd
Bath, UK
timcraske50@gmail.com

**presenting author asterisked*

SUMMARY

Systems thinking is used to study interactions. It is different from simple event orientated thinking that implies chains of cause and effect along a time line. In systems, the systemic behaviour emerges from its structure, the flows and feedback loops, rather than any individual element. Mineralising geosystems and ore systems are often complex and self-organising. As mineral explorers it is unlikely that we will be able to truly understand complex mineralising geosystems if we do not understand the theory of systems thinking.

Mineralising geosystems operate at different scales at different times and sometimes at several scales at the same time. By using systems theory tools we can begin to close the gap in predictive targeting effectiveness between the regional and camp scale, and in the process unlock new search spaces. One way we can do this is by measuring and mapping the evidence for feedback loops in the geological record.

A mineralising geosystems map for tin deposits was produced in 2017 as an example of the systems approach to modelling mineralisation processes. Tin is well-studied simple mineral system that has both a sedimentary phase and a magmatic phase. This mineralising geosystem map has challenged paradigms that also apply to other mineralising geosystems, especially the role of sedimentary processes in driving the ultimate quality of deposits.

Key words: systems, geosystems, mineral systems, tin, sediment hosted copper, self-organising, feedback.

INTRODUCTION

Systems thinking is used to study interactions. It is different from simple event orientated thinking that implies chains of cause and effect along a time line. In systems, the system behaviour emerges from its structure, the flows and feedback loops, rather than any individual element or node (Figure 1). The root causes in systems are the forces emerging from the feedback loops. This is an important difference between systems maps and traditional mineral systems flow diagrams. Systems can exhibit feedback loops that may cause delays, drive growth or act as governors on system behaviour. This can sometimes produce unexpected results that are hard to predict based on simple study of the components alone (Meadows, 2008).

Reductionist analytical thinking that we usually use to study components does not work well when we model systems holistically. The whole becomes not merely more but very different from the sum of its parts (Anderson, 1972). The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe (Corning, 2002).

The most basic structures in systems maps are termed “archetypes”. An archetype is a structure or sub-system that produces the repeatable recognisable behaviour or set of behaviours in a system. Learning to identify archetypes can help us understand the workings of a system and to better predict its behaviour. Predictive behaviour is the benefit of studying geology in a systems world. With better prediction we can expect improved discovery returns from our exploration programmes.

SYSTEMS THEORY APPLIED TO MINERALISING SYSTEMS

To work with systems you need to properly understand the tools of systems theory. Without application of the correct thinking tools we risk assigning false causality or producing erroneous forecasts in complex systems (Figure 2).

One reason why emergent behaviour, such as the growth of an ore deposit, is hard to predict in mineralising systems is that the number of interactions between components of a system increases exponentially with the number of components, allowing for many new and subtle types of behaviour to emerge. Emergence is often a product of particular patterns of interaction that can be mapped. It should be expected then that systems thinking, in turning simple causality on its head, will result in breakthroughs in understanding and prediction.

Mineral Systems and ore systems are often self-organising (Hronsky, 2011). Most depictions of ore systems, from petroleum systems onwards, have been largely in the form of event maps. Whilst a tool for visualising aspects of systems these event maps neither describe the entire system, nor emphasise important feedback loops across scales. Systems thinking allows positive and negative feedback loops and system interactions to be more fully acknowledged. We do not just want to study mineral systems in an academic environment, but rather we want to understand and better predict the occurrence of ore systems, the important wealth generating subset of mineral systems.

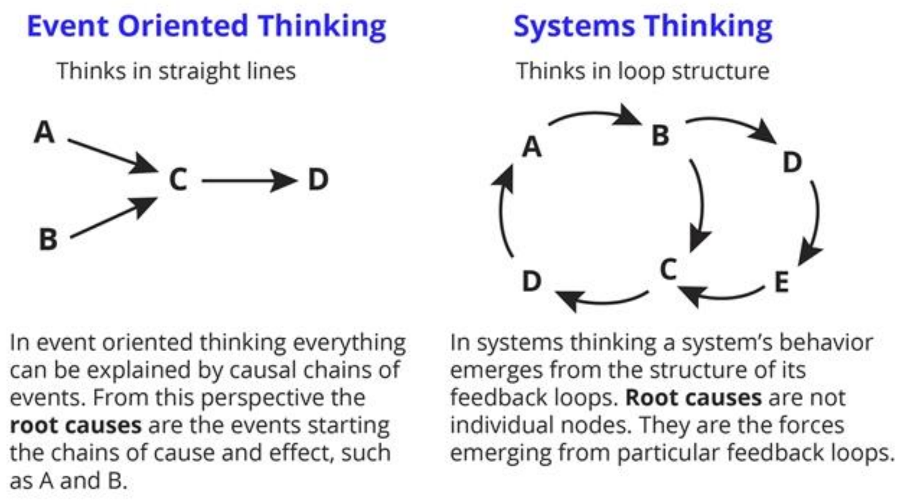

Figure 1. To understand and map Mineral Systems we need to move from event orientated thinking to Systems Thinking. Mapping the structure and feedback loops gives us insight into the system's behaviour and potential leverage points (image source: thwink.org)

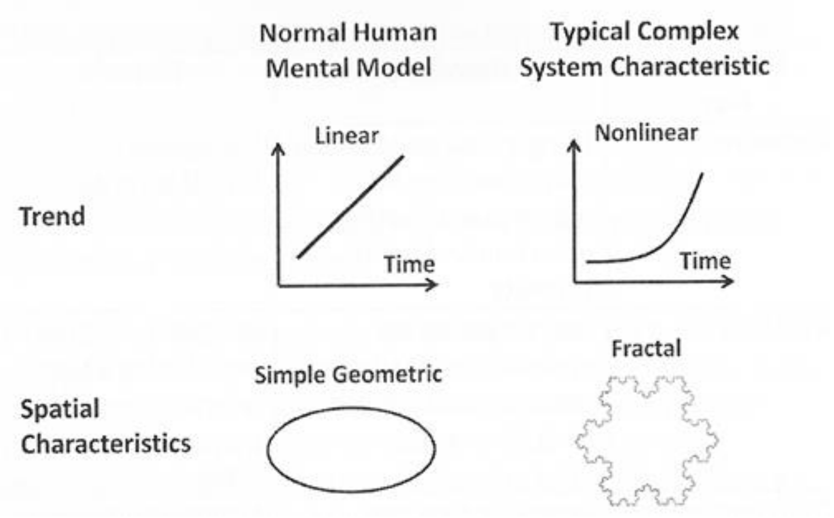

Figure 2. Comparing normal human mental models to characteristics of typical complex systems. The snowflake geometry is governed by a simple rule, and while still had unique emergent properties, it also displays convergence; all snowflakes show fractal geometry (after Jolly, 2015).

Natural systems are all open systems. It is geologists that set the boundaries of geological systems. Hence geologists should clearly state where their self-imposed boundaries lie (Craske, 2017). Ore forming systems emerge from the behaviour of mineral systems over time. Similarly, going up the hierarchy, mineral systems emerge from the actions of geosystems (e.g. back-arc basins, volcanic arcs, intracontinental basins etc.) whilst geosystems are all part of Earth systems.

Most giant mineral systems are formed within a few kilometres of the Earth's surface. So to ignore the role and overlap of the hydrosphere, biosphere and atmosphere systems in the upper crust is to miss important feedback loops in ore systems. For example, preservation is not necessarily the best result for an ore system since weathering, erosion and hydrological redistribution of elements are often keys to deposit economics and to exploration detection. Moreover, supply of mineralised detritus to sedimentary systems can become feedstock for placer and beach strand ore deposits. In some systems such as the tin mineralising geosystem, the recycling of mineralisation products back into the sedimentary cycle allows the tin to be reconcentrated in subsequent cycles of supercontinent breakup and amalgamation.

TIN DEPOSIT MINERAL SYSTEM MAP

Successful mapping of mineral systems using stock and flow, and causal loop maps, requires inputs from a broad set of research inputs. The Systems geologist must start by considering all possible sources of metal and where this metal may enter the system during its development. In general it is best to map only a single element such as Sn rather than try to map multiple elements such as Sn-W-Ta-Li in a system map, as ore elements do not always travel together in every phase of a mineralising geosystem.

The tin mineralising system is an excellent example of a three phase system, with a sedimentary phase, a magmatic phase, and a weathering-recycling phase. In a simple event thinking approach we might be tempted to start with a source rock concept that looks for an initial tin rich sedimentary rock protolith that can be melted to produce a tin rich S-type granite. But a systems geologist would question this. Is a high initial Sn grade required in the source or is the grade of Sn in the granite controlled by the efficiency of melting and fractionation processes in the magma. Or do both concepts contribute?

A mineralising geosystems map can cope with this ambiguity and honour both concepts. It also allows us to add the levers that might control the rate and efficiency of each process. Then there are software tools to model these ideas and test them via iterative simulations to help us think about the relative impact of each lever. This contrasts with a traditional source-transport-trap event thinking map that encourages geologists to consider metal sources as root causes rather than to see mineralisation as the product of many process steps that can occur with lesser or greater efficiency within the mineralising geosystem.

The tin mineralising geosystem map (Craske et al, 2017) currently has over thirty reservoirs or stocks. Each stock can be a final resting place for the tin of a temporary container that the tin passes through on its way to its final resting place. The stocks are linked together in a "stock and flow" structure. Each link represents a process that moves the tin ions form one stock to the next. It is the rate and efficiency of these movements that control the quality of the mineralising process, as well as the amount of tin in each stock. Thinks that control the process rates are called levers. These levers may be positive feedback loops that push the tin forward through the system or negative levers that set up balancing loops in the system, preventing processes from growing exponentially. In general, for ore formation that requires many orders of magnitude increase in metal concentrations from source to deposit, we need multiple upgrading process. Alternatively we need a large supply of metal and a highly efficient process that goes exponential. Such behaviour often happens due to the removal of balancing loops in the system rather than a "special" process. The typical feedback loops of confining pressure, ambient temperature, and fluid supply act well at depth, but as mineralising systems reach approach the Earth's surface these balancing levers wane allowing positive feedback to take over and ore bodies to form.

The tin mineralising geosystem map has over eighty process levers, indicating there are more controls on process than there are stocks. This is the norm in most systems. Yet as geologists we have traditionally mapped the stocks, such as sediment packages, granite plutons, veins and mantos. If we also looked for evidence of the levers and feedback in the system we would have many more potential vectors to ore. Whilst eighty may sound like a lot of features or concepts to map, only some of these concepts will leave evidence in the geological record. Moreover, there are some levers that are master levers in the system, whilst others are bit players. So whilst mapping mineralising geosystems is an exercise in mapping complexity. The final list of key parameters that we might build into a new kind of prospectivity map will be relatively few. Beyond complexity lies simplicity.

Analysis of the tin mineralising geosystem map reveals the key processes in the system to be:

1. The efficiency of the sedimentary processes that put large amounts of clay into offshore marine basins on extended continental margins during supercontinent breakup
2. The tectonic processes during basin inversion and orogenesis during continental collision that push these formerly clay, now phyllosilicate rich sediments into the lower crust where they can be melted
3. A heat source that is strong enough to melt all the micas, not just the white micas, thereby releasing the maximum amount of tin into the magma; generally requiring delamination and mantle upwelling, mafic under-plating and mingling
4. Upgrading of the tin concentration in the melt though staged magmatic differentiation in the mid-crust before the tin granite reaches the upper crust
5. An efficient process of moving the somewhat neutrally buoyant tin pregnant magma from the mid-crust to the upper few kilometres of crust; where the tin granite's final differentiation can result in ore magmatic-hydrothermal fluid formation.

In terms of identifying well-endowed camp scale targets, it is levers that control the first process (1) that appear to be the controlling levers (Romer and Kroner, 2016), whilst the (3), controls the metal suites in the deposits, including the introduction of copper into the Cornish tin systems (Shail et al, 2014)

CONCLUSIONS

Mineral Systems are exceedingly complex multi-dimensional systems. They operate at different scales at different times and sometimes at several scales at the same time. Systems models can capture multiple hypotheses of ore formation in a single map, rather than forcing geologists to consider only one process model.

Systems have levers that control the rates and efficiencies of processes, sometimes reinforcing and sometimes balancing, and can be these can modelled both qualitatively and quantitatively. In general, whilst systems can be complex they are rarely so complicated that they cannot be understood. Beyond complexity often lies simplicity. Studies of systems in other fields of science has shown that for most complex systems only a few levers actually control the outcomes. Interestingly these levers are often the less obvious and less intuitive levers. This is where gaining expertise in systems thinking can really help mineral explorers identify and map those geological levers that really count.

Systems thinking may be the key to filling the gap between regional scale predictive targeting and prospect scale detection targeting. The mineralising system's feedback loops can leave their own evidence in the geological record that can be identified measured and mapped. When systems become self-organising and goal seeking, they effectively become more predictable in their behaviour. This may be the key to increasing rates of ore discovery.

The systems mapping approach has proved useful in reframing our understanding of what is important in forming major tin camps. The approach is currently being developed for better understanding of sediment hosted copper deposits and reinforcing the link between deposit formation and the supercontinent cycle. The ultimate aim of this work is to develop keys to greater predictive capability in the greenfield exploration space.

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