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**Ample Rare Elements
A Geochemical Anomaly in the
Earth's Crust at Norra Kärr**

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Abstract

The Norra Kärr alkaline complex in southern Sweden (58°06'N, 14°34'E) is a classic occurrence of agpaitic rocks, which contains a large mineral deposit of rare-earth elements (REE), Zr, and Nb. The complex consists of different varieties of agpaitic peralkaline nepheline syenite that are defined by the occurrence of Na-rich Zr–Ti silicate minerals that contain volatiles F and Cl, including members of the rinkite, catapleiite, and eudialyte groups. The eudialyte-group minerals in Norra Kärr contain different ratios of light to heavy REE across the lithological domains.

The magmatic age of the alkaline complex, which is poor in common chronometric minerals, was determined at 1.49 ± 0.01 Ga (2σ) by U–Pb dating of zircon that formed during alkali metasomatism (fentisation) of the surrounding 1.8 Ga granite. The $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic ratio of this metasomatic zircon is different from Hf isotopes in the granite, but is identical with the Hf isotope composition of Lu-poor eudialyte from the alkaline complex. The relatively highly radiogenic composition of the Hf isotopes is consistent with a mantle source for the agpaitic magma.

New radiometric dating methods were developed. These allow precise *in situ* measurements of isotope ratios of the Rb–Sr and K–Ca as well as Sm–Nd systems in K-rich and Nd-rich minerals, respectively. Three varieties of alkaline rocks in Sweden were dated by the *in situ* Rb–Sr method. Biotite Rb–Sr cooling ages in the region east of Norra Kärr are approximately coeval with the emplacement of the alkaline rocks.

The complex has been affected by metamorphic overprinting. The foliated and folded fine-grained nepheline syenite is frequently cross-cut by coarse-grained eudialyte-rich pegmatoids. One eudialyte crystal with primary zoning from a pegmatoid was pre-characterised by SEM BSE imaging and *in situ* chemical analysis by LA-ICP-MS, including full REE composition and precise Sm/Nd ratios. Sampling at a resolution of <200 μm by micromill provided a sufficient Nd aliquot for routine high-precision ID-TIMS Sm–Nd isotope analysis. Eudialyte crystal growth was dated at 1144 ± 53 Ma (2σ) in the undeformed pegmatoid vein, about 350 million years after the magmatic event. The pegmatoid is suggested to have formed by low-temperature partial melting of the peralkaline nepheline syenite host at the margin of Sveconorwegian orogeny.

The agpaitic rocks were produced from a magma that formed by extensive fractional crystallisation of an alkali basaltic parental magma. The concentrations of highly enriched incompatible elements in the most differentiated nepheline syenite may indicate 98 % crystallisation of the parental magma.

Keywords: rare-earth elements; eudialyte; geochemistry; geochronology; ore geology