New Models to Aid Discovery of CRM Deposits for the Green Stone Age

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Abstract

Critical raw materials (CRMs) will be crucial for the delivery of the technologies society requires to meet its decarbonization goals and successfully address the current climate crisis. Although there are a number of well-established ore deposit models, few have been developed for CRMs. History demonstrates that ore deposit models are commonly developed to explain new discoveries. However, it is also possible to develop new ore deposit models based solely on basic geochemical and geological principles. We review the development of several ore deposit models, suggest some deposits for which models have not yet been developed, and utilise the specific example of hydrothermal nickel deposits in the Central African Copperbelt to illustrate how new ore deposit models for CRM deposits may be formulated. The current impetus to discover new resources of what have been up to the present elemental curiosities should spur significant research including work to determine the geochemical behaviour of CRMs across a range of physio-chemical conditions. There is no reason to believe that economically significant concentrations of any of the newly critical elements do not exist in nature. Imagination should make the future of CRM discovery in the Green Stone age bright.
Introduction

As noted by Smelror et al. (this volume), critical raw materials (CRMs) will be crucial for the delivery of the technologies required for society to meet its decarbonization goals and successfully address the current climate crisis. Many CRM elements are currently recovered as by-products from production of metals such as aluminium, copper or nickel (Verplank and Hitzman, 2016). Because they commonly contribute relatively little economic value compared to the main metal being produced, research on the reasons for enhanced content of CRMs in primary ores has been scant. There has been even less research devoted to understanding if stand-alone CRM deposits may exist. While exploration geologists commonly operate on the principle that all the major types of mineral deposits are already recognized, clear examples from the recent past are presented below demonstrating this is not the case.

Modern mineral exploration relies heavily on ore deposit models which provide a conceptual framework for how a particular type of deposit forms. Such models, which mirror a petroleum model approach (the “petroleum system”: Demaison and Huizinga, 1991), focus on the sources of metals, their mobilisation and transport, and their trapping at a specific location. The petroleum sector is concerned exclusively with the timely convergence of generation, transport, and trapping of liquid and gaseous hydrocarbons. Mineral systems involve a wide range of geologic physio-chemical environments ranging from those involving sedimentary systems with analogies to petroleum systems (and often involving hydrocarbons as part of the system), magmatic systems (magma, dominantly aqueous fluids exsolved from magmas, and aqueous fluids driven by magmatic heat), to metamorphic systems where enhanced pressure, temperature and tectonic movement drive metal-bearing fluids. Thus, development of useful new ore deposit models requires cognizance of a broad range of geological processes as well as an understanding of the geochemistry of both compositionally diverse fluids and a variety of dissolved metals at a wide range of temperatures and pressures.

A mineral system approach has been increasingly utilised since its formal introduction in the 1990’s (Wyborn et al., 1994) and has led to the development of a number of distinct, yet often overlapping, ore deposit models for different types of mineral deposits (Groves et al., 2022). However, such models have not been constructed for a number of poorly known mineral deposits and ore deposit models have rarely been developed for theoretically possible mineral deposits for which we do not yet recognize examples. Development of ore deposit models for fundamentally new or previously unconsidered mineral deposit types, especially for CRMs, is essential for the successful discovery and production of the elements required in the Green Stone age.

Recent Examples of “New” Deposit Types

Perhaps the most famous example in the past fifty years of the discovery of a “new” deposit type is that of the giant Olympic Dam copper-gold deposit in South Australia in 1975. This discovery resulted from the search by Western Mining Corporation for “blind” (buried) Proterozoic sedimentary rock-hosted copper deposits based upon a model of altered continental basalt as source rocks (Haynes, 2006). The Olympic Dam drill target was developed from interpretation of government-funded regional magnetic and gravity data (Rutter and Esdale, 1985; Esdale et al., 2003). The spectacular discovery did not conform to the initial exploration ore deposit model. The size and grade of the deposit, as well as its unusual style of mineralization, generated intense interest within the exploration community. An overarching ore deposit model for the deposit style evolved in the years after the Olympic Dam discovery (Hitzman et al., 1992) culminating in what is now recognized
as the iron oxide-copper-gold (or IOCG) deposit model which, while still somewhat contentious (Skirrow, 2022), is widely applied.

Hydrothermal nickel deposits are another example of a new style of mineral deposit. The vast majority of the world’s nickel resources (Mudd and Jowitt, 2014) are present in magmatic sulphide deposits (Naldrett, 2004) and within nickeliferous laterites (Golightly, 2010). However, the 1997 discovery of the Avebury Ni deposit in Tasmania (Keays and Jowitt, 2013) followed by the 2007 discovery of the Jaguar Ni deposit in Brazil (Ferreira Filho et al., 2021) and the 2011 discovery of the Enterprise Ni deposit in Zambia (Capistrant et al., 2015) provided impetus for developing models for hydrothermal nickel deposits (González-Álvarez et al., 2013a). Adjacent or nearby mafic-ultramafic rocks appear to be the source of nickel for all these deposits. While such a relationship is clear and demonstrable at Avebury (Keays and Jowitt, 2013) and at the Doriri Creek deposit (González-Álvarez et al., 2013b), a mafic-ultramafic source can only be reasonably inferred due to regional geology at Jaguar (Ferreira Filho et al., 2021) and is even more speculative at Enterprise (Capistrant et al., 2015). The Jaguar deposit is now classified as an IOCG type of deposit, in the same class as Olympic Dam. However, in contrast to the granitic host rocks at Olympic Dam, Jaguar formed in a geologic setting that allowed scavenging of nickel from nearby ultramafic wall rocks.

Other nickel-bearing deposits that do not conform to the dominant magmatic sulphide or lateritic types are also known and have attracted recent attention. These include the black shale deposits in the Paleoproterozoic of Finland (Loukola-Ruskeeniemi and Heino, 1996) and those of the Early Cambrian in China and late Devonian of northwest Canada (Pagès et al., 2018). The source of nickel for these deposits is unclear but most do not appear to have a direct link to mafic or ultramafic rocks. Instead, they may have originated from either hydrothermal fluid exhalation or seawater scavenging of metals by organic material.

All these deposits demonstrate that nickel can be mobilised and transported in hydrothermal solutions at relatively low temperatures (<350°C) although the ligands responsible for transport appear to have been variable for different deposits with some deposits having evidence of very high chlorinity (e.g., Enterprise; Zimba, 2012) while others appear to have contained abundant fluorine (e.g., Jaguar; Ferreira Filho et al., 2021). Precipitation mechanisms for the different deposits may also have varied from redox change to temperature decrease. Thus, though a comprehensive integrated model to link these disparate deposits may not be possible, they demonstrate that nickel can be sought in settings that were previously considered unprospective for this metal. Although other factors in these deposits, such as feasibility of nickel extraction from its mineralogical hosts, may largely determine whether or not significant exploration efforts are dedicated to their discovery, it is clear that a much wider variety of geological environments are now recognized as being prospective for nickel.

Another new ore deposit model type for CRMs that will likely be important in the Green Stone Age is that for regolith-hosted rare earth element (REE) deposits (Hei, 2017; Xie, 2016). These deposits, which are currently the largest source of heavy rare earth elements globally, are concentrated in South China though apparently similar styles of mineralization have recently been recognized in other parts of the world (e.g., Madagascar; Ram et al., 2019). It appears these deposits form from subtropical weathering of somewhat REE-enriched granitic rocks where the igneous minerals are leached and the released REE are fixed in clays and other mineral phases. Work continues to develop a robust ore deposit model for this type of deposit (e.g., Li et al., 2020; Huang et al., 2021).

Deposit Types Where a Deposit Model is Unclear or Unknown
There are several examples of known deposits for which we do not have a well-defined ore deposit model.

One is the Merlin molybdenite deposit in the Cloncurry district of Australia, a deposit that contains significant amounts of the CRM rhenium. This high grade (>6Mt of 1.5% Mo, 26 g/t Re) deposit was discovered in 2008 and several other prospects with enhanced Mo and Re values have subsequently been identified in the district (Babo et al., 2017). The genesis of the Merlin deposit has not been well established. Observations indicate that mineralization occurred within structures cutting highly carbonaceous rocks suggesting that a change of redox state resulted in the precipitation of anomalous amounts of both Mo and Re (Babo et al., 2017). If global demand for either Mo or Re were to rise significantly, more effort would undoubtedly be expended to devise a testable ore deposit model for this deposit type.

Another deposit for which we currently lack a well-defined genetic or exploration ore deposit model is the Serra Pelada Au-Pd-Pt deposit in the Carajás district of Brazil (Berni et al., 2014, 2016, 2019). While this deposit currently appears to be unique, unlike the Mo-Re type deposits above for which more than one example is known, features of the Serra Pelada mineral system – highly oxidised fluids, a highly reducing trap lithology, and nearby ultramafic source rocks – are present in a number of other locations around the world. Similar geological features are present in better understood ore systems such as unconformity-related uranium deposits (Cuney and Kyser, 2009) and sedimentary rock-hosted stratiform copper deposits (Hitzman et al., 2005) suggesting genetic links with these styles of mineralization. Thus, development and testing of an ore deposit model for Serra Pelada-type deposits should be possible.

Utility of New Deposit Type Models

Development of a new ore deposit model does not always result in a shift in exploration paradigms. The development of new ore deposit models for non-sulphide zinc deposits (Hitzman et al., 2003) did not lead to major exploration efforts due to both the economic difficulties in processing these types of ores as well as the ready availability of high-quality exploration plays for conventional, sulphide ( sphalerite) deposits. The ore deposit model developed for IOCG deposits on the other hand stimulated extensive worldwide exploration given the obvious significance of the Olympic Dam deposit. These efforts led to the discovery of significant new IOCG deposits such as the Ernest Henry deposit in the Cloncurry district of Australia (Rusk et al., 2010) as well as recognition that several previously discovered deposits, such as the giant Salobo deposit in the Carajás region of Brazil (Campo-Rodríguez et al., 2022; Requia and Fontboté, 2000) and the Candelaria deposit of Chile (Marschik and Fontboté, 2001), belong to the IOCG class.

Current Challenges for New Models

Our current challenge is to develop new ore deposit models for mineral deposits containing the elements that are now critical for green technologies. Development of such ore deposit models has not been a focus for the minerals industry primarily because world demand for these elements was met by sufficient by-product production (e.g., cobalt, germanium, tellurium). In some cases, such as cobalt, although a number of deposits containing this metal are known (e.g., Hitzman et al., 2017), many do not have well constrained geological or exploration ore deposit models. For many CRM elements, thermodynamic data to accurately predict their geochemical behaviour at different temperatures, pressures, and fluid compositions is lacking or inadequate. However, the fundamental issue is that one generally does not find something if they are not looking for it. For many CRMs
potentially economic concentrations will be extremely low, less than 10,000 ppm and in some cases perhaps hundreds of ppm. Thus, without extensive geochemical analyses, the presence of potential deposits containing the CRMs goes unrecognised. Meeting our CRM needs will require sleuthing our existing databases and geological records, gathering more geochemical data, and most importantly utilising our curiosity and imagination to develop ore deposit models as a framework for exploration.

Towards Development of New Ore Deposit Models – An Example

As noted above, many hydrothermal Ni deposits show a close association with nearby mafic-ultramafic rocks. This relationship is less obvious at the Enterprise deposit in the Central African Copperbelt, where significant volumes of mafic-ultramafic rocks are not found in the vicinity of the deposit (Capistrant et al. 2015). Geochemical maps of the regions surrounding the deposit show Cu-depletion coincident with talc- and monazite-enrichment in the basal metasedimentary rocks which host the Enterprise deposit (Halley et al., 2016) indicative of intense fluid flow at the basement-cover interface and suggesting that nickel may have been leached from basement rocks below the host sedimentary sequence.

Another Ni-bearing ore system in the Central African Copperbelt is the Menda prospect in the Democratic Republic of Congo. Research has shown that Mg-chlorite in local haematitic siltstones is nickel enriched and may form a potential nickel source (Bàll, 2015). Mafic-ultramafic rocks have not been identified in the Menda area; thus, the ultimate source of Ni is unknown though it may also reside in the basement. The mechanisms of nickel transport and deposition at Menda are unclear. The Menda prospect also contains significant zones of copper mineralisation. One, Kavundi Ouest, contains hydrothermal veins composed of coarse-grained kyanite, chalcopyrite, magnesite, monazite and quartz cutting carbonate and shale lithologies (Figure 1a). Kyanite, also intergrown with nickel sulphides at the Enterprise deposit (Figure 1b), is a high-pressure aluminosilicate that is often observed in high-grade metamorphic rocks. The lowest temperature kyanite-forming reaction involves the dehydration of pyrophyllite at approximately 440-470 °C (Kerrick, 1968; Haas and Holdaway, 1973). However, argillaceous rocks at Menda are dominated by chlorite-bearing lithologies suggesting a peak temperature in the range of < 400 °C. Thus, the occurrence of kyanite suggests the existence of unusual geological conditions.

Examples of metamorphic vein kyanite are recognized in high metamorphic grade kyanite-bearing rocks where Al₂O₃ and SiO₂ depletion haloes are present immediately surrounding veins (Widmer and Thompson, 2001). These veins are interpreted to form as a result of local segregation during metamorphism, rather than fluid dehydration (e.g., Beitter et al., 2008) or hydrothermal activity (e.g., Ague et al., 2003). Unlike these metamorphic examples, kyanite veins at Menda have kyanite-rich selvages and kyanite porphyroblasts in adjacent Al-poor, carbonate-rich host rocks. The textural relationships at Menda indicate Al was not sourced locally by diffusive mass transfer as in known metamorphic environments but was instead transported by hydrothermal fluids involving processes such as advective mass transfer (e.g., Bucholtz and Ague, 2010).

Aluminium is generally assumed to be immobile during both metamorphic and metasomatic processes (e.g., Carmichael, 1969) owing to the low solubility of Al₂O₃ in H₂O at high pressures and temperatures (Ragnasdottir and Walther, 1985; Walther, 1997; Tropper and Manning, 2007). However, Al₂O₃ solubility is enhanced by raising or lowering pH (e.g., Hemley and Jones, 1964; Barns et al., 1963), in solutions of high ionic strength (Walther, 1997), and in the presence of KOH solutions where alkali-Al-Si polymerisation can transport Al (Manning, 2007; Wohlers and Manning, 2009). Thus, normally insoluble elements can in the right circumstances be mobilised and transported
in fluids in high-grade metamorphic systems approaching the solidus (Wohlers et al., 2011) or in the presence of bittern brines. The Central African Copperbelt is recognized to have produced hot (200-300 °C), saline (30-60 wt% NaCl + KCl) brines that had a significant capacity for metal transport (Davey et al., 2021). This highly saline environment facilitated transport of generally immobile elements such as Al at a large scale.

A combination of textural, geochemical, mineralogical, and isotopic observations from the Enterprise and Menda Ni deposits allows an understanding of the physicochemistry of the highly saline fluids responsible for mineralisation and provide parameters for novel means of metal transport that had not previously been considered. Such understanding can provide the knowledge required to develop new ore deposit models potentially for a wide range of CRMs.

Metamorphism and Critical Raw Materials — An Avenue for Developing New Ore Deposit Models?

Metamorphism comprises changes to the physical and chemical environment which trigger reactions where the existing mineral assemblages are no longer stable (Yardley and Warren, 2021). While there are numerous studies of metamorphosed ore deposits, we have a relatively poor appreciation for how metamorphism can cause mineralisation. An exception is the orogenic gold class of ore deposits which formed at a range of metamorphic environments in upper to mid-crustal depths (Goldfarb and Groves, 2015). However, orogenic gold deposits rarely contain CRMs.

Studies of metamorphosed ore deposits may allow us to better understand what CRMs can be transported by metamorphic fluids. Just like surface and shallow waters, metamorphic fluids can carry varying amounts of a dissolved load (Yardley and Cleverley, 2015). Evidence from fluid inclusion studies records fluids with salinities greater than seawater in metamorphosed continental shelf sequences and salt-saturated fluids from amphibolite-facies evaporite-bearing successions (Yardley and Graham, 2002). We know that some atypical element associations such as Co are commonly observed in ore deposits in metamorphosed regions such as north Finland where the probable involvement of salt-saturated fluids during metamorphism has been invoked (Vasilopoulos et al., 2021). This suggests somewhat unusual metamorphic fluids to transport and concentrate critical elements may be a feature of new ore deposit models. It also appears that a combination of mechanical and chemical processes can lead to recrystallisation of minerals where trace elements such as In, Sn and Ag are preferentially incorporated into sulphides during metamorphism (Zhau et al., 2021). Thus, metamorphism may be able to increase the relative amounts of CRMs in some metamorphosed mineral deposits.

Our current understanding of how elements are redistributed during metamorphic processes is limited in large part to major mineral-forming elements. We currently have the tools to gather the information required to predict which processes affect CRMs at the different physical and chemical conditions present during metamorphism. However, our current ore deposit models do not consider the diversity of processes occurring in metamorphosed terranes. To develop new CRM ore deposit models in metamorphosed regions we must expand our knowledge of element mobility in metamorphic environments. Such research could prove fruitful as metamorphic rocks account for large portions of cratonic regions (Figure 2) but in general have probably received less exploration attention, especially for CRMs, given the paucity of ore deposit models related to metamorphic processes. It is important to note that recent compilations of data on mineral occurrences and historic mines, such as the GeoERA FRAME (https://geoera.eu/projects/frame2/) and Mintell4EU (/geoera.eu/projects/mindesea2/) projects completed by European Geological Surveys do provide a
firm foundation for potential development of new ore deposit models in areas such as metamorphic terranes.

**Conclusion**

There is no reason to believe that economically significant concentrations of any CRMs do not exist in nature. History clearly demonstrates there are styles of mineralization and types of deposits that we have not recognized or appreciated even when their distinct characteristics are obvious, at least in retrospect. The current impetus to discover new resources of what have been up to the present elemental curiosities should spur significant research and exploration for new CRM ore deposit models. Research should include analysis of historical geological data as well as new experimental work to better constrain the geochemical behaviour of CRMs across a range of physiochemical conditions. The abundance of metamorphic rocks and the relative lack of knowledge of the behaviour of CRMs in these environments suggests it may be a fruitful topic of study. Imagination, combined with fundamental science and rigorous data gathering, should make the future of CRM discovery in the Green Stone age bright.

**Acknowledgements**

This publication/research has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under grant number 16/RP/3849 and 13/RC/2092_P2. For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.
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**Figure Captions**

**Figure 1**: a. Coarse kyanite (ky) crystals in magnesite (mgs) vein with chalcopyrite (cpy) from the Menda prospect, Congolese Copperbelt. b. Altered rock (silica-albite-haematite) with kyanite spots, cut by quartz (qtz)-kyanite veins and late nickeliferous pyrite and vaesite (va) from the Enterprise deposit, Zambian Copperbelt.

**Figure 2**: Representation of the global lithological map database (GLiM) (Hartmann and Moosdoorf, 2012) showing the distribution of metamorphic rocks exposed at the Earth’s surface, a broad lithological class which includes shales to gneisses and amphibolites to quartzites. This does not include weakly metamorphosed or foliated rocks, greenstone belts or ophiolites which are instead classified by their parent lithologies as described in Hartmann and Moosdoorf (2012). Major mineral deposits of the world (database compiled by Schultz & Briskay, 2005 and references therein, accessed from [https://mrdata.usgs.gov/major-deposits/](https://mrdata.usgs.gov/major-deposits/)) are plotted as circles with metamorphic deposits plotted as yellow triangles. Metamorphic deposits are classified in this database as rocks that are subjected to higher temperature and/or pressure and are distinct from hydrothermal deposits, regardless of pressure-temperature conditions experienced during hydrothermal activity. For example, orogenic gold deposits are classified as hydrothermal. The distribution and occurrence of metamorphic rocks and deposits shown on this figure is therefore underrepresented and therefore considered as a minimum.
Figure 2