

Critical Metal Mineralogy: Preface to the special issue of Mineralogical Magazine

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THE phrase ‘critical metals’ has become widely used over the last decade. Critical metals are those for which demand is increasing, largely due to their use in new technologies, but for which there are restrictions to supply. These supply restrictions are normally not due to a natural shortage of these elements, but instead can be attributed principally to a concentration of production in a small number of countries. Markets for many of the critical metals are still small when compared with those for major industrial metals such as copper or lead, and at the time of writing prices for almost all metals are low; as a result it can be difficult to diversify production. A number of reports, books and special issues have been published on the subject (Graedel *et al.*, 2012, EC, 2014, Gunn, 2014, Chakhmouradian *et al.*, 2015, Lusty and Gunn, 2015, Graedel *et al.*, 2015).

There is no single definitive list of critical metals, because the exact definition varies according to the context and the author. The designation of a metal as critical can also change with time, as prices and demand vary. One of the most widely accepted lists of critical raw materials is that published by the European Commission (EC, 2014). This list recognizes the rare-earth elements (*REE*), particularly the heavy *REE* (*HREE*), as among the most critical of all raw materials, because they are vital components of the high-strength magnets and phosphors that are widely used in many modern technologies. Other metals recognized as critical by the EC include tungsten, antimony, niobium, magnesium and cobalt. Lithium may also be considered as critical (Evans, 2014), and is notable for consistently growing demand, due to its importance in batteries used in electric cars (Vikström *et al.*, 2013, Maxwell, 2014). A metal

that is on the verge of criticality is manganese, which is a crucial raw material for the steel industry. Demand for manganese has shown growth in recent years, and there is some vulnerability to supply restriction (Nuss *et al.*, 2014, Graedel *et al.*, 2015).

Geological resources of critical metals are found commonly in complex natural systems that are not always well understood. These metals occur in a wide range of ore minerals with highly varied properties. For example, more than a hundred potential *REE* ore minerals occur in nature, although processing methods for beneficiation, extraction and separation of the *REE* have only been proven for a relatively small number of these minerals (Chakhmouradian and Wall, 2012, Jordens *et al.*, 2013). Before any critical metal deposit can move towards production, it is vital to understand the mineralogy in detail, as this underpins development of flowsheets for mineral processing (Jordens *et al.*, 2013). This special issue therefore addresses the mineralogy of critical metal deposits. Most of the papers included here were first presented in 2014, either at the European Rare Earth Resources conference in Milos, Greece, or at the 21st General Meeting of the International Mineralogical Association in Johannesburg, South Africa.

Despite a significant focus on research and exploration since the ‘rare earths crisis’ of 2009–10 (Gschneidner Jr., 2011), *REE* production is still almost entirely concentrated in China, and the *REE* are still considered among the most critical metals. The majority of the world’s light *REE* (*LREE*) come from the Bayan Obo carbonatite mine in northern China, whilst almost all the *HREE* come from the ion-adsorption clays of southern China (Kynicky *et al.*, 2012). Several of the papers in this volume address the potential for alternative sources of the *REE* across the world. In a global context, some of the world’s largest identified *REE* resources are

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found in the Ilimaussaq complex of southern Greenland (Sørensen, 1992), which hosts two advanced exploration projects, Kringlerne and Kvanefjeld (Goodenough *et al.*, 2016). Of these, the Kringlerne prospect lies within a zone of layered apgaitic nepheline syenites in which the *REE* are hosted largely in eudialyte-group minerals. In this volume, Borst *et al.* (2016) show that a high percentage of these minerals have in fact been hydrothermally altered and replaced by a range of other mineral assemblages. They provide detailed descriptions of these assemblages, including the first recognition of gittinsite as an alteration product of eudialyte, and show that fluid compositions have a significant effect on the alteration mineral assemblage formed. *REE* are most typically retained within the pseudomorphs. However, the authors note that the alteration assemblages may have different properties to the original eudialyte-group minerals, and thus this may have significant implications for mineral processing.

Research presented here by Friis (2016) also studies alteration and mineral replacement in the Ilimaussaq complex, using samples from Kvanefjeld. This work provides the first description of moskvinite-(Y) in Ilimaussaq, and shows that alteration of original *REE* minerals can lead to fractionation of the *LREE* from the *HREE*, producing pseudomorphs that include both *LREE* minerals such as britholite-(Ce) and *HREE* minerals such as moskvinite-(Y). As at Kringlerne (Borst *et al.*, 2016) it is evident that the *REE* are retained within the boundaries of the original crystal, despite the change in mineralogy.

Mining and processing of the *REE* from hard-rock sources is highly energy intensive, with the need for blasting, crushing and milling of the rock, followed by complex beneficiation procedures to concentrate the *REE* ore minerals. In order to reduce energy usage and thus environmental impacts, research into alternative *REE* sources is developing. Deady *et al.* (2016) investigate the potential for *REE* resources in red muds, the waste products of aluminium production, which are currently stockpiled across Europe. Using case studies from Greece and Turkey, they review the mineralogy and *REE* geochemistry of the bauxite ores and the red muds produced from them. They show that *REE* are concentrated into the red muds during processing, and demonstrate that these waste red muds have significant potential as an *REE* resource for Europe.

Most of the world's *HREE* supply is currently derived from ion-adsorption clays in China

(Kynicky *et al.*, 2012, Weng *et al.*, 2015). The *REE* are typically recovered from these deposits through *in situ* leaching processes, which are much less energy intensive than production from hard-rock deposits. The paper in this volume by Moldoveanu and Papangelakis (2016) provides an overview of leaching procedures for extraction of *REE*, as tested on a range of ion-adsorption clay samples from different localities. Their work shows that tropically weathered clays from localities in South America, Africa and China are all easily leachable, indicating the presence of physically adsorbed *REE* on clay surfaces, and they have established benchmark procedures for leaching. They also show that only some ion-adsorption-type ores are enriched in the *HREE*, suggesting a strong control by the original bedrock composition and mineralogy.

Exactly how original bedrock composition and mineralogy control the nature of the ion-adsorption deposits is the subject of the paper by Sanematsu *et al.* (2016). They consider which minerals have controlled light versus heavy *REE* ratios during magmatic differentiation and weathering of calc-alkaline granites in southern Myanmar. They find that ion-exchangeable *REE* in weathered granites tend to be depleted in *HREE* relative to the whole-rock compositions, i.e. that the *HREE* are more likely to be held in insoluble residual minerals. Ion-adsorption deposits may be economic at much lower concentrations than conventional deposits, and values as low as 500 ppm *REE* are of interest. However, the key to economic success is likely to be in finding deposits with sufficiently high proportions of the more expensive *HREE* and this will require soluble *HREE*-enriched minerals in the protolith.

Global lithium resources are typically found in brine deposits, particularly in South America, and in pegmatite deposits (Kesler *et al.*, 2012). The paper in this volume by Roda-Robles *et al.* (2016) provides an overview of one of Europe's main areas of lithium mineralization, in the Iberian Massif of Spain and Portugal. The mineralization here is associated with peraluminous granites and pegmatites of Variscan age, and is of significant economic importance: Portugal is now the world's 6th largest lithium producer. Roda-Robles *et al.* describe a range of potential Li ore minerals in these intrusions, including Li-micas, Li-aluminosilicates such as spodumene and petalite, and Li-phosphates of the amblygonite–montebrasite and triphylite–lithiophyllite series. Classification of the intrusions into groups with varying Li content and different

dominant minerals allows improvement of exploration targeting in the area.

Finally, as demand for manganese is growing, there is an interest in a wider range of deposit types. Zarasvandi *et al.* (2016) present a study of the manganese deposits associated with Tethyan ophiolites in Iran, and use their geochemistry to investigate their origin.

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