Self-Organized Critical Systems and Ore Formation: The Key to Spatial Targeting?

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Introduction

A goal of economic geology research is to provide the scientific framework to help us discover major new mineral resources. Great progress has been made by our community over recent decades in understanding the geology of ore deposits and their immediately adjacent systems, as exemplified by the various summary papers in the 2005 SEG 100th Anniversary volume. This knowledge has substantially improved our ability to mine and explore within the immediate environs of ore deposits. However, over the same period it has become increasingly clear that this knowledge is of limited relevance to the exploration challenge of predicting the location of new major ore districts and to discriminating between camps and provinces with different endowment potential.

As we progress into the 21st Century, the scientific framework needed to meet the challenges of spatial prediction is starting to emerge. This framework, commonly referred to as the “Mineral Systems” approach (e.g., Wyborn et al., 1994; Barnicoat 2007; McCuaig et al, 2010) is founded on a view of major ore-deposits as the foci of much larger scale fluid-driven mass-flux systems. The key elements in this framework, which are critical to targeting, are the physical processes that govern the dynamic and focused fluid flux, and the lithospheric architecture and history that provides the context for these processes. This framework focuses on the generic aspects that unify apparently diverse ore systems rather than their differences. This article is concerned with one particular aspect of this emerging new framework: the role of Self-Organized Critical Systems.

Self-Organized Critical Systems

The study of complex systems is a new area of multi-disciplinary science. Complexity science studies the way non-equilibrium, energy-flow systems spontaneously organize themselves such that complex patterns emerge which are not predictable from an analysis of the individual components of the system. Such systems organize themselves to maximize their entropy production. A central insight is that the degree of ordering of the

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system relates to the size of the potential energy gradient that the system seeks to remove (Schneider and Dorion, 2005).

There have been few attempts to apply complexity science concepts to economic geology. This is surprising because one of the classic examples of natural self organization commonly cited by physicists is a geological one: the Earth's seismogenic crust (i.e., as manifested by the Gutenberg-Richter Law). In Per Bak's best-selling book on the topic of the science of self-organised criticality, he states "Earthquakes may be the cleanest and most direct example of a self-organised critical phenomenon in nature" (Bak, 1996). The essence of this concept as applied to earthquakes is that the highly ordered patterns of energy release described by the Gutenberg-Richter Law are manifestations of a self-organisation induced by the brittle crust's resistance to the deformation imposed by plate motion.

In their seminal paper, Bak and his coworkers defined a particular type of complex system which they termed a Self-Organized Critical (SOC) system (Bak et al., 1987). This is the type of complex system considered by Bak (1996) to describe the seismogenic crust and the thesis of this paper is that SOC system concepts are also relevant to understanding ore formation.

SOC systems comprise many interacting components and the dynamics of the system is dependent on their conjunction and complex interaction (Jensen, 1998). The primary descriptive characteristics of SOC systems are that their energy release events show scale-invariant power-law behavior and their spatial manifestation shows fractal geometry (Bak, 1996).

Of more predictive interest, however, are the dynamic characteristics of SOC systems, which are characterized by situations where the driving energy flux is added slowly relative to the episodes of energy release from the system (e.g., heating of a hydrothermal system and slow mineral deposition, followed by sudden hydraulic fracturing and brecciation). The primary reason for this separation of time scales between energy input and output events is the presence of a local threshold, which provides a barrier to the flow of energy through the system (Jensen, 1998). The presence of this barrier is essential to the capacity of the system to self-organise (Jensen, 1998; Schneider and Dorion, 2005), although the fundamental reasons for this remain unclear.

Rapid, transient, energy-release events, termed avalanches, can only occur when this threshold is overcome. These avalanches exhibit scale-invariant, power-law behavior over a large range of scales, for reasons that are still not understood but are likely to relate to maximizing entropy production at the scale of the system. SOC systems exhibit behavior that physicists refer to as extremal dynamics, meaning that avalanches will nucleate where the net threshold barrier is smallest (i.e., the weakest link fails first). Therefore, local heterogeneity controls much of the dynamics of SOC systems.

The Link with Ore-Forming Systems

I propose that many, if not most, ore-forming systems are examples of SOC systems. In these systems, energy flux occurs primarily as advective fluid (including magma) flux. The primary reason SOC behavior is essential for ore formation is because it is the only viable physical mechanism in the crust to produce the concentrated fluid fluxes generally considered (e.g., Cathles and Adams, 2005; Cox, 2005) to be required for major metal accumulations. Background permeability is far too low for convective fluid flow throughout most of the crust (Manning and Ingebritsen, 1999). I also propose that fluids involved in ore formation occur in a continuum with general crustal fluids (e.g., Yardley, 2005). Thus, the fundamental key to ore formation is the anomalous dynamic processes that concentrate mass flux in a system. Several lines of evidence support this proposition.

Mineral deposits exhibit power-law size frequency distributions (e.g., Schodde and Hronsky, 2006), and it is also known that the spatial distribution of mineral deposits is best modeled as a fractal distribution (e.g., Carlson, 1991).

Many mineral deposits present evidence that their formation involved multiple transient pulses of intense fluid flow. This is commonly recorded as multiple overprinting generations of veins and brecciation, or layers within a single vein (e.g. Sibson et al., 1988; Cathles and Adams, 2005; Cox, 2005). Evidence for multiple fluid-flow events is supported by thermal modeling. For example, thermal constraints require that Mississippi Valley-type deposits are formed from episodic pulses of brine expulsion more than three orders of magnitude greater than those which could be produced by steady-state basin dewatering, with the most likely mechanism being the rupture of an over-pressured fluid reservoir (Cathles and Smith, 1983). Consistent with this, there is now direct evidence that, immediately after a seismic event, some fault-related damage zones can be associated with transient, extreme fluid permeability and fluid flow. In one case, the 1997 Umbria Marche earthquake sequence in Northern Italy, transient, post-seismic permeability for a localized zone in the hanging wall of a major rupture has been estimated as $4 \times 10^{-11} m^2$; this is 10^5 to 10^6 times greater than background crustal permeability at that depth (Miller et al., 2004).

Although common intuition suggests that ore deposits will form in the most dilational parts of the crust, this is not supported by observational data. Instead, evidence from a range of deposit types including orogenic gold, porphyry copper and magmatic Ni-Cu-PGE sulfide deposits commonly indicates exactly the opposite, with anomalous localized compressional geodynamics and/or barriers to fluid flow playing an important role (e.g.,

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Sibson et al., 1988; Czmanske et al., 1995; Cathles and Adams, 2005; Rohrlach and Loucks, 2005; Sillitoe, 2010).

Implications for exploration

The most important implication of these ideas for exploration targeting is that an essential element of ore-forming systems is a localized threshold barrier to flow. This barrier to flow is as critical an element of a mineral system as the classic trinity of "source, transport and trap".

In many cases, this threshold barrier will have a clear spatial identity and enclose an overpressured fluid or magma reservoir that is episodically ruptured. These threshold barriers are likely to include features such as the crystallizing carapaces of intrusions, antiformal culminations, and the steep-dipping structural margins of sedimentary basins, distal to fluid source regions. An important component of any targeting strategy then becomes the identification of potential paleo-overpressured fluid or magma reservoir sites via various proxies. These are likely to represent a much larger target than the ore environment itself. It is proposed here that the scale of these putative overpressured reservoirs defines the scale of associated mineral deposit camps (i.e., a cluster of closely related deposits). For example, according to Sillitoe (2010) the typical scale of clusters of porphyry copper deposits is 5-30 km, similar to the scale of underlying magmatic reservoirs that he infers to drive these systems. Interestingly, this same length scale (5-30 km) is, in the author's experience, also very typical for the scale of the antiformal culminations associated with major orogenic gold deposits.

As a point of clarification, it needs to be emphasized that the paleo-overpressured reservoir discussed above does not represent the entire mineral system, but rather the essential element which links the regional-scale processes which supply potentially ore-forming fluids or magma to the ultimate site of ore deposit formation.

The energy-release events in ore-forming SOCs comprise pulses of overpressured fluid or magma. These pulses will create their own conduits (although usually, but not always, utilizing existing structural weaknesses) and form pipe-like networks between their source and sink. Depending on the details of the composition of an ore fluid in a particular system, ore deposits will form either within the conduit or where the fluid discharges into its fluid sink. Understanding the relationship between ore and its host conduit system has critical implications for near-mine exploration programs. One of these is that, in structurally hosted ore-systems, the ore-fluid conduit is likely to be a much more extensive feature that any particular hosting structure. Therefore, it may be possible in exploration to trace the same fluid conduit downward from one host structure to another. An example of this was documented at the Emperor gold deposit by Begg (1996).

The SOC concept predicts that focused pulses of ore fluid will come together at sites, within the boundaries of the system, where the structural architecture is most conducive to failure driven by fluid pressure build-up. There are consistent spatial patterns of distribution for large mineral deposits that are repeated predictably across diverse deposit classes. These include a regional-camp scale spatial association with zones of localized complexity along long-lived, large-scale structures and a direct association between ore-fluid conduits and low bulk-strain fracture networks. It is also quite common for ore deposits widely separated in time to form in the same volume of rock (e.g., Kambalda NiS and St. Ives Au; Mt. Isa Pb-Zn and Cu; Carlin district Au). These coincidences must have an underlying explanation and it is proposed that only certain structural architectures may be favorable for the generation of an ore-forming SOC. Determining the nature of such architectures should be a target for further research.

One of the implications of the SOC concept is that systems with mineralization potential may only transiently organize to form ore deposits. This has implications at both the regional and deposit scale.

At the regional scale, this leads to the prediction that ore formation is likely to be associated only with specific favorable periods in the evolution of a terrane. Significant ore formation requires a (probably rare) temporary conjunction of fluid production with a period of low bulk crustal permeability. Such periods will facilitate the type of fluid-driven dynamics favorable for the formation of SOC systems. This prediction is consistent with empirical observations that, where well documented, the emplacement of major mineral systems occurs at restricted times during the geodynamic evolution of their host province (e.g., Tosdal and Richards, 2001). These times include transient periods of regional compression, switches in tectonic stress (e.g., from compression to transpression), and periods of low bulk strain during the final termination of an orogen.

Similar changes in dynamic regime with implications for ore formation may also occur at a deposit scale. In several ore systems (El Teniente, Olympic Dam, Kelian) there is, in detail, a well documented antithetic relationship between major polymictic breccia pipes, which are relatively barren, and smaller scale monomict hydrothermal breccias which host the majority of the mineralization. I suggest that these two types of breccias represent two contrasting dynamic states of magmatic hydrothermal systems. The large-scale phreato-magmatic breccias represent a physical state where the threshold barrier has been overwhelmed by the external driving dynamics of the system (i.e., massive eruptive volcanism) and therefore does not function to organize fluid flow. In contrast, the mineralized hydrothermal breccias represent the system in its organized state where the threshold barrier (possibly some sort of intrusive carapace at depth) remains intact, with only local transient fluid release events.

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In conclusion, I propose that ore formation is the by-product of transient, and rather rare, periods of anomalous dynamics during the evolution of large-scale fluid flux systems. Large-scale geodynamics, patterns of lithospheric architecture and the lithosphere history provide the critical spatial context for these dynamic systems. Future research that focuses on this approach is likely to yield significant improvements in our ability to predict the location of undiscovered giant ore systems.

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