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Review

Mineral system analysis: Quo vadis

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ABSTRACT

The concept of a mineral system was first formally introduced in 1994, two decades after the analogous petroleum system concept had been developed. Mineral systems involve: (1) tectonic events that trigger and define temporal windows for mineralising events, (2) geochemical and tectonic processes that produce 'source regions' often enriched in metals and hydrothermal fluids and magmas capable of mobilising these metals, (3) tectonic, sedimentary, diagenetic and structural processes that produce conduits that can act as pathways for fluid/magma flow at lithospheric, crustal, province and district scales, (4) processes that drive fluid flow, (5) focussing mechanism that concentrate (or throttle) the flow of fluids or magmas into depositional 'trap' sites at the camp to deposit scales, (6) chemical and physical processes that cause metal deposition at the trap site, (7) post-depositional geochemical processes that produce geochemical and geophysical features that allow later detection, and (8) processes that enhance exhumation, preservation and upgrading of mineralised material.

Although mineralising events are generally short-lived, important features of mineral systems can develop well before, or well after the mineralising event, and the evolution of a mineral system can extend over hundreds of millions to billions of years. For example, the architecture of mineral systems, which controls the location of source regions and conduits, is commonly established (long) before the mineralising event, and exhumation and upgrading through metamorphism and/or supergene enrichment occur (long) after the mineralising event. The advantage of the mineral system approach is that it focusses on the critical geological processes necessary to form a major mineral deposit and is not restricted to descriptive elements of a specific mineralisation style. Mineral systems can explain the spatial and temporal co-occurrence of mineral deposits within a specific mineral province. The mineral system concept can also explain families of coeval mineral systems that potentially formed in the same or adjacent terranes or provinces.

Presently, mineral systems are broadly subdivided into orthomagmatic and hydrothermal classes, with several transitional systems between these end-members not well defined (e.g., sediment-hosted deposits with hydrothermal overprints or enrichment). Coeval, or nearly coeval, mineral systems, such as IOCG and porphyry Cu–Au systems in Chile or orogenic Au and Cu–Au porphyry systems in the Lachlan Orogen in eastern Australia, can develop during the tectonic evolution of a given terrane. Overprinting mineral systems, potentially separated by tens of millions of years, can also develop where products of early-formed mineralising events (e.g. syn-volcanic or syn-sedimentary events) can be overprinted at a later stage by mineralisation formed during orogenesis or basin inversion (e.g., orogenic Au system).

The mineral system concepts and models can be translated into effective exploration targeting criteria and serve as the basis of robust, testable exploration models. Arguably, this is the main practical purpose for a systematic mineral system analysis and its main advantage over traditional descriptive deposit models. This advantage is enhanced in under-explored areas, particularly covered areas with poor or no outcrop, where known existing deposits, from which empirical models are developed, are lacking. Defining and mapping expressions of the critical elements of mineral systems can effectively focus exploration targeting. Major deep-crustal domain boundaries, often overlain by younger geological provinces and not clearly expressed in many traditional geological datasets, provide steep crustal zones of focused regional fluid flow for many orthomagmatic and hydrothermal mineral systems.

Significant challenges in the development of mineral system models and their effective practical applications remain. For example, there is not enough information on the tectonic setting of productive mineral systems and the existing information is commonly conflicting. This is often caused by a short-lived transient nature of specific tectonic conditions favourable for triggering and driving a productive mineral system, exacerbated by a lack of outcrop and/or lack of high resolution geophysics, geochemistry and geochronology in poorly explored geological terranes.

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An important challenge that mineral system geoscience can help to address is exploration area selection at the district to camp scale. At larger scales, conceptual understanding of the relationships between tectonism and metallogeny can identify potentially mineralised provinces, and at smaller scales, well established empirical relationships between deposits and geochemical and geophysical anomalies provide vectors to ore at the camp to deposit scale. It is the intermediate, district to camp scale where both conceptual- and empirical-based targeting commonly fail, providing a challenge to mineral exploration, particularly in greenfields terranes.
Finally, mostly end-member hydrothermal and orthomagmatic mineral systems have received much attention in recent years; sedimentary deposits (e.g., placers, phosphorites) have yet to be defined within the mineral system framework. However, recent developments in the mineral system geoscience provide an increasingly robust framework for more effective predictive regional exploration targeting.

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1. Introduction

Over the last few decades there is a widespread perception that mineral exploration, especially grassroots or greenfield exploration, has been unsuccessful, with some (Lord et al., 2001) suggesting that exploration can actually destroy value. This perception at least in part reflects the reality that most well exposed provinces around the world have been explored and that most of the 'easily found' deposits have been found.

In response to a need to improve success rates, the oil and gas exploration industry developed the so-called 'petroleum system' concept in the 1970s. Magoon and Dow (1994) defined a petroleum system as "a natural system that encompasses a pod of active source rock and all related oil and gas and which includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist." Petroleum systems analysis has become the standard conceptual framework in the petroleum exploration industry, and, although difficult to quantify, the petroleum system concept has improved the success of petroleum exploration (Australian Academy of Science, 2012).

Given this success of the petroleum system concept and the decreasing success rate in the minerals exploration industry, Wyborn et al. (1994) formally introduced the concept of a "mineral system", two decades after the petroleum system concept was developed. Uptake of the mineral system concept by the minerals exploration industry has