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Review

Orogenic gold and the mineral systems approach: Resolving fact, fiction and fantasy

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ABSTRACT

The fact that mineral deposit attributes such as the size frequency of orogenic gold deposits in specific provinces exhibit power law distributions similar to forest fires, earthquakes, and fault size populations, is a compelling motivation to examine their genesis from a systems context. Based on well-studied Earth systems such as climate, the systems related to mineral deposits are likely to be complex and potentially include sensitive dependent components that vary simultaneously and in subtly interconnected ways.

Although a "systems approach" was enunciated for mineral exploration by Fyfe and Kerrich as early as 1976, it is yet to be fully embraced by the geosciences community that commonly retain models dependent primarily on deposit-scale characteristics. Orogenic gold deposits are well studied and widely considered to represent a single class of deposit that has formed over much of Earth history in settings ranging from Archean granite-greenstone belts to Phanerozoic turbidite sequences. Accordingly, the deposit type is well suited for assessment within a systems context. If orogenic gold deposits do in fact represent a single class of deposits, then the simplest application of a systems approach highlights the fact that the nature of the host upper crustal succession cannot be a fundamental control, with specific granite suites and pyritic sediments not universal, or at least not essential, components of the system. Furthermore the scale of orogenic gold systems implicates processes capable of tapping sub-crustal source regions. Increasingly, advances in orogenic gold systems, and mineral systems in general, are linked to application of systems science that emphasize importance of system-driven criticality. Orogenic gold systems and other mineral systems are typically short in duration and linked in time and space to tectonic triggers. The latter promote a rapid release of energy ('avalanches') that overcome system thresholds and are strong indicators of complex systems that may show power-law behavior.

Only a rigorous application of a systems approach can cut through the confusion that arises from conflicting models based on local deposit studies. Only a systems approach can evaluate the significance of rare or anomalous features in a small number of deposits. Truly predictive models for mineral exploration will ultimately be developed by workers who adhere to the systems approach.

Contents

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1. Introduction

A recent Lithos special issue devoted to "Earth Systems" and dedicated to the memory of Robert Kerrich (Cawood et al., 2015) has prompted us to consider whether the "systems" approach is being employed effectively at present in aid of mineral deposit exploration and whether there are ways to improve its application. By a "systems" approach we mean one that encompasses the interacting or interdependent *components* that work together by way of some driving process(es), that can be modeled or visualized and *connections* drawn between them. This paper is not meant as a review of the systems approach *per se*. Instead, we illustrate, based principally on our own preconceptions and biases of Orogenic gold systems, how particular systems can facilitate research and clarify developments for end-users.

The importance of the systems approach lies in its ability to transform an information explosion into a knowledge explosion, as presaged by Vannevar Bush (1945) in his seminal article "As We May Think" in The Atlantic magazine. Based on examples where Earth systems have been recognized for some time, such as climate (Lorenz, 1969), the systems related to mineral deposits are likely to be complex and potentially include sensitive dependent components that are (fractally) organized such that they vary simultaneously and in subtly interconnected ways (Bar-Yam, 1997; Kastens et al., 2009). The recent expression of the multi-scale nature of hydrothermal mineralization, deformation and metamorphism within a systems framework (Henley and Berger, 2000; Ord et al., 2012; Hobbs and Ord, 2015), provides examples of how mineral systems must be understood in terms of the physical and chemical laws governing the coupled processes that operate in open, non-equilibrium, systems. The development of suitable system models, including mineral systems, that provide both knowledge and predictive application (i.e., for future exploration) is likely to require the collaboration of researchers with diverse skill sets. This paper attempts to demonstrate why such models are important.

Determining which system variables are interdependent leads to advances in our understanding of Earth and mineral systems. Earth systems often cannot be adequately presented without numerical or statistical analysis. For instance, many natural events (e.g., forest fires, earthquakes, fault size populations) have been found to follow power-law distributions (Bak, 1996; Miller and Nur, 2000). The fact that mineral deposit attributes (e.g., size frequency and distribution of mineral deposits, including orogenic gold deposits, in specific provinces; Henley and Berger, 2000; Robert et al., 2005; Rabeau et al., 2013) also exhibit these distributions is compelling motivation to examine their genesis from a systems context. A power-law distribution may be a consequence of scale invariance (fractal dimension) or to self-organized complexity that leads to predictive capabilities for mineral exploration (Hronsky, 2011). The crustal-scale fracture and plumbing systems associated with hydrothermal systems have been viewed as examples of critical systems (Perez-Reche et al., 2008) that self-develop and evolve as a swarm of seismic events (Miller and Nur, 2000; Cox et al., 2001), and which may display fractal dimension (Ord and Hobbs, 2013).

2. Birth and development of the "systems" approach to minerals

Fyfe and Kerrich (1976, p. 177) were among the first to enunciate a "systems approach" to mineral exploration when they noted that ore deposit formation involves chemical transport requiring "1) an appropriate transport medium of large mass, (2) an energy source of large capacity, (3) permeability at source and sink over large volumes, (4) a structure to promote flow over large volumes, and (5) a thermal gradient to promote focused deposition, or (6) a structure to promote mixing of transport fluid and precipitating fluid". They argued that it was inefficient to employ a standard geochemical exploration sampling campaign without an awareness of the types of systems that might be present in a given terrain.

Fyfe and Kerrich's (1976) ideas coincided with the introduction of the 'oil system' concept (Dow, 1974), which is based on the identification of an oil-source rock correlation, and led to the development of the 'petroleum system' (first used by Perrodon, 1980). Application of petroleum systems in exploration has led to significant improvement in petroleum discovery (Al-Hajeri et al., 2009), whereas to date minerals discovery rate has not improved through use of a system approach, possibly because it has not been either rigorously or extensively applied (e.g., Brown and Vearncombe, 2014).

Although the original 'ore deposit system' concept was put forward in the mid-1970s, it took almost twenty years before it was re-introduced to mineral exploration, apparently without awareness of the Fyfe and Kerrich contribution. Wyborn et al. (1994, p. 109) described a mineral system as "all the geologic factors that control the generation and preservation of mineral deposits … the processes that are involved in mobilizing ore components from a source, transporting and accumulating them in more concentrated form, and then preserving them throughout the subsequent geologic history." This approach recognized that ore deposits were the expression of a large number of geologic processes that align to trigger ore accumulation and preservation. The initial application of the approach used newly developed Geographic Information Systems to spatially 'filter' large data-sets for the observational (mappable) elements to constrain the aerial extent of related geological features (e.g., for orogenic gold these include proximity to large faults, intersection/complexity of fault systems, presence of specific lithologies; Knox-Robinson and Wyborn, 1997). Early adopters of the mineral systems approach (e.g., Knox-Robinson and Wyborn, 1997; Hagemann and Cassidy, 2000; Jaques et al., 2002) for hydrothermal gold deposits essentially followed the approach favored by the petroleum industry, considering the source(s) of energy, fluids and metals, and transport and subsequent trapping of fluids and metals. In contrast, Henley and Berger (2000) emphasized coupling of processes at the site of deposition to explain the distinctive characteristics, such as oscillatory laminations, of epizonal deposits.

Both Fyfe and Kerrich (1976) and Wyborn et al. (1994) stressed the importance of the scale of a minerals system, and in particular that the system was generally larger than the footprint of constituent deposits. Although this approach continues to be promoted in both the academic and minerals industry space (e.g., Hronsky et al., 2012), it is yet to be fully embraced by the geosciences community that commonly retain models dependent primarily on deposit-scale characteristics. For example, Vearncombe and Zelic (2015) looked at the application of ten structural paradigms, such as "brittle-slip" and "stress mapping", for Orogenic gold exploration over the past fifty years. They found that application of particular paradigms was largely explanatory rather than predictive, and as a consequence have been "stunningly unused or unsuccessful in the exploration for gold (p.18)".

The birth of these 'Systems' approaches coincided with major advances in our understanding of present day plate tectonics and the recognition that deposit types generally exhibited a preferred association with particular tectonic settings (e.g., Meyer, 1981). As noted by the