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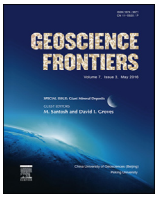

Research paper

From mantle to critical zone: A review of large and giant sized deposits of the rare earth elements

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ABSTRACT

The rare earth elements are unusual when defining giant-sized ore deposits, as resources are often quoted as total rare earth oxide, but the importance of a deposit may be related to the grade for individual, or a limited group of the elements. Taking the total REE resource, only one currently known deposit (Bayan Obo) would class as giant ($>1.7 \times 10^7$ tonnes contained metal), but a range of others classify as large ($>1.7 \times 10^6$ tonnes). With the exception of unclassified resource estimates from the Olympic Dam IOCG deposit, all of these deposits are related to alkaline igneous activity – either carbonatites or agpaitic nepheline syenites. The total resource in these deposits must relate to the scale of the primary igneous source, but the grade is a complex function of igneous source, magmatic crystallisation, hydrothermal modification and supergene enrichment during weathering. Isotopic data suggest that the sources conducive to the formation of large REE deposits are developed in subcontinental lithospheric mantle, enriched in trace elements either by plume activity, or by previous subduction. The reactivation of such enriched mantle domains in relatively restricted geographical areas may have played a role in the formation of some of the largest deposits (e.g. Bayan Obo). Hydrothermal activity involving fluids from magmatic to meteoric sources may result in the redistribution of the REE and increases in grade, depending on primary mineralogy and the availability of ligands. Weathering and supergene enrichment of carbonatite has played a role in the formation of the highest grade deposits at Mount Weld (Australia) and Tomtor (Russia). For the individual REE with the current highest economic value (Nd and the HREE), the boundaries for the large and giant size classes are two orders of magnitude lower, and deposits enriched in these metals (agpaitic systems, ion absorption deposits) may have significant economic impact in the near future.

1. Introduction

The rare earth elements (REE) are currently a focus of global attention because of geopolitical controls on their supply (Hatch, 2012), which have led to them being included in recent and current lists of critical metals (US Department of Energy, 2011; British Geological Survey, 2012; European Commission, 2014). Their importance comes from their use in the production of high strength magnets, fundamental to a range of low carbon energy production approaches, and in a wide range of high technology applications. Reviews are given in Chakhmouradian and Wall (2012), Gunn (2014), and Wall (2014). Production is currently limited to a small number of large deposits (e.g. Bayan Obo, China; Mountain Pass, USA; Mount Weld, Australia; Lovozero, Russia), by-products (e.g. mineral sands, India) or to deposits that have enrichments in specific elements of current high demand, notably dysprosium (Dy), terbium (Tb) and other HREE (e.g. the so called ion absorption deposits in weathered granite of southern China; Kanazawa and Kamitani, 2006). However, a number of deposits are known from relatively recent past production, are currently at the stage of feasibility studies, are at advanced stages of exploration or have been the focus of research. Of these, given the small size of the REE market, most are large enough to have a significant impact on

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global supply, although only Bayan Obo may truly be considered as giant.

The formal definition of a giant ore deposit was proposed by Laznicka (1999) on the basis of the tonnage accumulation index (Laznicka, 1983). This is the amount of metal in a defined ore body divided by its average crustal concentration (or ‘Clarke value’). The aim of this was both to show the relative enrichment of different metals in a directly comparative manner, removing the absolute variation of concentration between different metals, and to remove economic bias from discussion of the scale of ore bodies. The latter aim can only ever be partly successful as it is dependent on the cut-off grade used to define an ore body—an inherently economic consideration. However, this approach remains the most clearly defined way to address the problem. Laznicka (1999) defined a giant ore deposits as having a tonnage accumulation index of 1×10^{11}, and a large ore body a tonnage accumulation index of 1×10^{10}. For these values, and using an average REE crustal concentration of 1.5×10^2 ppm (Wedepohl, 1995), a large REE deposit would have 1.7×10^6 tonnes of contained REE_2O_3, and a giant deposit would have 1.7×10^7 tonnes of contained REE_2O_3 (calculated assuming an intermediate atomic mass for REE of 150). The available data for resources in REE deposits from Orris and Grauch (2002) and Long et al. (2010) and other sources are shown in Fig. 1A, and the deposits of large size or greater are shown in Fig. 1B. Because of the current scarcity of data for many of these deposits, resource estimates are commonly not JORC/NI43101 compliant, and for simplicity in this review we have used the figures quoted by those authors. Where compliant data are available they are mentioned below. Of all currently known REE deposits, only Bayan Obo, China, with the ore grade defined at 4.1 wt.% REE_2O_3, counts as

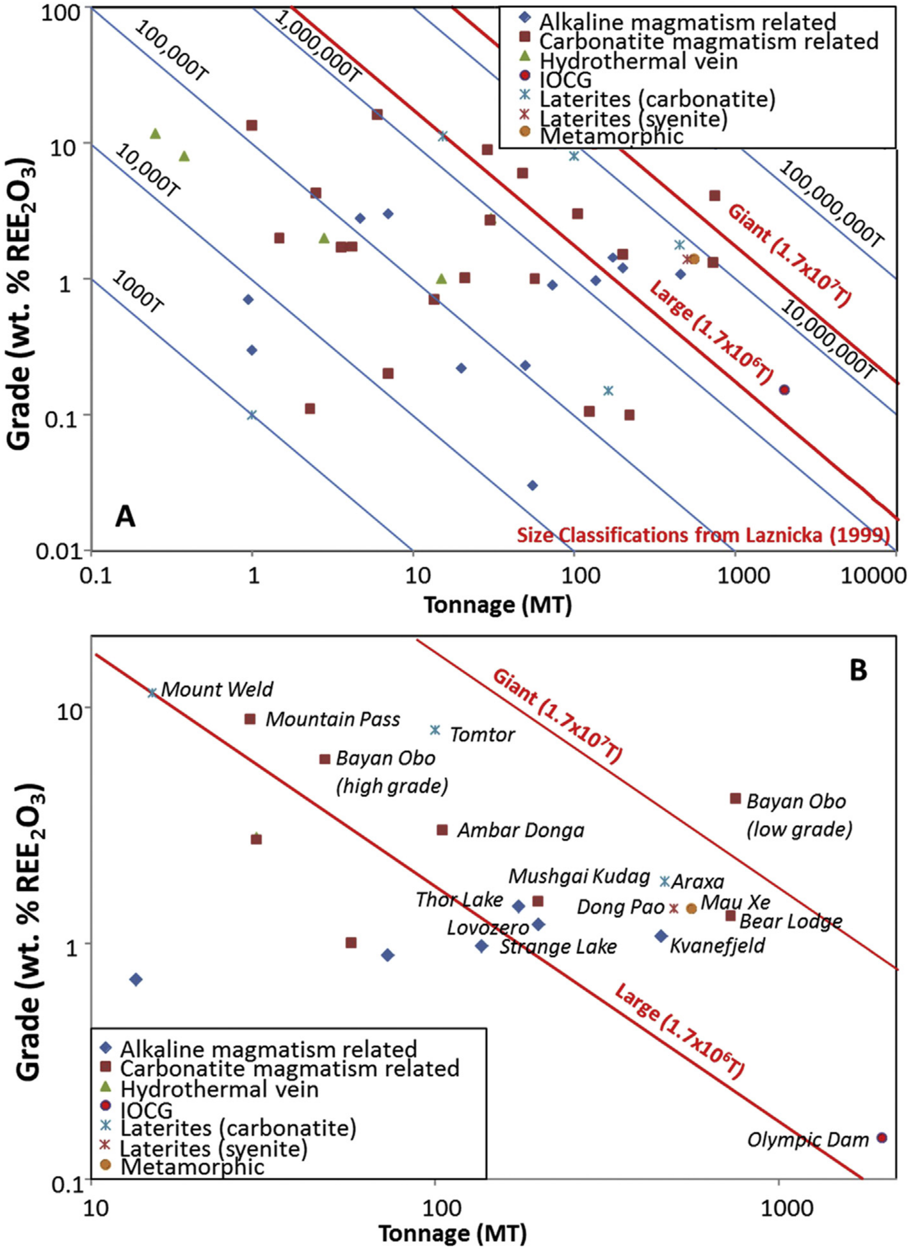

Figure 1. Grade-tonnage plot for resource estimates in REE deposits from Orris and Grauch (2002) and Long et al. (2010). Size classifications after Laznicka (1999) calculated as described in the text.