

## Critical metal mineralogy and ore genesis revisited: thematic set arising from the Third International Critical Metals Meeting, Edinburgh

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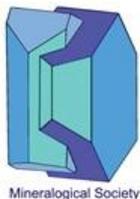
The Applied Mineralogy Group (AMG), a special interest group of the Mineralogical Society of Great Britain and Ireland, hosted the Third International Critical Metals Meeting in Edinburgh in May 2019. The objective of the meeting was to bring academic, geological survey, non-governmental organisations and industry stakeholders together to discuss the challenges presented by the risk of supply interruption, the changing nature of criticality and of course, the mineralogy of ore deposits. Following in the tradition of the meeting (e.g., Chakmouradian et al., 2015), we have curated a thematic set of publications addressing critical metal mineralogy, ore genesis, and in a departure from typical Mineralogical Magazine content, some social science applied to critical metals.

Critical raw materials, typically defined as those at risk of supply interruption while essential to economic development, are also the metals and industrial materials identified as essential to our transition to a carbon neutral world (e.g., Gunn, 2014). Given their importance for the production of high-strength permanent magnets required in efficient electric vehicles and wind turbines, it is no surprise that most papers in this thematic set focus on the rare earth elements (REE). The criticality 'level' of the REE continues, at least from the viewpoint of Western organisations, to be among the highest of all the critical raw materials (e.g., European Commission, 2017). This is largely due to supply security concerns, owing to the concentration of REE production in a limited number of jurisdictions (Wall, 2014), compounded by poor recycling rates (Binnemans et al., 2013) and unacceptable decreases in magnet performance from non-REE-bearing magnet substitutes (Riba et al., 2016).

Setting the scene in the first paper of this thematic set, Schmid (2020) use REE as a case study to examine the challenges that insecure supply presents to the European automotive industry. Through a series of interviews, the author highlights how the industry was initially caught off-guard during the 2011 REE crisis, where REE prices spiked substantially. The European automotive industry is now aware of the issues of supply security for critical raw materials, but Schmid (2020) show that REE prices remain the most important criterion when considering alternative supplies. Few of the interviewed manufacturers are involved in earlier aspects of the supply chain, and instead are focussed on removing supply risk through substitution with non-REE-bearing technology. Despite this finding, Schmidt (2020) note that substitution is not an industry-wide trend, and that 90% of manufacturers are using REE-bearing magnets in new electric vehicles. As such, demand for the REE, particularly Nd, is projected to continue to increase beyond 2026 (Goodenough et al., 2017).

There is no global shortage of potential REE deposits but, more so than for most commodities, mineralogy is a key factor regarding their viability for extraction and processing and, therefore, ensuring the price of production is kept low. The role of the mineralogist is, thus, important for ensuring a secure future supply of the REE. REE mineralisation can include a wide diversity of minerals, comprising 6% of all known mineral phases (IMA, 2019), yet only four (xenotime, monazite, bastnäsite and loparite) are presently processed commercially (Krishnamurthy and Gupta, 2015). Many mineral exploration companies plan on beneficiating other REE minerals, such as those of the eudialyte group, but often the formation conditions and substitution controls for these phases are not well known.

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The diversity of REE minerals is compounded by their tendency to accommodate individual REE in varying proportions. Only some REE (e.g., Nd) are in demand for magnet production while others (e.g., Ce) are over-supplied— a mismatch termed the ‘balance problem’ (Binnemans et al., 2018). Understanding the geological and mineralogical processes which fractionate the REE to the right ‘balance’ is essential in order to ensure metal demand is appropriately met. In the second paper of this thematic set, Borst et al. (2020) investigate the structural state of the REE in eudialyte group minerals in order to determine why this phase has a well-balanced proportion of REE. Borst et al. (2020) use X-ray spectroscopy to demonstrate that, in eudialyte, REE substitute for Ca in a single crystallographic site. In most minerals single-site substitution would preferentially favour either the larger light (L)REE or the smaller heavy (H)REE, but the authors suggest that the REE are ‘balanced’ by site ordering or through coupling of the heavy (H)REE with other small ions. Thus, the balanced REE distribution of eudialyte group minerals is primarily a mineralogical control, rather than dictated by formation environment.

The remainder of the papers in this thematic set focus on mineralisation related to carbonatites, which are particularly well-endowed with deposits of several critical raw materials, such as P, Nb, F and the REE in particular (Verplanck et al., 2016). Broom-Fendley et al. (2020) present X-ray spectroscopy data investigating the incorporation of sulfur into the structure of monazite group minerals. Sulfur is potentially an important agent for the transport of REE in deposits which form through hydrothermal processes (e.g., Migdisov et al., 2016). Broom-Fendley et al. (2020) demonstrate that monazite accommodates sulfur as sulfate, but can also incorporate a small amount of the sulfite and sulfide species. In the studied example, sulfur-bearing monazite formed in a weathering environment. However, sulfur is known to occur in monazite in some REE deposits, and in these cases its composition may be indicative of the ore-forming environment.

The importance of sulfur as a potential REE-transporting ligand is highlighted in the first of two studies by Cangelosi et al. (2020a). These authors present detailed textural and compositional analyses of small-scale REE mineralisation at the Okorusu carbonatite, Namibia, demonstrating that the formation of late-stage REE mineralisation at this complex is associated with the breakdown of magmatic pyrite. Such breakdown would release sulfate into a hydrothermal fluid, which the authors suggest is responsible for the alteration of primary REE-bearing phases and the subsequent re-distribution of REE into newly-formed REE minerals. Continuing the theme of the importance of sulfate, Cangelosi et al. (2020b) present work on the Dashigou carbonatite, China, where early-formed monazite is hydrothermally replaced by a relatively HREE-rich mineral assemblage (Smith et al., 2018). In this second contribution, Cangelosi et al. (2020b) demonstrate that the fluid responsible for the hydrothermal replacement is preserved in fluid inclusions trapped in quartz lenses in the carbonatite. These inclusions are very sulfate-rich, further supporting the notion that sulfate-rich fluids are capable of transporting REE and breaking-down pre-existing REE-bearing phases.

The last paper of this thematic set continues the theme of looking at carbonatites for their mineral resources, but focusses on niobium mineralisation. Niobium is considered a critical raw material and is principally used as an alloy in steel. Production, however, is presently limited to only three mines, of which the two largest are in Brazil, accounting for 92% of global production (Mitchell, 2015). Mitchell et al. (2020) describe an unusual occurrence of pyrochlore, the principal ore mineral for Nb, associated with apatite in clasts from the Good Hope carbonatite, Canada. Based on the texture of these clasts, the authors suggest the apatite and pyrochlore did not form from the same melt and, instead, are the result of mechanical mixing of two different magmas. The occurrence of the apatite-pyrochlore rocks in clasts is an attractive indication that such a mixed magma may exist at depth in

this complex. Given that both apatite and pyrochlore are minerals of economic interest, and critical raw materials, such mineralisation could present an attractive exploration target.

Understanding the genesis of critical metal deposits, and even more importantly the processing of the variety of critical metal-bearing phases, are key challenges to the critical raw materials community. With the contributions arising from this thematic set, we move steadily towards a better understanding the genesis of such deposits, in particular those of the REE and carbonatite hosted mineralisation. However, these contributions highlight the complexity of the ore forming minerals, with implications for processing, a key challenge in diversifying our range of mineable deposits. This thematic set is now the third compiled on Critical Metals in Mineralogical Magazine (see also Goodenough and Wall, (2016) and Bowles et al. (2018)). Perhaps this is the start of a biennial Mineralogical Magazine tradition on such a subject? In any case, it is one to which we thank the AMG for their financial support to the meetings from which these contributions have arisen.

The next Critical Metals Meeting will be held in September 2020 at Northwest University, Xi'an, China. The principal focus of the meeting is on mineralisation processes, with sessions on shallow plumbing systems and geology and geophysics for geomodels. The scientific sessions will be complemented by expert-led field trips. For further details see <http://criticalmetalsmeeting.com>.

The guest editors, Eimear Deady and Sam Broom-Fendley, would like to thank the meeting delegates for lively debate and participation and in particular the contributors to this thematic set of publications for their interesting and thought provoking research. We are also grateful to Helen Kerbey and Kevin Murphy for their support in preparation of this issue, as well as to those who took the time to review the manuscripts.

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