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Direct and indirect evidence for the composition of REE-mineralising fluids

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Rare earth elements (REE) are among the most 'critical' of the metals required for green- and high-tech applications. Rare earth deposits can be considered to be generated through one or more of four processes: (1: mantle) enrichment and then low-degree partial melting of the mantle source; (2: magmatic) subsequent fractionation of REE-poor minerals; (3: hydrothermal) a degree of hydrothermal 'upgrading'; and (4: weathering) passive enrichment through dissolution and removal of REE-poor minerals. For example, the formation of REE deposits in alkaline rocks and carbonatites (which account for the majority of deposits under active exploration) requires low-degree partial melting from a fertile mantle, combined with subsequent mineral fractionation. This contribution, deals with stage 3: the hydrothermal 'upgrading' of REE deposits.

Hydrothermal fluids are important for the transport and concentration of the REE and can significantly 'upgrade' a deposit where elevated REE levels have been attained from mantle and magmatic processes. Furthermore, hydrothermal fluids can play a substantive role in the fractionation of the light (L)REE from the heavy (H)REE, the latter generally considered most critical. Evidence for the fractionation of the REE in hydrothermal fluids comes from both experimental work [1,2] and from natural examples [3].

Despite the importance of hydrothermal fluids in fractionating and concentrating the REE in carbonatites and alkaline rocks, little is known about the composition of these fluids. Our current understanding is derived from both direct and indirect sources:

- Direct evidence comes from the analysis of fluid inclusions related to REE deposits. Data are only available from two localities: Kalkfeld, Namibia (carbonatite, [4]) and the Capitan Pluton, New Mexico (granite, [5]). The composition of fluid from these deposits is somewhat contrasting: the carbonatitic fluid contains very high REE and CO_2 contents, while the granitic fluid has low REE and CO_2 but elevated Cl and SO_4 concentrations.
- Indirect evidence for hydrothermal transport and fractionation of the REE is more common. This is typically inferred from changing mineral assemblages and compositions in REE ore deposits, as well as from observations in fluid inclusions. Natural examples and laboratory experiments indicate that chloride is an important anion for the transport of the REE [1]. Additionally, there is growing evidence that sulphate is present in some deposits, and may be linked to HREE enrichment [6]. Carbonate complexes, too, may be of importance, especially for REE deposits linked to carbonatites. This is supported by the abundance of CO_2 in carbonatite-related fluid inclusions, carbonate daughter minerals in fluid inclusions [7] and the abundance of carbonate-bearing REE minerals in REE deposits. However, the predicted solubility of REE-carbonate minerals is low, potentially limiting the importance of carbonate as a transporting agent [2].

In this talk we present a summary of available data on REE deposit-forming fluids, as well as ongoing research, both directly and indirectly, into their composition. Our case studies include the Lofdal and

Eureka carbonatite complexes, Namibia; the Songwe Hill, Tundulu, and Kangankunde carbonatites, Malawi; and low temperature fluids at the Kovdor carbonatite, Russia.

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