Enrichments in the critical metals: interplay of magmatism, deformation and fluid flow

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The critical metals are those metals used in a range of new technologies, for which demand is increasing and there are potential threats to security of supply. At BGS, we are researching the processes by which these metals are concentrated in the crust, using examples in the UK and abroad. We have studied a number of different igneous suites to investigate the importance of magmatic and hydrothermal processes in critical metal mineralisation, specifically studying the REE, Nb and Ta.

A key area of study has been the syenite-dominated alkaline intrusions of the Northwest Highlands of Scotland, particularly the Loch Loyal Complex. These intrusions are enriched in the Light Rare Earth Elements (LREE) relative to other igneous intrusions elsewhere in the UK. Our work has shown that higher total REE contents are found in the more mafic rocks, due to early crystallisation of LREE-bearing minerals, chiefly allanite. At Loch Loyal, hydrothermal activity has caused variable alteration of these more mafic syenites, focused along narrow anastomosing veins. These veins of altered syenite are dominated by biotite, magnetite, allanite and apatite, with whole-rock TREO contents up to 2%, and contain evidence for more than one episode of hydrothermal activity.

Despite being emplaced in a collisional setting, the Northwest Highlands intrusions are chemically more similar to plutons found in extensional rift zones. We have studied rift-related intrusions in Botswana and Greenland, where parental magmas are relatively enriched in the REE. In the Semarule syenite of Botswana, the highest REE contents (approaching 1% TREO) are again found in mafic, allanite- and apatite-bearing syenitic varieties. In the Gardar Province of South-west Greenland, high REE contents occur in more evolved igneous rocks, and hydrothermal alteration has played an important role in increasing REE concentrations.

The Northwest Highlands alkaline intrusions are syn- to post-collisional to the Caledonian Orogeny, but are distinctly more alkaline than post-collisional intrusions in many other orogenic belts. We have studied post-collisional Pan-African granitoids in both Madagascar and Nigeria, and these have relatively low REE concentrations, although it is notable that the highest concentrations are found in more mafic rocks and close to major shear zones. However, pegmatites around these granitoid intrusions have been mined for Ta. In North-east Scotland, enrichment of critical metals such as Li and Ta is also found in post-collisional granitoid intrusions, associated with the Cairngorm granite suite. The highest contents of these critical metals are chiefly found in pegmatites, but also occur in the highly evolved and hydrothermally altered Gairnshiel granite. In this area, very evolved, volatile-rich magmas appear to be the main source of critical metal mineralisation.

In summary, our research shows that a range of geological processes contribute to the enrichment of the REE, Nb and Ta in crustal settings. Parental magmas that have some enrichment in these metals are an important starting point, and critical metal contents are enhanced by crystallisation processes and magma evolution. Although these metals are normally considered to be incompatible, the examples we have studied show that the REE are commonly concentrated in more mafic igneous compositions, whereas Li, Nb and Ta are found in the most evolved compositions. These contrasting behaviours have important implications for exploration. In our studies, post-magmatic hydrothermal processes appear to have played a dominant role in concentrating the critical metals. The presence of shear zones that provide pathways for movement of late fluids may be significant in determining the location of mineralisation.