CHAPTER

THE ARCHEAN SIILINJÄRVI CARBONATITE COMPLEX

4.3

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ABSTRACT

The Siilinjärvi carbonatite complex is named after the nearby village of Siilinjärvi, located some 5 km west of the southern extension of the complex. It is one of the oldest carbonatites on Earth, and the oldest presently being mined. Due to its age, it has been metamorphosed, particularly during the 1.8 Ga Svecofennian event, and intruded by several generations of younger, mafic to intermediate dikes, and a tonalite-diorite intrusion. Despite this overprint, the bulk of the rocks of the complex show well-preserved igneous textures, primary magmatic compositions of constituent minerals, and retain most of their primary isotopic compositions, which point to a mantle derivation. As such, the carbonatite and associated rocks provide a rare opportunity to constrain the mineralogy and geochemistry of the Archean mantle. Dominant rock types in the complex include carbonatite, silicocarbonatite, carbonatite-glimmerite, and glimmerite (mainly tetraferriphlogopite) within the main intrusion, all of which are surrounded by a halo of metasomatically produced fenites. Primary magmatic saline aqueous fluids rich in alkali elements have been identified in fluid inclusions in zircon and apatite from the carbonatite, explaining the formation of the well-developed metasomatic fenite syenite halo. Mining for apatite as a source for phosphorus began in 1979 by Kemira Oy, but since 2007 the deposit has been under the ownership of Yara International ASA, presently producing about 11 Mt of ore per year combined from the main Särkijärvi pit in the south, and the satellite Saarinen pit in the north.

Keywords: carbonatite; glimmerite; tetraferriphlogopite; apatite; phosphorus ore; mine.

INTRODUCTION

The Siilinjärvi carbonatite complex is located in eastern Finland close to the city of Kuopio. 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 km^2 intruded into basement gneiss (Fig. 4.3.1). It was discovered in 1950 after local mineral collectors sent samples of carbonatite to the Geological Survey of Finland (GTK). Exploration drilling began in 1958 by Lohjan Kalkkitehdas Oy and continued between 1964 and 1967 by Typpi Oy, and from 1967–1968 by Apatiitti Oy. After 1968, Kemira and its subsidiaries moved forward with laboratory and pilot plant work. An open pit mine for phosphorus ore was commissioned in 1979. The mine was sold to Yara Suomi Oy in 2007.

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 and

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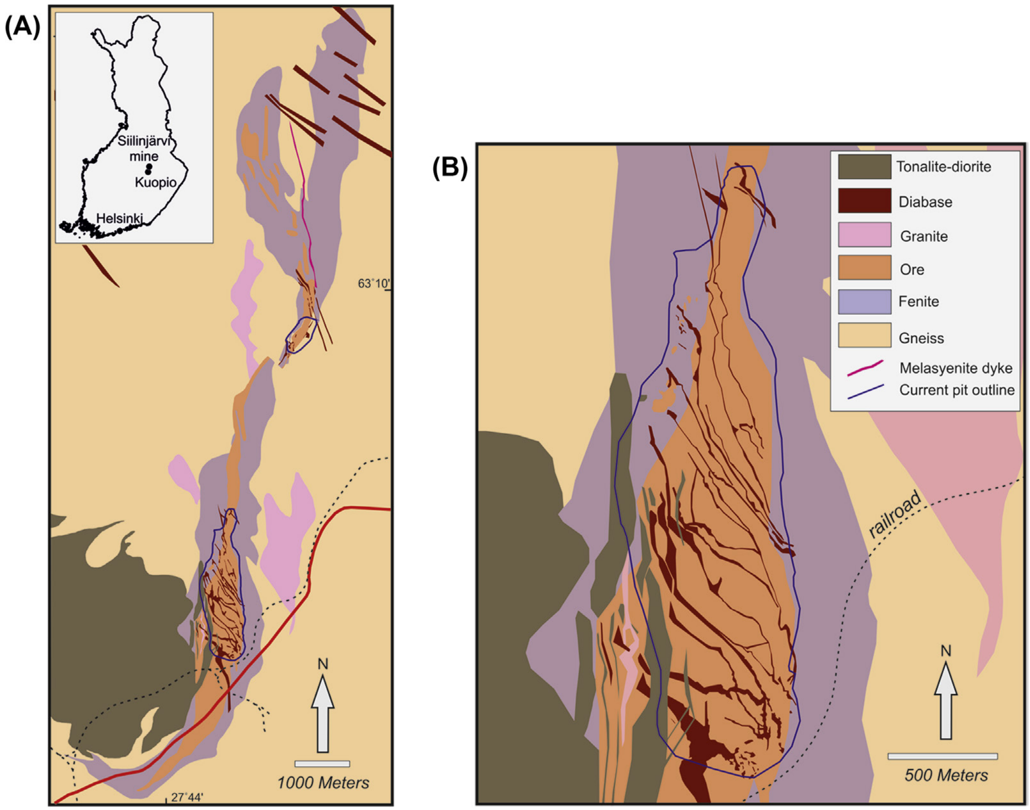

FIGURE 4.3.1 (A) Geological map of the Siilinjärvi carbonatite complex and (B) the area of the main pit at larger scale.

glimmerites 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. 4.3.2). 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 (Fig. 4.3.3).

ROCK TYPES

FENITES

Fenites surrounding the carbonatite-glimmerite central core developed as a result of sodium and potassic metasomatism of the surrounding granite gneiss country rocks. The main minerals in the fenites are microcline, amphibole, and pyroxene, but there exists a wide variety of fenite types

FIGURE 4.3.2 Photograph from the south wall of the main pit showing alternating glimmerite-rich and carbonatite-rich bands of the central portion of the main ore zone.

Source: *Photo by Esko Koistinen, GTK.*

FIGURE 4.3.3 Eastern wall of main mine pit, showing megablocks of fenitic syenite supported in a black biotite glimmerite matrix.

Biotite and chlorite have formed after primary tetraferriphlogopite in areas that have undergone significant shearing. Photograph shows about 90 m vertically of the 250 m high main pit wall.

including: pyroxene, amphibole, carbonate, quartz, aplitic, and quartz-aegirine varieties. Compositions of the fluids that produced these fenites have been determined from fluid inclusions within magmatic zircon and apatite (Poutiainen, 1995). Zircon crystals, which are thought to be more common in the amphibole-rich parts of the intrusion, contain two types of fluid inclusions trapped prior to emplacement of the carbonatites.

Type 1 fluid is an H_2O-CO_2 mixture with low salinity (1–4 wt% NaCl equivalent) whereas type 2 is of moderate salinity (7–18 wt% NaCl equivalent), alkali- and H_2O-rich. Thus, the development of H_2O- and alkali-rich late-stage fluids that formed the fenite halo was a direct consequence of the early crystallization of predominantly carbonate and apatite (Poutiainen, 1995). Ascent and hydrofracturing by the evolving H_2O-rich fluid may have facilitated the ascent of the parental magmas along deep crustal shears, with attendant fenitization along the path.

GLIMMERITE-CARBONATITE ROCK SERIES

The vast majority of the central ore body is made up of phlogopite-rich rocks ranging from almost pure glimmerite (dominantly tetraferriphlogopite, 0–10 modal% carbonates) to carbonate glimmerite (10–25 modal% carbonates) to silicocarbonatites (25–50 modal% carbonates). White to pinkish, medium-grained carbonatite (>50 modal% carbonates), typically with a greenish tinge reflecting the apatite grains it contains, represents roughly 1.5 vol% of the main intrusion (1.4 and 2.3 vol% at the Särkijärvi and Saarinen pits, respectively). Carbonatite occurs mostly as thin subvertical veins in glimmerite, with the veins being concentrated toward the center of the intrusion. In addition to carbonate and phlogopite, blue-green rocks with up to 50 modal% richterite can also be abundant in places (Puustinen, 1972).

Figure 4.3.4(A–D) shows textural examples of rock types from the glimmerite-carbonate series, including magmatic laminar texture, foliated texture due to shearing, less common pegmatoidal texture of mica, and an example of a zircon-rich sample. Even though all varieties of this magmatic pulse contain apatite, apatite is nonetheless only slightly more abundant in the glimmerite based on a new geochemical database (summarized in Table 4.3.1). The overall mode of the carbonatite-glimmerite portion of the complex, as indicated by the average composition of the Siilinjärvi ore, is 65% phlogopite (including tetraferriphlogopite), 19% carbonates (with a 4:1 calcite:dolomite ratio), 5% richterite, 10% apatite (equivalent to 4% P_2O_5 in the whole rock), and 1% accessory minerals comprising mainly magnetite and zircon.

MICA-BEARING DIKES

Crosscutting the surrounding bedrock, the fenite halo, and the central intrusive body is a 4-km-long, 20–30 m wide, north-trending mafic dike within the northern part of the complex (see Fig. 4.3.1) that was termed melasyenite by Puustinen (1971) and thought to be related to the same intrusive event as the carbonatite. The melasyenite is composed of alkali feldspar, biotite, alkaline amphibole, apatite, and magnetite. Suspected to be one of a series of dikes (H. Lukkarinen, personal communication, 2003), another dike discovered in 2005 (sample 14-PTP-05), taken from the same area, proved to be ultramafic in character. It is composed of minerals similar to those found in the Siilinjärvi carbonatite: phlogopite, alkali-amphibole, primary carbonate, apatite, magnetite, and titanite (Fig. 4.3.5(A)).

In a hand sample, a foliation is apparent, which in thin sections can be seen to have caused recrystallization of much of the mica. Nevertheless, remnant large phlogopite crystals with epitaxial alkali-amphibole overgrowths, along with primary carbonate segregations, can be observed in thin section

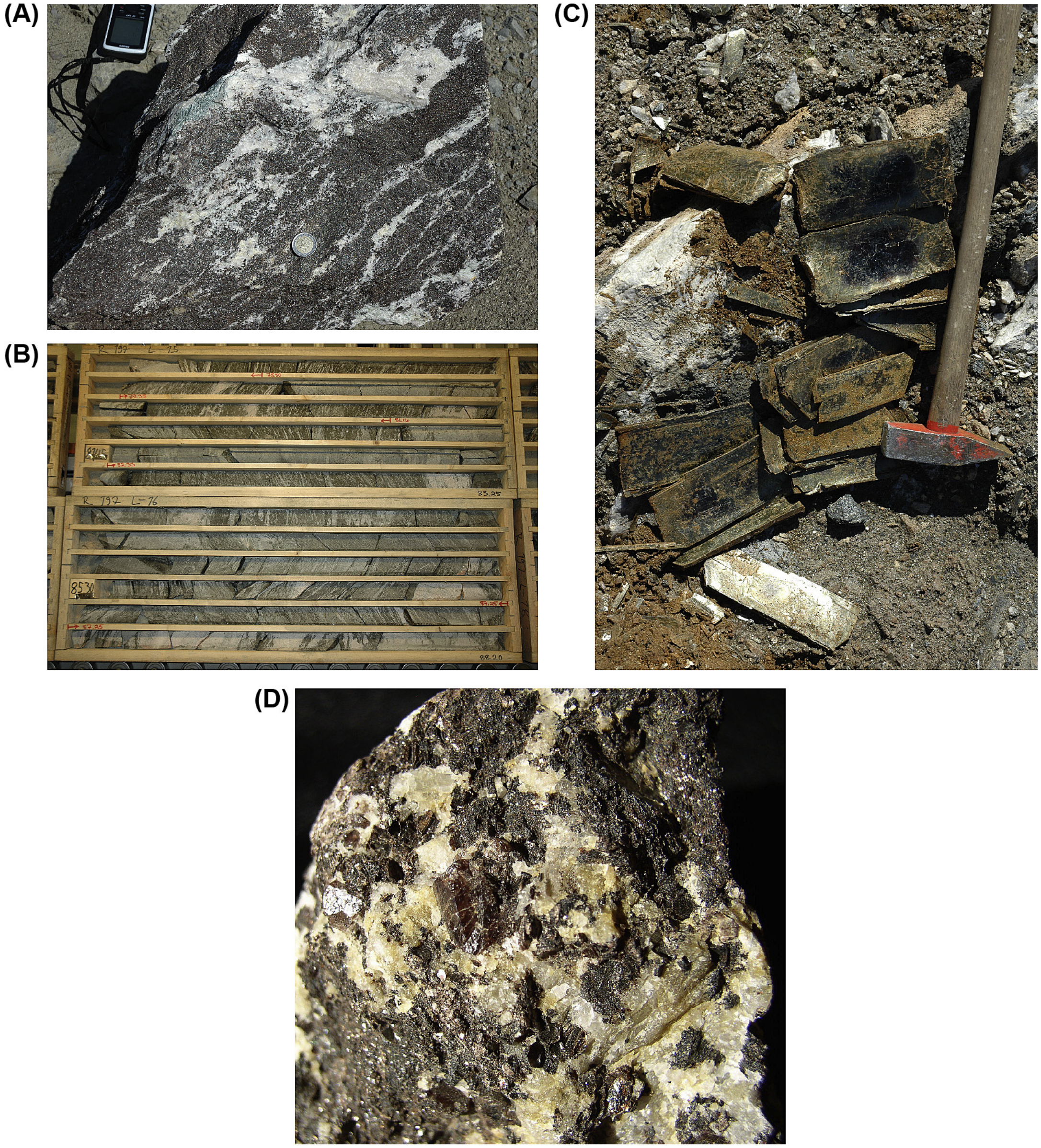

FIGURE 4.3.4 Examples of the Siilinjärvi glimmerite-carbonatite rock series.

(A) Laminated glimmerite-carbonatite typical of the main intrusion, primary magmatic texture. (B) Highly foliated carbonatite. This type of metamorphic foliation is not typical of most of the glimmerite-carbonatite rocks series, but can be found in the southern extension of the ore body. (C) Pegmatitic phlogopite book in carbonate matrix. (D) Zircon-rich sample of silicocarbonatite with no visible richterite, showing that zircon occurs also in relatively SiO_2-poor rock types.

Table 4.3.1 Siilinjärvi ore zone rocks, modal mineralogy, and calculated major element chemistry

	Ore[1]	Glimmerite	Carbonatite apatite containing	Carbonatite apatite poor	Lamprophyre dike[3]
Micas[2]	65.0	81.5	14.7	1.2	
Amphibole	5.0	4.5	0.6	0.2	
Calcite	15.0	1.6	61.2	86.8	
Dolomite	4.0	0.9	13.4	10.6	
Apatite	10.0	10.4	9.9	0.8	
Others	1.0	0.7	0.1	0.4	
wt%					
Na_2O	0.2	0.2	0.1	0.1	0.6
MgO	18.3	20.8	8.1	4.6	15.3
Al_2O_3	7.0	8.8	1.8	0.2	6.1
SiO_2	30.2	37.5	7.8	1.3	43.3
P_2O_5	4.2	4.1	4.5	0.5	0.3
K_2O	6.2	7.6	1.6	0.2	4.5
CaO	13.9	6.8	38.6	47.0	6.8
TiO_2	0.3	0.5	0.1	<0.1	2.9
MnO	0.1	0.0	0.1	0.2	0.2
Fe_2O_3	7.1	8.3	3.0	1.6	18.1

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

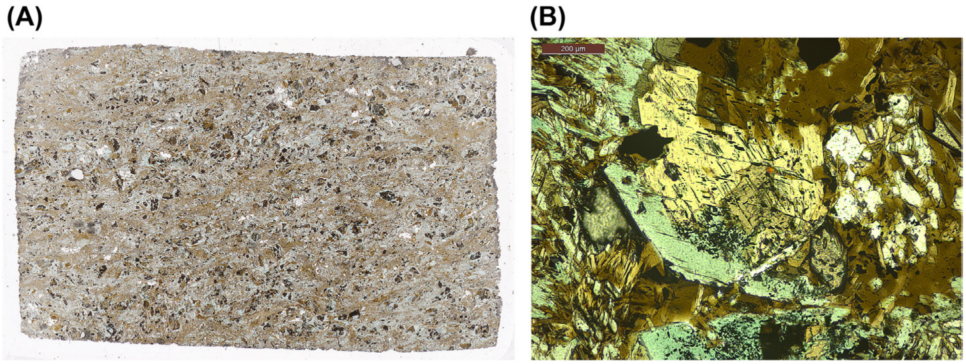

FIGURE 4.3.5 Thin section of ultramafic lamprophyre dike 14-PTP-05 from the northern part of the intrusion.

(A) Scan of thin section showing amphibole (blue) and mica (brown) with small euhedral clusters of calcite grains and opaque magnetite. Rock piece is 3 cm × 2 cm. (B) Photomicrograph of same, displaying epitaxial overgrowth of amphibole on mica. Plane polarized light.

(Fig. 4.3.5(B)). Further study is required to determine whether this is an amphibole-bearing aillikite (ultramafic lamprophyre) or some other type of lamprophyre. The magma from which this dike crystallized could be a potential candidate as a parental magma of the Siilinjärvi complex.

Even closer in appearance and mineralogy to the main carbonatite-glimmerite ore body are a number of 0.5-m to several-meters-thick potassic dikes that transect the fenites and in places form the matrix to fenite megablocks, which can be studied in exposures along the railroad track southeast of the main pit, in drill cores of the western margin of the main pit, and in the walls of the northern satellite pit.

These dikes are mineralogically similar to the main ore body, but importantly, they lack the laminar texture of the former, and instead show a much more chaotic distribution of carbonate-rich, amphibole rich, and phlogopite-rich patches. They lack foliation and in some cases are pegmatoidal (Fig. 4.3.6). These textures exclude their formation as fault breccias. Further study is required to determine whether

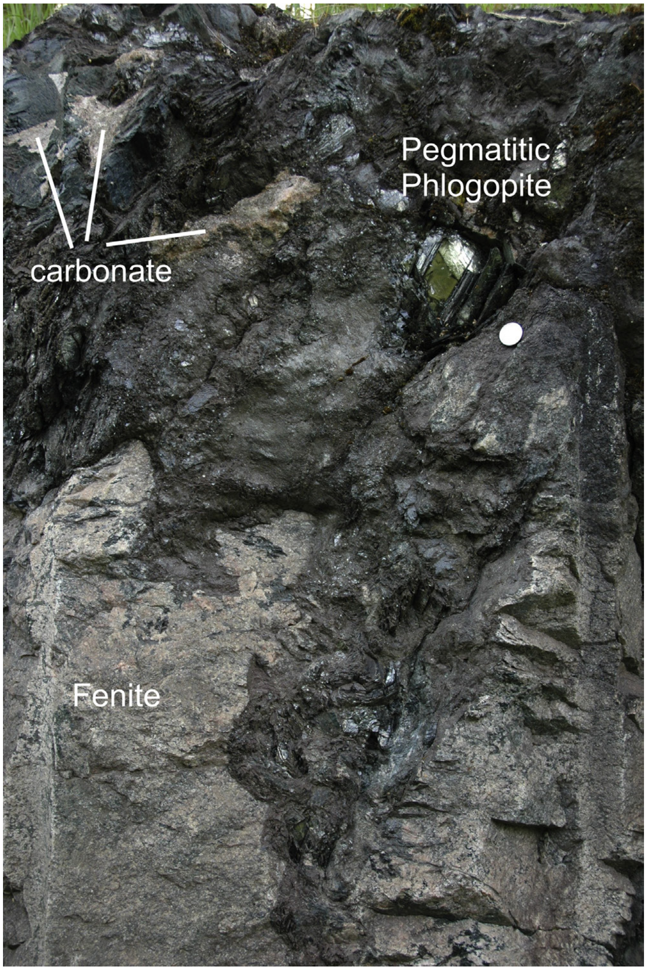

FIGURE 4.3.6 Glimmerite-carbonatite dike exposed in the railroad cut southeast of the main pit (see Fig. 4.3.1).

these dikes represent feeders to the main intrusion or apophyses derived from the main intrusion, but their importance lies in the clearly displayed relationship that at least some of the carbonatite component was unequivocally part of the same magmatic system as the glimmerite.

DIABASE DIKES

Crosscutting the entire Siilinjärvi complex are diabase dikes of basaltic composition with widths that range from centimeters to several meters (rarely up to 60 m), (refer to Fig. 4.3.1). The dikes show a strong northwest–southeast or north-northwest–south-southeast orientation. Where they are sufficiently wide they form non-ore rock that is stockpiled separately. To our knowledge, these dikes have not been studied in detail, but preliminary studies show that there are at least three varieties, including calcite-bearing diabase (with calcite probably derived from the carbonatite), sulfide-bearing diabase, and barren diabase (without calcite or sulfides). Sulfides in the diabases tend to be enriched in more highly sheared zones, especially in the northern Saarinen pit area.

STRUCTURES

Contacts between the country rocks and the main Siilinjärvi ore body are either primary magmatic or sheared. For example, contact between the ore and the surrounding fenite in the eastern part of the Särkijärvi pit is sharp and well preserved, whereas the southwest corner of the pit shows a mosaic of sheared blocks containing mingled tonalite-diorite, diabase, and fenite, as well as the carbonatite-glimmerite ore (see Fig. 4.3.1). In this chaotic zone, Paleoproterozoic diabase dikes, as well as apophyses of a younger tonalite-diorite intrusion, are intermingled and together transect the ore.

Overall, a roughly north–south striking, steep shearing is a common feature near the contacts of the deposit as well as within the carbonatite-glimmerite ore. The vertically laminar structure of carbonatite-glimmerite is “folded” at least twice. An older “folding” stage has produced open to tight fold structures with an almost horizontal north- and south-trending fold axis. Whether this represents a process during late consolidation of the cumulates or later deformation is not well understood, but flow folding is a common primary feature of carbonatite intrusions (R.E. Harmer, personal communication, 2015).

The second deformation stage comprises an induced, intense vertical north–south striking shearing that is also observed at the ore contacts. The shearing has produced small-scale left- and right-sided folds in the incompetent glimmerite ore. This younger folding event can be observed in both the ore and the Paleoproterozoic diabase dikes that crosscut the complex. These structural observations provide evidence of several deformation events that have affected the Siilinjärvi complex, perhaps earlier than, but certainly also during, the Svecofennian orogeny.

MINERALOGY

MICA

The dominant mica at Siilinjärvi is reddish-brown tetraferriphlogopite, much the same as at Sokli, described in Subchapter 4.2. This variety of mica crystallizes in magnesian alkaline magmas that have low Al, forcing ferric Fe into the tetrahedral site to fill the structure. A direct comparison of the micas from

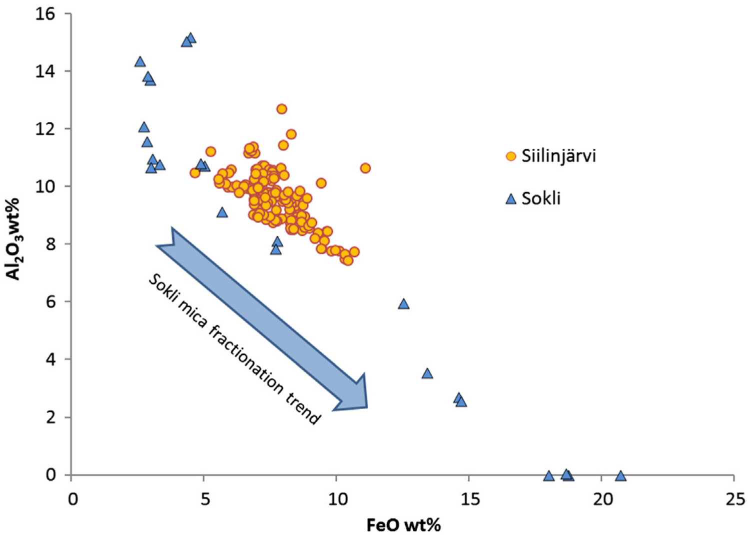

FIGURE 4.3.7 Mica compositions from Siilinjärvi compared to those from Sokli.

Siilinjärvi tetraferriphlogopites are restricted in composition and similar to those in the Sokli second series phoscorite-carbonatite conjugate pair (see Subchapter 4.2).

these two carbonatites (Fig. 4.3.7) shows that the Siilinjärvi tetraferriphlogopite is similar in composition to the Sokli cycle's two phoscorite-carbonatite tetraferriphlogopite compositions (see Section 4.2), but does not show the large compositional range to highly evolved varieties. The restricted Siilinjärvi mica compositional field implies a moderate level of fractionation of the source magma, and a large magmatic system that could produce enormous quantities of phlogopite of relatively constant composition.

In shear zones and contact zones where younger diabases have transected the carbonatite, tetraferriphlogopite has been converted to brown biotite-phlogopite and, in the most intensely affected zones, to black biotite and even chlorite. This is particularly true at the margins of the main intrusion, which appear to have absorbed considerable strain during regional metamorphism and acted as "great greasy shear plane(s)" (Puustinen, 1971).

CARBONATES

White to pink to gray calcite is the dominant carbonate mineral. Dolomite is nevertheless nearly ubiquitous, and commonly occurs as fine exsolution lamellae in calcite (refer to Fig. 9 in Puustinen, 1971; Puustinen, 1974). Microprobe analyses of 170 grains of calcite from a representative suite of main ore samples show that calcite contains a relatively uniform content of minor elements: 1.1 wt% SrO and 0.2 wt% MnO, along with <2 wt% MgO and <0.8 wt% FeO.

By running a scanning electron microscope (SEM)-based heavy mineral search on a set of thin sections from representative Siilinjärvi samples, tiny grains of strontianite, on the order of 100 µm wide, were discovered occurring as patches of small blocky grains within calcite (Al-Ani, 2013). This strontianite contains less than 1 wt% rare earth elements $(REE)_{tot}$, consistent with the low REE content of Siilinjärvi carbonatite in general.

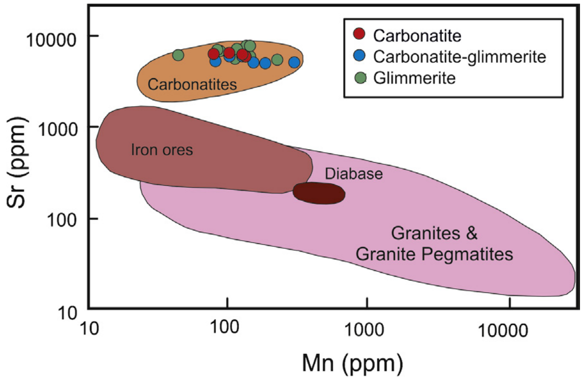

FIGURE 4.3.8 Sr-Mn discrimination diagram for apatite, with averages for about 340 Siilinjärvi ore apatite grains.

All data plotted in the field typical for carbonatite and cannot be differentiated based on host rock type.

Source: *Diagram after Belousova et al. (2002).*

APATITE

Light green to slightly gray apatite occurs in roughly equal amounts (~10 vol%) in ore rocks ranging from glimmerite to carbonatite, except for some examples of exceptionally apatite-rich glimmerites and carbonatites that have up to 30% apatite, and some 10–50 cm wide apatitite veins with up to 80 vol% apatite. Apatite forms rounded grains or euhedral hexagonal rods, typically several millimeters in diameter and several centimeters in length. All apatite at Siilinjärvi is fluoroapatite with between 2 and 4 wt% F, with an average for 160 grains of 3.2 wt% F and 0.75 wt% SrO. Despite the relatively low REE content of Siilinjärvi apatites (Hornig-Kjarsgaard, 1998), the Sr and Mn contents of the apatites are very typical of carbonatites (Fig. 4.3.8).

AMPHIBOLE

Blue-green richterite amphibole forms generally less than 15 vol% of the glimmerites and averages 5 vol% overall. However, Puustinen (1971, 1972) described carbonate-amphibole rocks that contain up to 50 vol% or more amphibole with richterite crystals up to several centimeters in length. In our experience, these rock types must be extremely rare. Microprobe analyses of 20 grains show uniform Al_2O_3 (<0.3%) and FeO/MgO, but variable K_2O (0.4–4.2 wt%) and Na_2O (1.0–6.3 wt%), indicating a range of amphibole types that require further study, particularly to determine their distribution within the ore body.

SERPENTINE

Serpentine is not a common mineral at Siilinjärvi; however, Puustinen (1971) reported a mica-bearing rock in the northern part of the Siilinjärvi complex that contains up to 80 vol% serpentine as pseudomorphs after olivine, along with apatite and magnetite. In this case, the rock is a serpentinized mica peridotite, or may represent a serpentinized phoscorite. Unlike other well-known carbonatites, including Sokli and Phalaborwa, phoscorite has not yet been described from the Siilinjärvi carbonatite.

OXIDES AND SULFIDES

Magnetite is the most common accessory mineral of both the carbonatites and the glimmerites, but generally represents less than 1 vol% of the ore. Pyrite, pyrrhotite, and lesser chalcopyrite represent the main sulfide minerals. They mostly constitute a small proportion of the ore, but can locally occur in massive form. Little research has been done on these minerals.

OTHER MINERALS

Relatively rare accessory minerals at Siilinjärvi include barite, strontianite, monazite, pyrochlore, zircon, baddeleyite, and ilmenite. Compositions of a number of these rare minerals from the Siilinjärvi carbonatite were reported by Al-Ani (2013) and are summarized here. Barite occurs as sparse, <50 μm inclusions in calcite, or as intergrowths with strontianite and contains 1–4 wt% SrO. Monazite occurs as <50 μm subhedral inclusions in calcite or apatite, or as more irregular grains along grain boundaries; grains up to 100 μm wide have been located. The grains analyzed so far show enrichments typical for carbonatite monazite with up to 23 wt% La_2O_3 and up to 40 wt% Ce_2O_3, but their relative rarity equates to low whole rock REE content.

Pyrochlore forms euhedral, typically 50–200-μm-wide grains as inclusions mostly in phlogopite. Few analyses exist, but these show typical compositions (77 wt% Nb_2O_5; 15 wt% CaO) with low contents of Ti, Ta, F, and REE. Zircon is rare in carbonatites, mostly because it requires a relatively high silica activity to become saturated in a melt. At Siilinjärvi, it occurs as euhedral grains ranging from tiny 100-μm-wide grains to megacrysts several centimeters in diameter, the latter typically containing large inclusions of baddeleyite. Allanite has been reported in thin section scans, but full microprobe analyses remain to be done.

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). In short, the most precise data appear to be from U-Pb analyses of zircon, particularly a concordant zircon U-Pb of age 2610 ± 4 Ma (2σ; Fig. 4.3.9) measured by Olavi Kuovo (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, clearly show a Svecofennian orogenic overprint that is well documented throughout much of the Archean terranes of eastern Finland (Kontinen et al., 1992).

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. 4.3.10). All ore samples essentially plot on a binary join between glimmerite and carbonatite. However, given the much greater volumes of glimmerite relative to carbonatites, the bulk composition of the Siilinjärvi

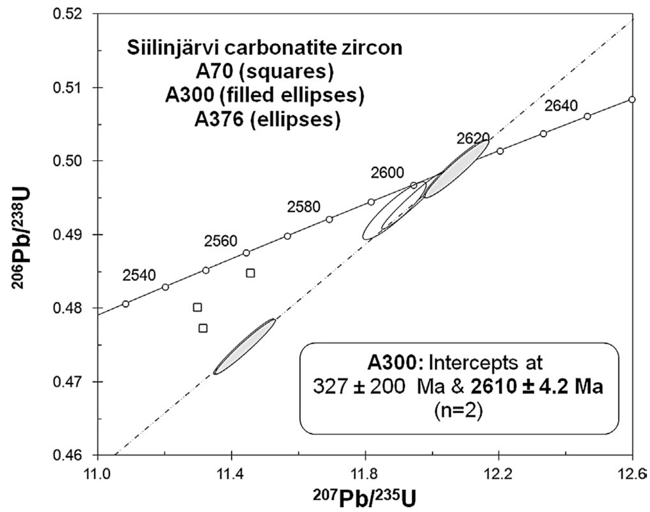

FIGURE 4.3.9 U-Pb concordia diagram for zircons from Siilinjärvi.

Source: *From original GTK report by O. Kouvo to H. Lukkarinen (1984).*

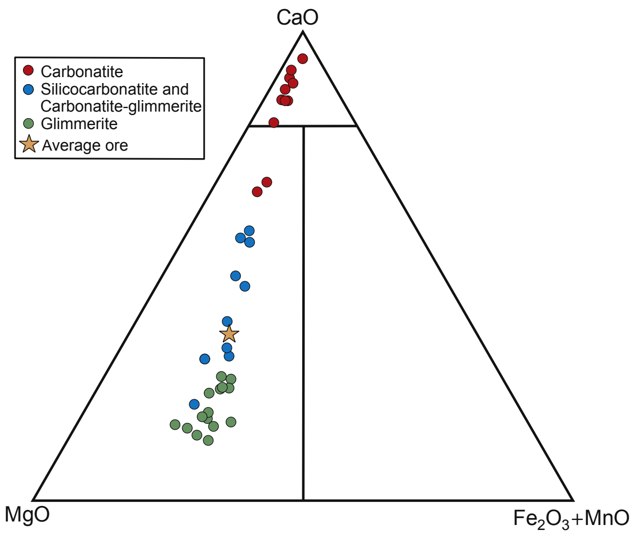

FIGURE 4.3.10 MgO-CaO-(FeO + MnO) diagram for 37 whole-rock analyses of the ore rocks and the average ore composition for comparison.

The two carbonatites with higher MgO contain 10–20 modal% dolomite.

main ore body differs only slightly from average glimmerite (see Table 4.3.1 and Fig. 4.3.10). 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

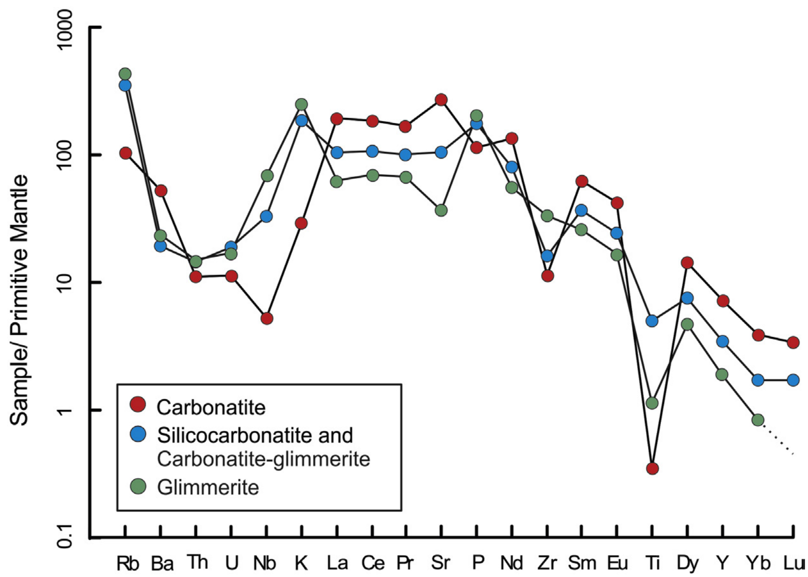

FIGURE 4.3.11 Primitive mantle-normalized diagram showing average compositions of the different ore type rocks.

Source: *Normalizing values from Sun and McDonough (1989).*

14-PTP-05 described in the preceding (Table 4.3.1). 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 Fig. 4.3.11. 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) and also overlaps with the data from Sokli (Demeny et al., 2004). The lowest Sr_i = (0.70137) (equivalent to εSr = 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, plotting near the bulk earth composition, and fully within the Ocean Island Balsalt (OIB) isotopic compositional field (see Fig. 4.1.3 and the discussion in Subchapter 4.1).

GENESIS OF THE SIILINJÄRVI GLIMMERITE-CARBONATITE

As described for the general case in Subchapter 4.1, 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 importance of studying the potassic dikes was outlined earlier, and calculations of the total carbonate budget need to be made.

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.

SIILINJÄRVI MINE

The Siilinjärvi mine has been active since 1979. Currently the mine comprises two pits; the relatively large southern Särkijärvi pit is shown in Fig. 4.3.12. It is approximately 250 m deep, with a bench height of 28 m. The overall blast rate at the mine is 600,000 t per week (450 kt from the Särkijärvi pit and 150 kt from the Saarinen pit). Almost all of the glimmerite-carbonatite series rocks constitute ore, while the fenites and crosscutting diabases are stockpiled separately. Exceptions include late apatite-poor carbonatite veins and certain blocks of carbonatite-glimmerite with <0.5 wt% P_2O_5 that seemingly have had their apatite removed by some unknown process, perhaps related to metamorphism and fluid flow. Understanding this process and facilitating identification of these low-grade blocks is an important ongoing topic of research.

The Siilinjärvi mine is the only operating phosphorus mine in Western Europe, with the closest competition located in the Kola alkaline province of northwest Russia. The main product is apatite, which is processed by flotation in the concentrator near the Särkijärvi pit (seen at the left side of aerial photograph in Fig. 4.3.12) to phosphoric acid using sulfuric acid derived currently from pyrite of the Pyhäsalmi mine, about 130 km northwest of the Siilinjärvi mine. By-products from the

FIGURE 4.3.12 Aerial photograph of Siilinjärvi mine, southern Särkijärvi pit.

Source: *Yara Suomi Oy.*

Siilinjärvi mine include mica concentrate and calcite concentrate. Since the beginning of full operation, almost 400 Mt of rock have been mined, 260 Mt tons of this being ore. The mine optimization to the year 2035 gives ore reserves as of January 2014 of 234 Mt, and waste rock of 157 Mt. Current production is roughly 11 Mt of ore per year, while the average in situ grade is 4.0 wt% of P_2O_5. A new optimization and reserve update is planned for 2015 following completion of a major Särkijärvi infill drilling campaign.

SUMMARY

1. Siilinjärvi represents the second largest carbonatite complex in Finland, and one of the oldest carbonatites on Earth at 2610 ± 4 Ma.
2. The complex hosts a significant ore deposit of apatite, mined since 1979, and through 2014 had produced 21.4 Mt of apatite concentrate out of ~260 Mt of ore.
3. Mineral compositions, particularly apatite and phlogopite, do not show any systematic compositional variability based on rock type. This is consistent with the glimmerite-carbonatite rocks representing an equilibrium assemblage of cumulate minerals. The Siilinjärvi complex probably represents a deeper level magma chamber than at Sokli; this is depicted for plutonic complexes in Subchapter 4.1, Fig. 4.1.2.
4. 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.

5. Tetraferriphlogopite was converted to biotite and chlorite in shear zones, and by inference, its dominance in the main ore zone suggests that the laminated, alternating glimmerite-carbonatite texture is a primary magmatic feature. These laminated-textured rocks are cut by numerous carbonatite veins and dikes that represent the final stages of magmatic influx into the Siilinjärvi system.
6. 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. This includes the melasyenite and ultramafic lamprophyre from the northern portion of the intrusion, and the glimmerite dikes with primary carbonate segregations along the railroad cut and in drill core.
7. 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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