

Alteration Dynamics as a Key to Ore Mineralogy—Insights from the Nechalacho REE-Nb-Ta-Zr Deposit (Canada)

Volker Möller^{1*} and Anthony E. Williams-Jones¹

¹McGill University, Montreal, Quebec H3A 0E8, Canada

*E-mail, volker.moeller@mail.mcgill.ca

The Nechalacho deposit at Thor Lake, northwest Canada, comprises one of the world's largest high-grade resources of heavy rare earth elements (HREE). The deposit formed by magmatic accumulation of eudialyte (a REE-Nb-zirconosilicate) in a 2176-m.y.-old layered nepheline syenite intrusion. Peripheral pegmatites (the T- and S-zones) are rich in Li, Be, and light REE. A strong hydrothermal alteration overprint of the Nechalacho deposit resulted in the replacement of eudialyte by zircon, fergusonite, bastnäsite-(Ce), columbite-(Fe), and -(Mn), allanite-(Ce), and other secondary REE and Nb minerals. Based on an integrated set of isotopic, petrographic, and geochemical data, we reconstruct the hydrothermal events that led to the modification of the ore and gangue mineralogy.

Petrography, geochemical systematics, and mass balance calculations indicate that C, F, Mg, and Ca were introduced hydrothermally. 3D-interpolations of magnetic susceptibility data show that the distribution of hydrothermal magnetite is strongly controlled by the igneous layering, but restricted to the SW part of the intrusion. Maxima for Mg concentration (monitoring hydrothermal chlorite and biotite) are independent of the primary layering and lie along a SSE-trending zone that crosscuts the NE sector of the intrusion. Calcium, which is largely hosted in hydrothermal ankerite, is enriched in magmatic layers and crosscutting domains. Ankerite is intimately associated with vein-style hydrothermal bastnäsite + allanite mineralization.

The carbon and oxygen isotope signatures of ankerite ($\delta^{13}\text{C}$ from -6.3 to -2.7‰, $\delta^{18}\text{O} = 11.3$ -15.0‰) lie along a trend that is consistent with ankerite precipitation at ~300°C from a CO₂-bearing magmatic-hydrothermal fluid degassed from the magma that formed the layered syenites ($\delta^{18}\text{O}_{\text{melt}} = 5.1$ -7.8‰, calculated from magmatic minerals) which contained mantle-derived carbon ($\delta^{13}\text{C}$ of ~ -6‰). The stable isotope trend also coincides with values previously reported for ankerite from the T-zone, demonstrating a genetic link to the peripheral pegmatites at the magmatic-hydrothermal interface. Oxygen isotope geothermometry involving secondary quartz, magnetite, zircon, and biotite indicate alteration temperatures between 295° and 313°C. Corresponding $\delta^{18}\text{O}_{\text{fluid}}$ of 3.1 to 9.3‰ and a $\delta\text{D}_{\text{fluid}}$ of -24‰, suggest that recycled meteoric water or seawater may have been a component of the alteration fluid.

Hydrothermal monazite was dated at 1871 ±14 Ma (LA-ICP-MS U-Pb concordia age) and 1835 ±57 to 1854 ±27 Ma (Th-Pb ages), indicating that it is ~300 m.y. younger than the Nechalacho Layered Suite and similar in age to the nearby McDonald fault zone. This suggests a late-stage introduction of crustal fluids that overprinted the layered suite. Our results demonstrate that the alteration was multiphase and had contributions from magmatic and externally derived fluids. The auto-metasomatic alteration by late magmatic, Ca-, fluorine, and carbon-bearing fluids caused remobilization of REE and their re-deposition as REE-fluorocarbonates. The late regional overprint by external fluids resulted in Mg-metasomatism, formation of secondary magnetite and monazite, and decomposition of eudialyte. The alteration overprint of the ore mineralogy had a profound impact on metallurgy. Whereas eudialyte is difficult to process hydro-metallurgically due to silica gel formation, its secondary products, simple oxides such as fergusonite and columbite and the REE-fluorocarbonates are readily amenable to hydro-metallurgical extraction.