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Radiogenic isotopes, ore deposits and metallogenic terranes: Novel approaches based on regional isotopic maps and the mineral systems concept

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ABSTRACT

Radiogenic isotopes have long been used in mineralisation studies, not just for geochronological determinations of mineralising events but also as tracers, providing, for example, information on the source of metals. It was also evident early on that consideration of isotopic data on a regional scale could be used to assist with metallogenic interpretation, including identification of metallogenic terranes. The large amounts of isotopic (and other) data available today, in combination with readily available graphical software, have made possible construction of isotopic maps, using various isotopic variables, at regional to continental scales, allowing for metallogenic interpretation over similarly large regions. Such interpretation has been driven largely by empiricism, but increasingly with a mineral systems approach, recognising that mineral deposits, although geographically small in extent, are the result of geological processes that occur at a variety of scales.

This review looks at what radiogenic isotopes can tell us about different mineral systems, from camp- to craton-scale. Examples include identifying lithospheric/crustal architecture and its importance in controlling the locations of mineralisation, the identification of metallogenic terranes and/or favourable geodynamic environments on the basis of their isotopic signatures, and using juvenile isotopic signatures of intrusives to identify metallogenically important rock types. The review concentrates on the Sm–Nd system using felsic igneous rocks and the U–Th–Pb system using galena, Pb-rich ores and other rocks. The Sm–Nd system can be used to effectively 'see' through many crustal processes to provide information on the nature of the source of the rocks. For voluminous rocks such as granites this provides a potentially powerful proxy in constraining the nature of the various crustal blocks the granites occur within. In contrast, Pb isotopic data from galena and Pb-rich associated ores provide a more direct link to mineralisation, and the two systems (Pb and Nd) can be used in conjunction to investigate links between mineralisation and crustal domains.

In this contribution we document: the more general principles of radiogenic isotopes; the identification of time-independent isotopic parameters; the use of such variable to generate isotopic maps, and the use of the latter for metallogenic studies. Regional and continental scale isotopic maps (and data) can be used to empirically and/or predictively to identify and target (either directly or indirectly by proxy) larger scale parts of mineral systems that may be indicative of, or form part of metallogenic terranes. These include demonstrable empirical relationships between mineral systems and isotopic domains, which can be extracted, tested and applied as predictive tools. Isotopic maps allow the identification of old, especially Archean, cratonic blocks, which may be metallogenically-endowed, or have other favourable characteristics. These maps also assist with identification of potentially favourable paleo-tectonic settings for mineralisation. These include: old continental margins, especially accretionary orogenic settings; and juvenile zones, either marginal or internal, which may indicate extension and possible rifting, or primitive arc crust. Such isotopic maps also aid identification of crustal breaks, which may represent major faults zones and, hence, fluid pathways for fluids and magmas, or serve to delineate natural boundaries for metallogenic terranes. Finally, isotopic maps also act as baseline maps which help to identify regions/periods characterised by greater (or lesser) magmatic, especially mantle input. Of course, in any exploration model, any analysis is predicated on using a wide range of geological, geochemical and geophysical information across a range of scales. Sm–Nd and U–Th–Pb isotopic maps are just another layer to be integrated with other data. Future work should focus on better constraining the 4D (3D plus time) evolution of the lithosphere, by integrating isotopic data with other data, as well as through better integration of available radiogenic isotopic systems, including the voluminous amounts of in situ isotopic analysis (of minerals) now available. This should result in more effective commodity targeting and exploration.

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1. Introduction

Radiogenic isotopes have long been used in mineralisation studies, not just for geochronological determinations of mineralisation but also commonly as tracers, i.e. to provide information on geological processes and the components involved in such processes. Isotopes can provide information on the nature, age and source of mineralisation, the pathways of fluids, possible metal sources, and on the processes responsible for mineralisation, and there is a voluminous literature regarding the use of radiogenic isotopes, including a number of review papers (e.g., Tosdal et al., 1999; Lambert et al., 1999; Ruiz and Mathur, 1999, and references therein). It was recognised many years ago that regional-scale isotopic maps could be generated and used to assist with metallogenic interpretation and identification of metallogenic terranes (e.g., Zartman, 1974; Farmer and DePaolo, 1984; Wooden et al., 1998). Today large amounts of isotopic (and other) data are available and are being produced at an ever increasing rate. These data, in combination with readily available graphical software, have made possible construction of isotopic maps, using various isotopic variables, at regional to continental scales. Examples include Cassidy et al. (2002), Champion and Cassidy (2007, 2008), Champion (2013), Huston et al. (2014), and Mole et al. (2013) for the Sm–Nd system, Huston et al. (2014, 2016-in this volume) for the Pb system and Mole et al. (2014) for the Lu–Hf system. These include the first continental-scale isotopic map, produced by Champion (2013) for the Australian continent.

The usefulness of such isotopic maps for metallogenic studies has also become increasingly apparent since pioneering studies such as Zartman (1974). This has been driven largely by empiricism, e.g., Zartman (1974), Wooden et al. (1998), Cassidy and Champion (2004), Cassidy et al. (2005), Huston et al. (2005, 2014), but increasingly by the development and application of a mineral systems approach (Huston et al., 2016-in this volume). Mineral deposits form through the coincidence of favourable geological processes within a given spatial setting and commonly at a specific geological time. Like the petroleum system concept (Magoon and Dow, 1994), an analogous mineral system concept can also be defined, encompassing “all geological factors that control the generation and preservation of mineral deposits” (Wyborn et al., 1994). Although there are a variety of interpretations of what a mineral system is (e.g., Wyborn et al., 1994; Barnicoat, 2007; McCuaig et al., 2010; Huston et al., 2012; see Fig. 1), most include factors such as the geological setting, the timing and duration of deposition, the source(s) and nature of mineralising fluids (including magmas), the pathways utilised by the respective fluid and fluid flow drivers, the depositional site, mechanisms of metal transport and deposition, and post-depositional modifications (Fig. 1A). The mineral systems concept, e.g., Wyborn (1997), recognises that mineral deposits, although geographically small in extent, are the result of geological and geodynamic processes that occur, and can be mapped at, a variety of larger scales (Fig. 1; e.g., McCuaig et al., 2010; Hronsky et al., 2012). Accordingly, a better knowledge of the space-time evolution of geological terranes and their components provides important constraints on prior geodynamic regimes and lithospheric architectures which may have played an important role in mineral systems. This increased understanding has the potential to explain the often heterogeneous distribution of mineralisation within regions. A good example of this are models for the generation of the strong Ni-endowment present within the Norseman-Wiluna belt, Eastern Goldfields Superterrane (EGST), Yilgarn Craton, Western Australia (e.g., Begg et al., 2010; Barnes and Fiorentini, 2010a, 2010b, 2012; Mole et al., 2014), which implicate a strong role for pre-existing lithosphere architecture in controlling fluid flow (in this case ultramafic magmas) and pathways and the location of komatiitic nickel deposits. This example highlights an important point regarding the mineral systems approach as used here, namely that important controls on mineralisation may have been in place prior to the mineralisation event.

Just as the mineral system works over a range of scales so too does the applications for radiogenic isotopes. At the larger scale (camp- to continent-scale), radiogenic isotopes have the potential to inform on the architecture of the system and the geological framework, i.e., on the geodynamic and geological history of the lithosphere the respective deposit occurs in. It is at these scales that regional isotopic maps are at their most useful and informative. This review, therefore, looks at what radiogenic isotopes can tell us about different mineral systems, particularly focussing on their use for mineral systems at the craton- to camp-scale. Examples include: identifying lithospheric/crustal architecture and its importance in controlling the locations of mineralisation; the identification of metallogenic terranes and/or favourable geodynamic environments on the basis of isotopic signatures; and identifying metallogenically important rock types by their isotopic signature.

The paper concentrates on the Sm–Nd and U–Th–Pb isotopic systems, which have been in use for a long period (e.g., Zartman, 1974; Farmer and DePaolo, 1983, 1984; Bennett and DePaolo, 1987), and for which the most comprehensive regional isotopic data are available. We document the general principles of radiogenic isotopes; the identification of time-independent isotopic variables; the use of such variable to generate isotopic maps, and the use of the latter for metallogenic studies. Examples from other systems (Lu–Hf, Re–Os) are also included, particularly coupled isotopic systems, which provide additional constraints on the links between lithospheric processes and mineralisation.

2. Mineral systems and radiogenic isotopes

The multi-scale mineral systems approach means that knowledge of the four-dimensional evolution of any geological terrane is important for both a better understanding of metallogeny and for more efficient mineral exploration (e.g., McCuaig et al., 2010). A better understanding of the four-dimensional evolution of any geological terrane encompasses a greater knowledge of the lithosphere of that terrane, including not just the more readily mappable upper crust but the more inaccessible lower crust and mantle lithosphere components (Fig. 1B). This is where radiogenic isotopes are most useful as they can supply not just potential ages of these regions but also constraints on their nature, such as their composition and how they may have formed. This is particularly the case when applied to rocks that may have either formed in the lower crust or mantle lithosphere, or have interacted with these regions. A good example of this approach is the extensive work over many decades on the characterisation of the asthenosphere on the basis of isotope systematics and geochemistry of basalts and other mantle-derived rocks (e.g., Zindler and Hart, 1986). A similar approach can be used to constrain crustal evolution by using the isotopic (and geochemical and geochronological) characteristics of granites and other felsic igneous rocks, as has been done in the western United States (e.g., Zartman, 1974; Farmer and DePaolo, 1983, 1984; Bennett and DePaolo, 1987; Wooden et al., 1998). Because such rocks are dominantly derived from the (lower-middle) continental crust, usually in significant volumes (e.g., granite plutons can have volumes in the order of tens to hundreds of km^3), these rocks provide direct constraints on the timing, extent and nature of crustal growth. Studies of felsic igneous rocks also provide important, but less precise, indirect constraints on the nature and age of the crustal domains these rocks occur within (e.g., Farmer and DePaolo, 1983, 1984).

Another approach to constraining the crustal evolution of a metallogenic province is to use geochemical characteristics of the mineral deposits. Like granites, the geochemical and isotopic characteristics of a mineral deposit, in part, reflect their source which, depending upon the specific mineral system can be the mantle and all parts of the crust. Like granite, the geochemical and isotopic characteristics of a mineral deposit are averages of the sources that can be affected, in many cases fundamentally, by processes that occur at the site of mineralisation. However, despite these complexities, isotopic mapping using data