Carbonatite exsolution from Nepheline Syenite: The Lillebukt Nepheline Syenite-Carbonatite Complex, Northern Norway

Lead supervisor: Professor Adrian Finch, University of St Andrews

Co-supervisors: Dr Sami Mikhail, University of St Andrews; Dr Sam Broom-Fendley, Camborne School of Mines; William Hagell, Sibelco Nordic A/S; Dr Roar Sandøy, Sibelco Nordic A/S.

Project Highlights:

- Geochemical and petrographic analysis of a deeply dissected nepheline syenite – carbonatite complex
- Fieldwork in Northern Norway with the CASE partner Sibelco Nordic
- Addressing a fundamental question in critical metal petrogenesis as well as the origin of ceramic grade nepheline syenite.

Overview:

The origin of carbonatite, and its mineralisation, are key unknowns in understanding how critical metal deposits (e.g. rare earth and Nb) in carbonatite form. Three hypotheses are postulated: 1. Carbonatite is a mantle melt, ascending through the crust; 2. Carbonate in lamprophyre magma exsolves into two liquids on ascent, 3. Carbonate in nepheline syenite magma exsolves towards the end of fractionation. Unfortunately each mechanism provides mantle geochemical fingerprints, hence constraining the genesis of a mineralised carbonatite is difficult.

The Lillebukt Igneous Complex in Norway is an alkaline system containing carbonatite and nepheline syenite. Glaciation has dissected the complex, and fresh exposures from quarrying create an extraordinary natural laboratory to explore the field and geochemical relationships. Field data show lenses of nepheline syenite pegmatite within carbonatite and carbonatite cuts altered nepheline syenite. The location is exceptional to test the hypothesis that the carbonatite and nepheline syenite are related by liquid immiscibility. We will also explore whether exceptionally fresh nepheline syenite (suitable for ceramics) occurs because carbonate was lost to form the adjacent carbonatite.

Geochemistry is a critical component of the project because magmas that are related by immiscibility should initially be in chemical equilibrium, but after unmixing they will diverge chemically as each evolves. The project will explore this through the partitioning of trace elements into apatite in both carbonatite and nepheline syenite, using laser ablation ICP-MS. There will also be an opportunity to look for melt inclusions that can record liquid immiscibility in situ. After rehomogenisation in a high-temperature heating stage, these can be analysed to measure melt composition(s) directly.

The outputs of this work will be the first analysis of an intimately interleaved carbonatite-nepheline syenite complex. It will test the hypothesis that liquid immiscibility is the cause of the unusual field relationships, where unmixing may have been caught in action. The candidate will also explore the distribution of metals and volatiles between the two components, to constrain how one might identify carbonatite formed by the same mechanism. In doing so, the candidate will constrain a key unknown in the genesis of many of the world's most important and critical resources.

Figure 1: Field exposures of the Lillebukt Carbonatite, Stjernøya Norway. The deformed carbonatite (brown) flows around flattened enclaves of nepheline syenite (largest 50 cm wide). Stringers of nepheline syenite are drawn from the side of the inclusion. Are these the product of in situ liquid immiscibility?

Methodology:

The student will complete field studies with the CASE partner, Sibelco Nordic, at their Lillebukt mine. The project will involve fieldwork in Arctic Norway and hence will appeal to a candidate with an interest in fieldwork and the outdoors. They will map the field relationships of the two rock-types, the variability within the carbonatite, and relate the geochemistry to that of the nepheline syenite. They will also map the distribution of fresh nepheline syenite to determine whether the syenite is fresher or less fresh approaching the contact. The petrography of the two will be explored using whole-rock and mineral geochemistry. Cathodoluminescence is a key tool is determining the freshness of nepheline and feldspar (blue luminescent samples are fresher) and will be a key tool.

Timeline

Year 1: Basic petrography and literature in first quarter, whilst also analysing material from Lillebukt currently in St Andrews collections. Electron probe microanalysis of nepheline syenite and carbonatite, assessment for melt inclusions, and preliminary LA-ICP-MS analysis of apatite. Fieldwork in the summer of year 1 in Northern Norway with Sibelco Nordic to map out the field relationships of the two components on large (km) and small (m) scales where necessary.

Year 2: Whole-rock and in situ geochemical and isotopic analysis of the two components, beginning with whole rock geochemistry, LA-ICP-MS of apatite and C-O analysis of carbonate and silicate components. Sulfur isotopes of the two components will also be explored to determine the temperature of crystallisation (by looking at sulfur isotope partitioning between co-existing mineral pairs) at which each part crystallised. The field data and analysis will be written for publication.

Year 3: Writing up the preliminary isotope data, and the exploration of the relationship between hydrothermal alteration and the presence/absence/proximity of carbonatite. The textural, geochemical and isotopic consequences of hydrothermal alteration will be constrained and, where possible, quantified. This will be related to the "ore quality" of the nepheline syenite for ceramic purposes. Publication of results in the open literature.

Training and skills:

TARGET researchers will participate in a minimum of 40 days training over the 3.5 years of study composed of:

- an annual one-week workshop dedicated to their year group, and tailored to that cohort's needs in terms of skills development – *for the first three years of their study*;
- an annual all-TARGET workshop with cross-year interactions, advanced training and opportunities to specialise in particular areas – *all years of study*;
- a number of one-day workshops;
- additional online events and in-person workshops attached to relevant conferences.

The project will train: a) petrography, including cathodoluminescence, optical and electron microscopy; b) sample preparation of whole-rock and in situ geochemistry; c) isotope, particularly S isotopes; d) in situ LA-ICP-MS; e) interpreting geochemical data for igneous systems.

The project also targets impact: a) Lillebukt extracts nepheline syenite for ceramics: hydrothermal alteration deteriorates ore quality; b) the relationship between carbonatite formation and its critical metal cargo – as well as identifying how to identify the origin of carbonatite – is essential for prospectivity mapping in critical metal resources globally. This project will have major impact in the resources from alkaline igneous rocks.

Partners and collaboration (including CASE):

Sibelco Nordic will support the candidate for either one or two field seasons (depending on the progress of the project) over the summer in Year 1 and 2 at their Lillebukt Mine on the island of Stjernøya, Northern Norway. The candidate will also visit Camborne once per year to make use of Broom-Fendley's extensive expertise in carbonatite systems. A key impact of the project will be to feed into Sibelco's mapping and prediction of nepheline syenite ore quality within the mine. The project may also make use of an existing collaboration with Professor Madeleine Humphreys at Durham University.

Further reading:

Borst AM, Finch AA, Siegfried PR, Heredia BD, Thomasen TB, Vassilieva E, Bambi A (2025) Mixing, mingling and metasomatism: Magmatic and hydro-carbothermal processes in an Angolan subvolcanic alkaline silicate complex. *Lithos*, **516-517**, 108253.

Finch AA, McCreath JA, Reekie CDJ, Hutchison W, Ismaila A, Armour-Brown A, Andersen T, Simonsen SL (2019) From Mantle to Motzfeldt: A Genetic Model for Syenite-hosted Ta,Nb-mineralisation. *Ore Geology Reviews*, **107**, 402-416.

Finch AA & Klein J (1999) The causes and petrological significance of cathodoluminescence emissions from alkali feldspar. *Contributions to Mineralogy & Petrology*, **135**, 234-243.

Rooks CJW, Finch AA, Hutchison W, Herd DA & Frangeskides G (2026) Rare Earth and Niobium Mobility at the Magmatic-Hydrothermal Transition: Motzfeldt Sø Centre, Greenland. *Ore Geology Reviews*, **188**, 107009.

Further details:

Please visit https://target.le.ac.uk/ for additional details on how to apply. The research group of Professor Finch (aaf1@st-andrews.ac.uk) has a website at: www.adrianfinch.co.uk and the lead institution will be St Andrews (https://www.st-andrews.ac.uk/earth-sciences/). Informal enquiries are welcomed.