Constraints on the formation of the Archean Siilinjärvi carbonatite-glimmerite complex, Fennoscandian shield

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Abstract
The Siilinjärvi carbonatite-glimmerite complex is the oldest carbonatite deposit currently mined for phosphorous, and one of the oldest known on Earth at 2610 ± 4 Ma. The carbonatite-glimmerite is a 900 m wide and 14.5 km long tabular body of glimmerite with subordinate carbonatite, surrounded by fenites. The rocks range from nearly pure glimmerite (tetraferriphlogopite = tfp) to carbonatite (>50% modal carbonate), but the latter forms only 1.5% by volume of the complex. Carbonatite occurs as as thin (few cm) roughly vertical anastamosing lamella in glimmerite which grade into slightly later and thicker (10 cms) vertical veins that are concentrated in the center of the complex. The laminated structures may represent late consolidation of cumulates. Despite the large carbonate-phlogopite modal variablity, the compositions of primary phases calcite, dolomite, tfp, apatite and richterite do not vary significantly across the complex. Moroever, the distribution of apatite is rather uniform, with average glimmerite and carbonatite containing 10.4 and 9.9 modal % apatite, respectively.
Compositionally the carbonatite veins are calsio-carbonatites, whereas the glimmerites are potassic ultramafic rocks with Mg# over 0.8. All are cumulates, but are geochemically linked, showing similar trace element trends, such as evident mantle normalized negative Ti- and Nb-anomalies, possibly related to early fractionation of Ti-magnetite or titanite. Average C-O isotopic compositions $\delta^{13}C$=3.7‰ and $\delta^{13}O$=7.4‰ indicate a mantle derivation. Characterisitics described above suggest that the Siilinjärvi complex formed via crystal accumulation from mantle-derived magmas passing through a large, well mixed magma chamber. Recently described mica-richterite-carbonate dykes in the vicinity are prospective as potential parental magmas, but further work is needed to understand the full range of dykes in the area.

Introduction
The Siilinjärvi carbonatite complex is located in eastern Finland close. It consists of a steeply dipping lenticular body roughly 16 km long with a maximum width of 1.5 km and a surface area of 14.7 km² intruded into granite gneiss (Puustinen, 1971; O'Brien et al., 2015; Figs. 1 and 2).

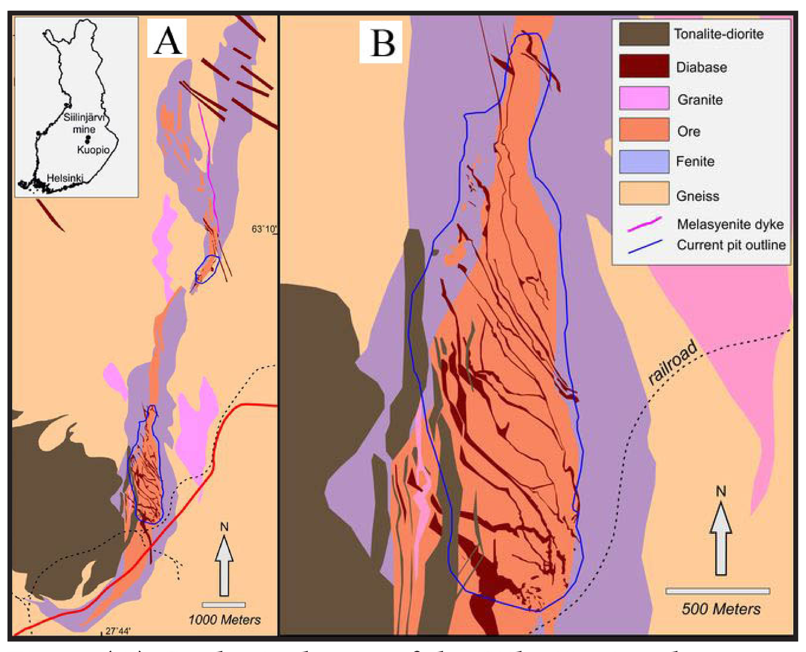

Fig. 1. (A) Geological map of the Siilinjärvi carbonatite complex and (B) the area of the main pit at larger scale.


Fig. 2. Aerial photograph of Siilinjärvi mine, southern Särkijärvi pit. Source: Yara Suomi Oy.


Fig 3. Eastern wall of main mine pit, showing megablocks of fenitic syenite supported in a black biotite glimmerite matrix. Biotite has formed after primary tetraferriphlogopite in areas that have undergone significant shearing.

The main glimmerite-carbonatite intrusion within the Siilinjärvi complex occurs as a central tabular, up to 900 m wide, body of glimmerite and carbonatite running the length of the complex, surrounded by a fenite margin. Unlike many other carbonatite-bearing complexes that contain a sequence of phlogopite-rich rocks intruded by a core of carbonatite (c.f., Kovdor, Phalaborwa), at Siilinjärvi, the carbonatites andglimmerites are intimately mixed, varying from nearly pure glimmerites (tetraferriphlogopitites) to nearly pure carbonatites, with a well-developed subvertical to vertical lamination. Although not strictly zoned, generally the volume of carbonatite is greatest near the center of the intrusion, which is cut by numerous subvertical carbonatite veins (Fig. 3). Glimmerites near the outer edges of the body can be nearly carbonate-free, yet still contain ore-grade amounts of apatite. Crosscutting relationships and xenoliths suggest that, at least at the present level of exposure, some of the fenites formed early because they occur as megaxenoliths within the magmatic glimmerite.

Age
There have been quite a number of studies concerning the age of the Siilinjärvi carbonatite complex (Puustinen, 1971; Basu and Puustinen, 1982; Karhu et al., 2001; Bayanova, 2006; Tichomirowa et al., 2006; Zozulya et al., 2007; Rukhlov and Bell, 2010; Tichomirowa et al., 2013). Most precise data appear to be from U-Pb analyses of zircon, particularly a concordant zircon U-Pb of age 2610 ± 3 Ma (2σ; Fig. 4) measured by Olavi Köuvo (GTK unpublished report, 1984) on a large zircon megacryst. These U-Pb data indicate that Siilinjärvi is one of the oldest carbonatites in the world. However, K-Ar data (Puustinen, 1971) and Rb-Sr isochron data (Tichomirowa et al., 2006) for carbonatite and glimmerite samples with results of 1785–2030 Ma and 1754–2031 Ma, respectively, show a Svecofennian orogenic overprint that is well documented throughout much of the Archean terranes of eastern Finland (Kontinen et l., 1992).

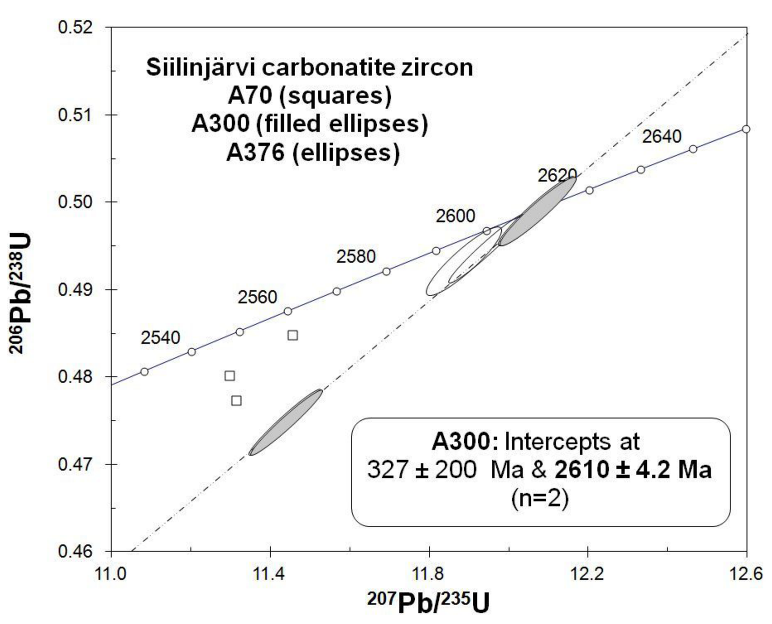

Fig. 4.U-Pb concordia diagram for zircons from Siilinjärvi. Source: From original GTK report by O. Kouvo to H. Lukkarinen (1984).

Geochemistry and isotopes
The extreme mineralogic variability within a small volume of glimmerite-carbonatite of the main ore body translates into a large variability in the chemical composition of analyzed samples (Fig. 5).

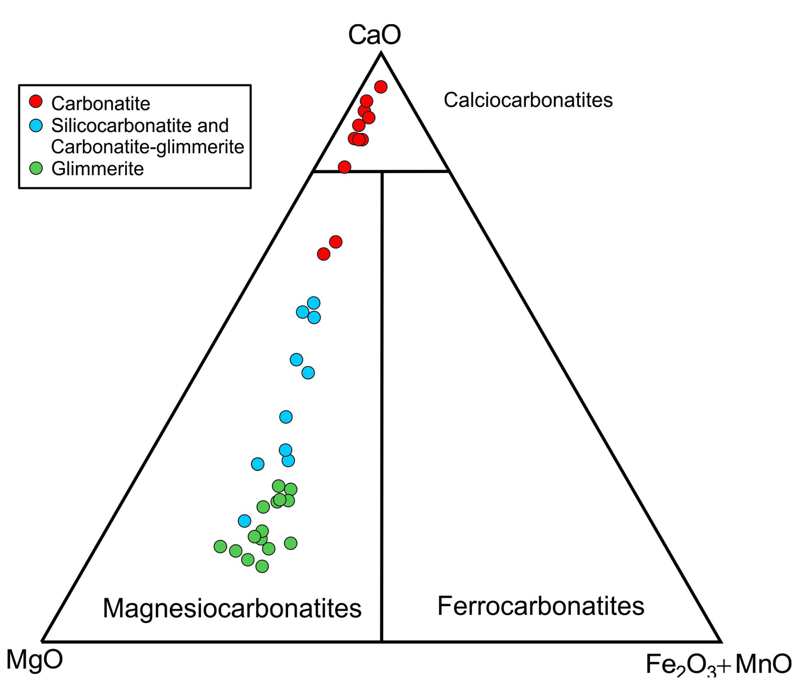

Fig. 5. MgO-CaO-(FeO + MnO) diagram for 37 whole-rock analyses of the ore rocks and the average ore composition for comparison. The two carbonatites with higher MgO contain 10–20 modal% dolomite.

All ore samples essentially plotted on a binary join between glimmerite and carbonatite. However, given the much greater volumes of glimmerite relative to carbonatites, the bulk composition of theSiilinjärvi main ore body differs only slightly from average glimmerite (see Table 1 and Fig. 6).

Table 1 Siilinjärvi ore zone rocks, modal mineralogy, and calculated major element chemistry.

	Ore1	Glimmerite	Carbonatite apatite containing	Carbonatite apatite poor	Lamprophyre dike3
Micas2	65	81.5		1.2	
Amphibole	5	4.5	0.6	0.2	
Calcite	15	1.6	61.2	86.8	
Dolomite	4	0.9	13.4	10.6	
Apatite	10	10.4	9.9	0.8	
Accessorices	1	0.7	0.1	0.4	
wt%					
SiO2	30.2	37.5	7.8	1.3	43.3
TiO2	0.3	0.5	0.1	<0.1	2.9
Al2O3	7	8.8	1.8	0.2	6.1
Fe2O3	7.1	8.3	3	1.6	18.1
MnO	0.1	0	0.1	0.2	0.2
MgO	18.3	20.8	8.1	4.6	15.3
CaO	13.9	6.8	38.6	47	6.8
Na2O	0.2	0.2	0.1	0.1	0.6
K2O	6.2	7.6	1.6	0.2	4.5
P2O5	4.2	4.1	4.5	0.5	0.3

1 Average ore composition; there is significant variation from block to block.
2 Mainly tetraferriphlogopite.
3 Dike 14-PTP-05, Siilinjärvi potassic magma

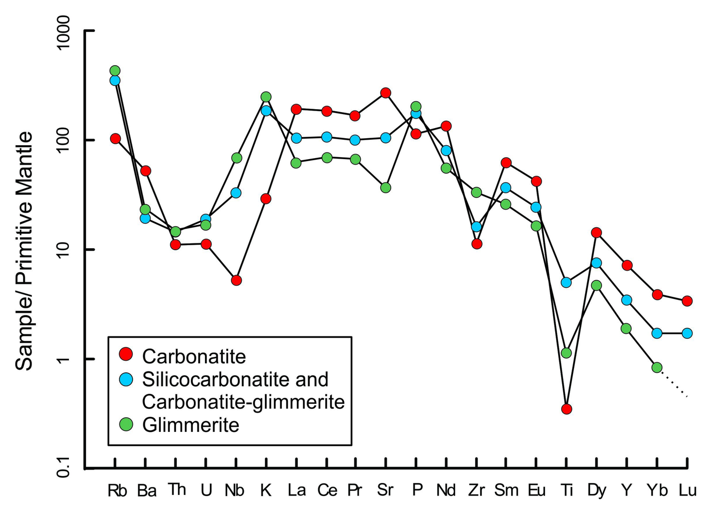

Fig. 6. Primitive mantle-normalized diagram showing average compositions of the different ore type rocks. Source: Normalizing values from Sun and McDonough (1989).

Thus, even though the carbonatites are the most striking feature at Siilinjärvi, the average ore could be considered as a cumulate rock derived from a potassic melt that contained some carbonate.
One way to test the cumulate hypothesis is to compare the bulk ore composition to dike rocks identified by their mineralogy as potential parental magmas, such as potassic ultramafic dike rock 14-PTP-05 described in the Table 1. In this case, it appears that there is too little P_2O_5 to have produced sufficient apatite and too much FeO, mostly as magnetite, for which there are no known cumulate counterparts in the ore body. Nevertheless, the dike rock is a fine-grained, approximate mineralogic analog to the main intrusion and, thus, theoretically contains all the necessary components to form the main glimmerite-carbonatite cumulate body. These preliminary results warrant further studies including additional sampling of dikes and information such as mineral chemistry and whole-rock chemistry (including isotopic data) to identify any parental magmas in the area.

The mantle-normalized incompatible trace element patterns for the average carbonatite, glimmerite, and intermediate rock are shown in Figure 6. Several features can be highlighted:

- A negative Zr anomaly in the carbonatite is not seen in the glimmerite, although this may be a nugget effect as zircon is generally rare.
- The large negative anomaly in Ti can have a number of origins, but likely candidates include Ti-magnetite or titanite fractionation. This may also explain the negative Nb anomaly in the carbonatite.
- The overall REE content of these rocks is not high considering the apatite and calcite content in the complex. Clearly the primary magma was not very REE-enriched.

The isotopic composition of Siilinjärvi has been determined by a number of researchers. Tichomirowa et al. (2006) measured the isotopic composition of amphibole, mica, carbonate, and apatite from a representative suite of Siilinjärvi rock types and reported a primary carbon and oxygen composition of $\delta^{13}C$ = –3.7 ‰, $\delta^{18}O$ = 7.4 ‰. This composition is very uniform throughout the complex, and it plots within the field of mantle-derived primary igneous carbonatites determined by Taylor et al. (1967) andεSr = 0), εNd of –2 to +5, and εHf of –1.4 to +0.4 at 2.61 Ga were measured on Siilinjärvi drill core and hand samples by Tichomirowa et al. (2006, 2013).
Corroboration of the Sm-Nd data comes from a richterite-apatite-phlogopite-whole rock isochron of Zozulya et al. (2007) with an inferred age of T = 2615 ± 57 Ma, providing a well-constrained initial εNd of +0.4 ± 0.2. The isotopic composition of the Siilinjärvi rocks are rather homogenous, and very much in line with the bulk of carbonatites globally.

Genesis
The Siilinjärvi glimmerite-carbonatite complex probably represents a plutonic complex formed as the result of passage of highly potassic magmas into and through a magma chamber, and the consequent accumulation of crystallizing minerals, a process that was active over the lifetime of the magma chamber. The observation of rather uniform apatite and tetraferriphlogopite compositions, which appears to be independent of ore rock type, suggest that the minerals crystallized in a large, well-stirred magma chamber. However, the ore rocks are clearly not uniformly distributed, and the process by which the diffusely laminated glimmerite-carbonatite texture of the central portion of the main cumulate body formed is still an open question. The similarity of orientation of the laminations and the late carbonatite veins along the same vertical to subvertical north–south trends strongly suggests their formation is linked.

Summary
1. Siilinjärvi represents the second largest carbonatite complex in Finland, and one of the oldest carbonatites on Earth at 2.609 Ga.
2. Mineral compositions, particularly apatite and phlogopite, do not show any systematic compo-sitional variability based on rock type. This is consistent with the glimmerite-carbonatite rocks representing an equilibrium assemblage of cumulate minerals
3. Comparing the tetraferriphlogopite at Siilinjärvi and Sokli suggests that the parental magma for the Siilinjärvi glimmerite-carbonatite complex was moderately evolved, and this fact can help identify potential parental magmas.
4. Further work will likely provide a larger variety of ultramafic dikes that may lead to a better understanding of the primary magma(s) of this system.
5. Fenite formed around the subvolcanic magma system as K and Na-rich fluids, produced through crystallization in the magma chamber, were forced into the surrounding bedrock. Acting over a significant period of time, the process converted country rock gneisses into a variety of fenites dependent on the fluid flux, composition, and distance from the fluid source.

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