Rare-earth deposits in igneous rocks: A mineralogist's perspective

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Globally, some 70% of advanced rare-earth exploration projects have focused their efforts on mineral deposits associated with igneous rocks (or their weathering products). Three groups of igneous deposits have attracted the most attention: (1) carbonatites; (2) peralkaline silica-undersaturated rocks; and (3) peralkaline anorogenic granites. The first two groups accounted for ~50% of the global production of rare earth elements (REE) prior to 1995. Deposits associated with carbonatites show the lowest levels of Y and heavy REE in their budget (Y/Nd ≤ 0.3) among the three groups, but are least depleted in Eu (Eu/Eu* = 0.7-1.1); these characteristics are in marked contrast to those of rare-earth ores in anorogenic granites (Y/Nd ≥ 0.8; Eu/Eu* ≤ 0.3). Postorogenic carbonatites associated with saturated alkali syenites have shown the greatest promise as a primary REE source (fluorocarbonates, monazite). Extreme enrichment of carbonatitic magmas in light REE cannot be explained satisfactorily with simple melting models. The presence of REE phases in their mantle source, low degree of contamination by crustal material, and fortuitous interplay between aF^- and $a(PO_4)^{3-}$ appear to be prerequisite to the formation of a commercially viable deposit. In anorogenic carbonatites, appreciable REE mineralization commonly develops through breakdown of apatite, calcite and other primary low-grade REE hosts during their hydrothermal reworking (fluorocarbonates, ancylite, monazite) or lateritic weathering (monazite and other secondary phosphates). A variety of minerals forming large-tonnage deposits in peralkaline undersaturated rocks have been proposed as the ultimate solution to looming critical-metal shortages; however, only loparite has been extracted and processed industrially to date. It remains to be seen if any of the other REE-bearing minerals (e.g., eudialyte) are amenable to profitable metal recovery. These minerals crystallize from extremely evolved melts derived by protracted fractional crystallization of aegirine, feldspars and nepheline (± sodalite) from basanitic magma in anorogenic extensional settings.

Timescales of metamorphism: A Hierarchical distribution

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Several tools now provide us information on the timescales of metamorphism: geodynamic modelling, spatially resolved isotopic dating, and diffusion modelling of compositional zoning are some of these. Using the different tools on the same set of rocks reveals processes that occur on a hierarchy of timescales. Geodynamic modelling as well as isotopic dating indicate that orogenies can last over hundreds of millions of years, spatially resolved isotopic dating and direct geological evidence indicates that individual metamorphic rocks go through their pressure-temperature cycles on timescales of a few million years, and individual reactions (e.g. melting) occur within a few hundred thousand years. Combination of the various tools can provide more detailed insights into thermal histories; these can be verified using thermomechanical modeling with realistic boundary conditions. For example, isotopic dating using systems with different closure temperatures provides absolute points along the T-t path of a rock and diffusion modelling helps to determine how these "dots" are connected. Diffusion modelling is now able to resolve non-linear cooling histories and it is found that cooling rates can vary (i.e. increase as well as decrease) significantly during cooling from peak temperatures, and the use of a single, average cooling rate to characterize metamorphic rocks is misleading. Moreover, cooling at high temperatures is not always associated with exhumation and other processes that may act as a thermal sink need to be considered. Finally, we find that regional metamorphic P-T cycles can be very short (e.g. ~ 3 m.y.) or relatively long (~ 20 m.y.), depending on the tectonic setting. Examples from the Himalaya and a UHT metamorphic sequence in the Central Indian Tectonic Zone will be used to elucidate these situations.

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