CHAPTER

4.2

THE SOKLI CARBONATITE COMPLEX

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ABSTRACT

The Sokli carbonatite complex is one of 22 alkaline complexes comprising the Devonian Kola alkaline province (KAP). It represents the largest carbonatite intrusion of the province, and possibly the largest carbonatite on Earth. The Sokli complex shows many important similarities to other alkaline complexes of the KAP, especially Kovdor and Vuorijärvi, such as associated early ultramafic cumulate rocks, a well-developed phoscorite-carbonatite association and late carbonatites that represent carbonate liquid evolution to dolomite carbonatites to a final light rare earth element (LREE)-Sr-Ba dolomite carbonatite pulse. However, a critically important difference with Sokli is the vastly greater abundance of carbonatite relative to the associated cumulate ultramafic rocks.

At Sokli, a core zone of magmatic carbonatite is surrounded by a zone of precursor ultramafic rocks that have been almost completely transformed into carbonatites by outward migration of magmas and fluids from the core zone; the resulting rocks are termed *metasomatic carbonates*. Surrounding this is a highly heterogeneous outer transition zone of mixed rocks, composed of phlogopite-rich, carbonate-bearing varieties that have a very complex history and are derived variably from country rocks, fenites, ultramafic cumulates, and metasomatic carbonatites.

To push forward research on the Sokli complex, in 2008, Yara International ASA commissioned the Geological Survey of Finland to fly a high-density aerogeophysical program over the Sokli area, acquiring magnetic, electromagnetic, and radiometric data. Geophysical images derived from this program are used here to complement this review of the petrology and mineralogy of the Sokli complex. The aerogeophysical data allow further definition of the geology of the carbonate complex, as well as permit differentiation of the ore types of the weathered regolith covering the carbonatite.

Keywords: Sokli; carbonatite; phoscorite; aerogeophysical mapping; regolith; phosphate ore.

INTRODUCTION

The Sokli carbonatite complex is one of the 22 alkaline complexes that constitute the Kola alkaline province (KAP; Fig. 4.1.4) intruded during the Devonian, from 410–362 Ma, with most bodies being intruded in the relatively short period of 382–362 Ma (Kramm and Sindern, 2004). Rb/Sr dating of 5 Sokli samples, using biotite, carbonate, apatite, and whole rocks, give ages for Sokli ranging from 365 ± 3 Ma (Kramm et al., 1993), putting it at the younger end of the KAP.

The KAP comprises a range of alkaline complexes from the giant Khibiny and Lovozero nepheline syenite-dominated plutons, with Khibiny representing the largest alkaline complex in the world, covering 1327 km^2 (Ilyin, 1989), to the relatively small Sallanlatvi complex at 4.2 km^2 (Zaitsev et al., 2004). Fourteen of the KAP alkaline intrusions contain carbonatites, and Sokli, at 18 km^2 is the largest carbonatite among them, and possibly the largest in the world.

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The enormous volume of alkaline magmas of the KAP event produced a wide variety of rock types. Some are close to magma compositions, but most represent predominantly cumulates. The reader is referred to the volume edited by Wall and Zaitsev (2004) for a full review of mineral chemistry, rock types, magma fractionation paths, and relative ages.

Exposure at Sokli is relatively poor and the top of the body is heavily weathered, restricting all work on paragenetic relationships to drill-core observation and sampling. Moreover, there has been extensive overprinting of all older silicate cumulate rocks at Sokli by late voluminous carbonatite magmatism, as explained later. Based on these criteria, the best analogs for Sokli appear to be its two nearest KAP neighbors, the Kovdor and Vuorijärvi complexes, and reference to these intrusions is made throughout this chapter.

AEROGEOPHYSICAL SURVEY

As part of a research and ore evaluation program aimed at developing a better geological model for the Sokli complex, Yara International ASA commissioned the Geological Survey of Finland (GTK) to carry out an airborne survey on the Sokli area in 2008. Specifications of the survey are given in Table 4.2.1. Geophysical parameters measured were the Earth's magnetic field, the electromagnetic field (four-frequency system with frequencies of 0.9, 3, 12, and 25 kHz), and natural gamma radiation. The measurement data were interpolated into grids with a pixel size of 18.75 m × 18.75 m. The measurement systems and data processing are described in Hautaniemi et al. (2005). In 2012 the data were released and GTK received full rights to them.

The measured total magnetic induction (TMI) was reduced to the northern pole (RTP) to minimize remanence caused by the magnetite-bearing intrusion. The aeroelectromagnetic (AEM) data of higher frequencies (12 and 25 kHz) were used to delineate shallow subsurface conductors and lower frequencies to reveal deeper structures and magnetite-bearing conductors. The aeroradiometric data reflect surface mineralogy, and the approximate depth penetration is 0.5–1 m.

Changes in uranium (U), thorium (Th), and potassium (K) concentrations and concentration ratios reflect both lithological variations and degree of weathering. The concentration values of thorium, uranium, and potassium were converted to units of radiation (UR) and scaled similarly to keep them comparable. Water attenuates gamma-rays significantly and therefore wet areas appear as black on the radiometric images.

Table 4.2.1 Aerogeophysical survey specifications

Flight direction	**East–West**
Line spacing	75 m
Nominal flight altitude	30 m
Total line length	1842.4 km
Magnetometers	Two cesium magnetometers
Electromagnetic system	Frequencies: 912, 3005, 11,962, and 24,510 Hz
Radiometric	256-channel spectrometer; NaI (Tl) crystal volume 41 l

GENERAL DESCRIPTION OF THE SOKLI COMPLEX

The Sokli carbonatite complex is located in Finnish Lapland, with a center point near 67° 48′ 12.2″ north latitude, and 29° 19′ 2.3″ east longitude. It was discovered in 1967 during an iron ore prospecting campaign by Rautaruukki Oy in the area of Finland nearest to the Kovdor alkaline complex. Sokli is ellipsoidal in plan, with a major axis oriented northwest–southeast of about 6.2 km and a minor axis of 4.8 km. The total area of the complex is about 18 km^2. A comprehensive study of the complex was undertaken by Vartiainen and Paarma (1979) and Vartiainen (1980) to assess its ore potential.

The three-dimensional shape of Sokli is of a concentrically zoned, funnel-like body (Fig. 4.2.1) with a younger, plug-like carbonatite magmatic core measuring 2.5 km in width at the surface and 1 km in width at 5 km depth, as indicated by deep seismic soundings (Paarma et al., 1981). As described in Subchapter 4.1,

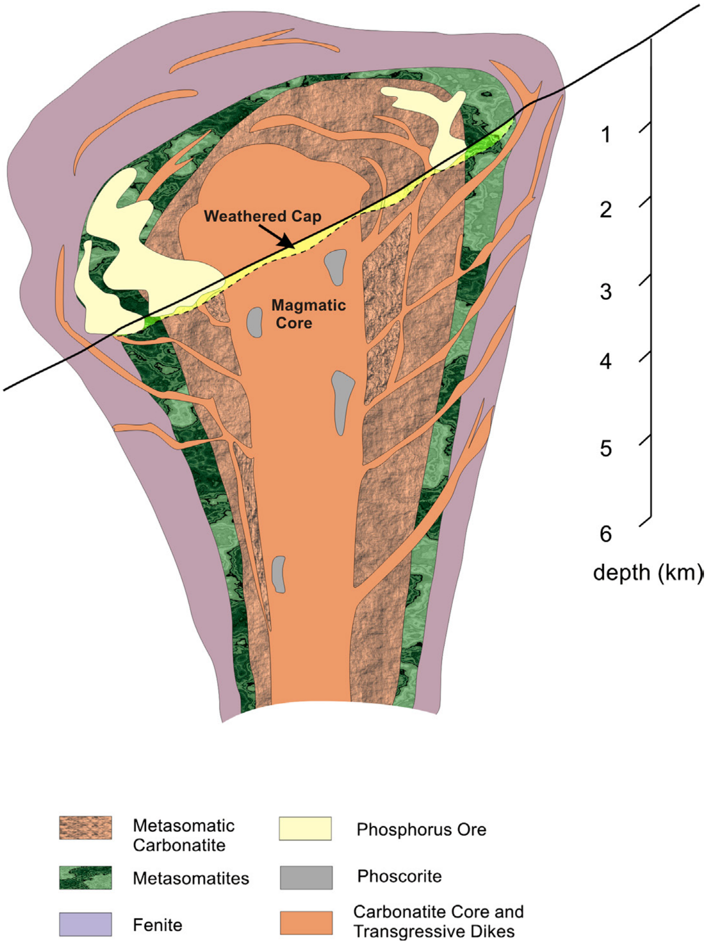

FIGURE 4.2.1 Schematic cross section through the Sokli carbonatite complex.

Source: *After O'Brien et al. (2005).*

the general model for carbonatite complexes around the world has carbonatite forming a distinctly younger intrusive body, typically as a central core, or at least the latest intrusive phase, of a zoned alkaline igneous complex (see Fig. 4.1.1). However, at Sokli, the younger magmatic core is not surrounded by neatly concentric layers of older, related cumulate rocks as in other KAP intrusions, but rather by a semicontinuous ring of metasomatically produced carbonated rocks. This in turn is followed outwards by an even more heterogeneous zone of carbonate and phlogopite-rich metasomatized ultramafic silicate rocks, amphibole rocks, pyroxene rocks, and blocks of fenite, all cemented together by metasomatic carbonate (Vartiainen, 1980).

ROCK TYPES

MAGMATIC CORE

Carbonatites with fully magmatic textures form an elliptical vertical pipe that is located relatively close to the center of the Sokli complex, although not exactly in the center. Within this inner pipe, carbonatite dominates, but there are many inclusions of metasomatic carbonatite, amphibole rocks, and mica-amphibole rocks ranging in size from centimeters to hundreds of meters. Crosscutting relationships led Vartiainen (1980) to suggest the following sequence of events for the Sokli central pipe: (1) emplacement of phoscorite following segregation from carbonatite magma, (2) main pulse of calcite carbonatite emplacement, (3) pneumatolitic-hydrothermal activity, (4) intrusion of dolomite and Fe-bearing carbonatites, and (5) intrusion of late dolomite veins containing also Sr and rare earth elements (REE) carbonates and barite.

Phoscorite is a forsterite-magnetite-apatite rock (Le Maitre, 2002), and has been described from only 21 localities globally (Krasnova et al., 2004). All of these occurrences are closely associated with carbonatites, providing strong evidence that they are genetically related to carbonatite. The textures of some of the phoscorites, described from Sokli and Vuorijärvi (Lapin and Vartiainen, 1983), provide strong evidence that liquid immiscibility has occurred in these systems. These observations include: (1) phoscorites with spherulitic structures, spherical to ellipsoidal aggregates of magnetite and forsterite with radial crystal habit, in a carbonate-rich matrix; and (2) phoscorites with orbicular textures, wherein ellipsoidal forsterite-magnetite, forsterite-tetraferriphlogopite-magnetite-calcite, or phlogopite-calcite-magnetite orbicules exist in a calcite ± magnetite matrix. The best interpretation of these phoscorite textures is that they represent conjugate immiscible oxide-phosphate-silicate magmas to carbonatite magmas, hence the similarity in the mineralogy and their major element compositions, with only a considerable variation in modal proportions of phases distinguishing the rocks.

Lee (2002) and Lee et al. (2004) conducted a detailed study of phoscorites and magmatic carbonatites at Sokli. Based on mineral chemistry data, he was able to show that the rocks formed through several immiscibility events, named P1C1 (phoscorite 1-carbonatite 1), P2C2, and P3C3. A thin section of a typical Sokli P1 is shown in Fig. 4.2.2. Lee was also able to show that phlogopite (Lee et al., 2003), oxide (Lee, 2005), and pyrochlore (Lee et al., 2006) compositions are all distinctive for each PC pair (see "Mineralogy" section, later). Moreover, each succeeding PC pair has minerals with increasingly evolved compositions. For example, phlogopite shows a systematic change from Ba-containing, slightly eastonitic phlogopite in P1C1 to steadily decreasing Al_2O_3 contents, leading to nearly pure Al-depleted tetraferriphlogopite in P3C3, indicative of crystallization from severely Al-depleted melts.

This evolutionary trend from normal phlogopite to tetraferriphlogopite is also seen at other phoscorite-bearing carbonatites of the Kola alkaline province, in particular at Kovdor (Kukarenko et al., 1965) and Vuorijärvi (Karchevsky and Moutte, 2004). In addition to overall magma evolution

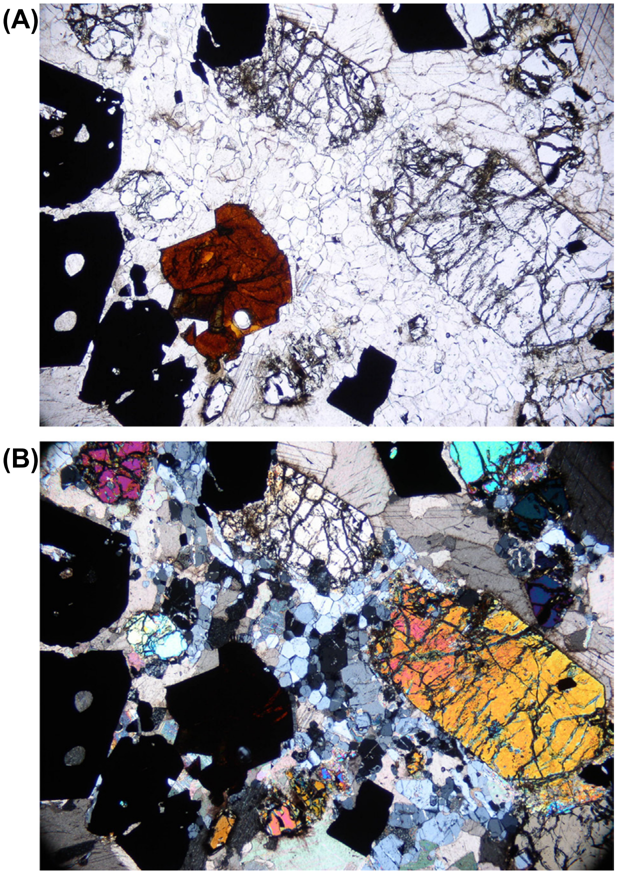

FIGURE 4.2.2 Photomicrographs of Sokli phoscorite (P1 phase) in thin section.

(A). Phoscorite composed of calcite, apatite, olivine, magnetite, and pyrochlore from magmatic carbonatite. Plane-polarized light. Width of field is 6.85 mm. (B). Same as A., polars crossed.

from P1C1 to P3C3, within each pair of immiscible magmas (crystals + liquid), the daughter liquids continued to evolve by fractionation, as evidenced by mineral core to rim zoning profiles (Lee, 2002). It appears that this immiscible process occurred three times on a large scale at Sokli, and, interestingly, despite the large differences in the size of the carbonatite systems, this is also the number of PC pairs reported at Kovdor and Vuorijärvi (Karchevsky and Moutte, 2004). The final product of this stepped process of magma immiscibility and fractionation at all three of these carbonatites led to a similar, highly evolved dolomite carbonatite (stage 5) containing a range of trace element rich minerals (Vartiainen and Vitikka, 1993).

In terms of its aeromagnetic response, the Sokli magmatic core is highly magnetic, heterogenous and fractured as seen in Fig. 4.2.3. The alteration zones surrounding the core are recognized by a decrease in magnetic intensity, forming a circular break that defines the edge of the magmatic core (Fig. 4.2.4).

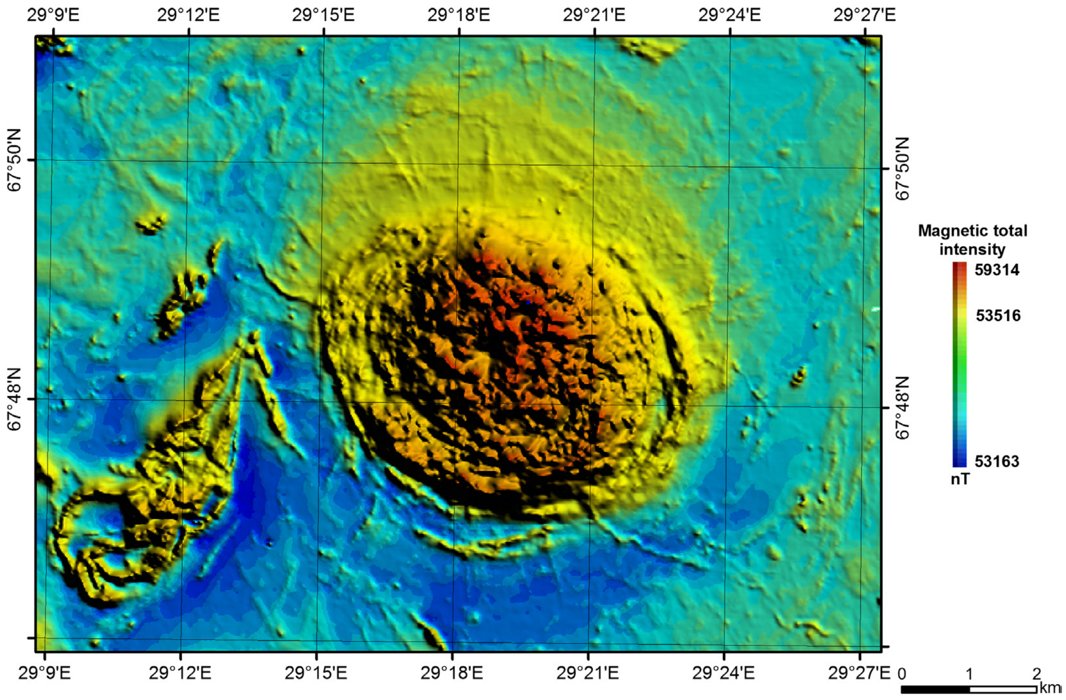

FIGURE 4.2.3 Shaded aeromagnetic TMI image of Sokli carbonatite complex and associated Tulppio olivinite.

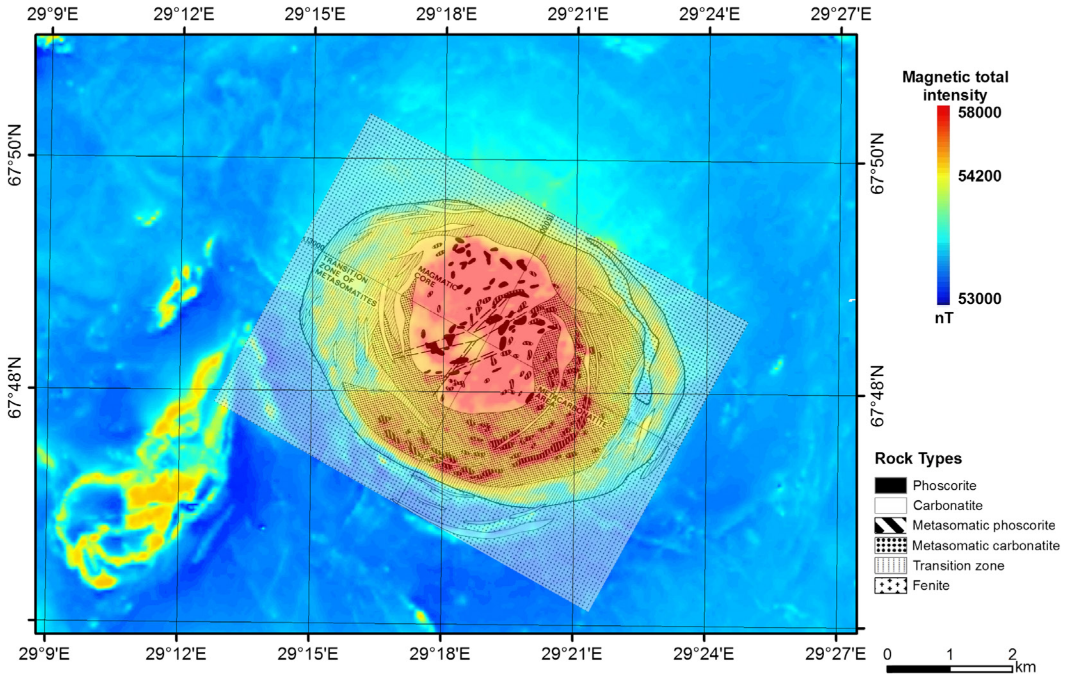

FIGURE 4.2.4 Geological map of the Sokli complex overlain on aerogeophysical TMI image.

Source: *Rotated and rectified from Figure 3 of Vartiainen (1980).*

METASOMATIC ROCKS

Based on petrographic evidence and gradational mineralogical contacts, Vartiainen (1980) was able to show that the metasomatic carbonatites (his "metacarbonatites") formed as a result of carbonitization of pyroxenites and coarse-grained olivinites (dunites with magnetite rather than chromite), the oldest rocks of the complex. The slightly carbonitized variants are massive, while the more strongly replaced ones are generally banded. Metasomatic silicate rocks formed from the ultramafic rocks of the original intrusion through complex replacement and substitution processes in a manner that, at its extreme, resulted in almost pure phlogopite rock. As intermediate products, there occurs a host of rock types containing variable amounts of amphibole, aegirine, and phlogopite as major minerals.

Although being just remnants, the few blocks of ultramafic rock within this zone allow analogies to be drawn between the precarbonatite rocks at Sokli and the more typical dominant rock types of the other Kola alkaline complexes. Especially relevant are the large volumes of ultramafic cumulates composed of olivine and clinopyroxene at Kovdor and Vuorijärvi. The geology of the Kovdor carbonatite complex is relatively well known, due to active mining of the carbonatite-phoscorite that has been ongoing for more than 50 years. Even though the rocks of the complex represent cumulates, they nevertheless record the sequence of magmas within the subvolcanic system now exposed.

Crosscutting relationships at Kovdor suggest the following sequence of emplacement: olivinite, phlogopite-diopside-olivine rock, clinopyroxenites, melilitolites, ijolite, and, finally, phoscorites, followed closely by carbonatite magmas (Krasnova and Kopylova, 1988; Verhulst et al., 2000; Krasnova et al., 2004). The cumulate sequence at Vuorijärvi is similar to Kovdor, but the volumes of each cumulate type are considerably different, with various types of clinopyroxenites constituting the vast majority of the Vuorijärvi complex, and olivinites occurring only as isolated blocks (xenoliths) within the pyroxenites.

These analogs suggest that there likely were large volumes of mafic mineral accumulations formed in subvolcanic magma chambers also at Sokli. Moreover, the olivinite mass at Tulppio, showing up as a distinctive 4 km × 2 km magnetic anomaly southwest of the Sokli complex proper (see Fig. 4.2.3), is likely a good example of what these cumulates were like, and clearly more studies of the Tulppio rocks are warranted. Summarizing these circumstantial pieces of evidence, it appears possible that prior to the emplacement of the main carbonatite, Sokli may have looked similar to the Vuorijärvi and/or Kovdor complexes.

Thus, what separates Sokli from the rest of the KAP intrusions is the amount of carbonatite magmatism that occurred. In the previously discussed Kovdor and Vuorijärvi cases, the volume of carbonatite is less than 10%, whereas at Sokli, magmatic carbonatite, or rocks that reacted with carbonatite magma or carbonate-rich fluid, represent nearly the entire intrusion. So thorough was this overprint in many cases that the precursor magmatic rocks are difficult, if not impossible, to identify, as these rocks are now composed of greater than 50% by volume of carbonate minerals.

The aeromagnetic response of the metasomatic zone is midway between that of the magmatic rocks and the transition zone in terms of intensity (see Fig. 4.2.3). Highly magnetic pods are more discrete, and far less abundant than in the magmatic core (see Fig. 4.2.4), but are still interpreted to represent magnetite-rich phoscorites (so-called metaphoscorites), as mapped by Vartiainen (1980).

TRANSITION ZONE

Composed of fragments of fenites and rocks formed of variable amounts of pyroxene, amphibole, and mica all enclosed in a matrix of metasomatic carbonatite, the *transition zone of metasomatites*, as termed by Vartiainen (1980), is clearly a very heterogeneous mixture of rock types with mineralogies and textures distinct from the remainder of the complex. Sequential potassic metasomatism turned initial ultramafic cumulates dominated by clinopyroxenites first into amphibole-rich, and finally phlogopite-rich, rock types (Vartiainen, 1980). Subsequent overprinting by later carbonate-dominated fluids or melts further transformed these original ultramafic rocks into mixed zones of silicate-dominated and carbonate-dominated rock types, now forming the "transition zone."

The fact that so much transformation of silicate to carbonate rock occurred distally to the magmatic core provides strong evidence that a considerable amount of carbonatite melt was, in fact, involved in producing the rocks, even of the transition zone. As we will show later (see "Ore deposits" section), this extensive overprinting was a very positive feature from an economic point of view, in that regolith ore deposits occur across the entire intrusion, derived from all three rock type zones, not just above the magmatic core.

The aeromagnetic response of the transition zone is markedly different from that of the two inner zones (see Fig. 4.2.3). Most importantly, there are no obvious highly magnetic pods as in the inner zones, suggesting no magnetite-rich phoscorites (see Fig. 4.2.4). In a number of places, sublinear anomalies, most likely representing dikes, appear to emanate from the two inner rock zones, and cut across the transitional zone while other anomalies seem to emanate from the edge of the outer transition zone. A circular zone of higher conductivity at AEM frequencies of 12 kHz and 25 kHz characterizes the rocks of the transition zone (Fig. 4.2.5). Because these conductors are recognized only from the high-frequency AEM data, they are shallow and mainly the result of weathering.

FENITES

Fenites surround the carbonatite-biotitite central core developed by sodium and potassium metasomatism of the surrounding granite gneiss, amphibolite, and hornblende schist. The Sokli fenite halo is developed up to 3 km from the carbonatite core and is manifested by the development of alkali feldspar, pyroxene (aegirine and aegirine-augite), alkali amphibole (arfvedsonite and eckermannite), and phlogopite, giving the rock a greenish cast (Vartiainen and Woolley, 1976). Levels of fenitization increase toward the carbonatite intrusion and in the zone of most intense fenitization proximal to the intrusion, potassic metasomatism is dominant, forming extensive phlogopitite and phlogopite-alkali amphibole rocks.

In terms of aeromagnetics, the fenites do not appear to have any noticeable effect on the country rock magnetic signature (see Fig. 4.2.3). Note that in this figure, the yellow region to the north of the Sokli complex is due to the dipole effect, and is unrelated to the fenite zone. Carbonatite ring dikes intruded into the fenite zone have highly magnetic signatures, similar to the rocks from the magmatic core.

AILLIKITE DIKES

Associated with many ultramafic alkaline complexes are ultramafic, phlogopite-rich, olivine- and carbonate-bearing dikes that are termed aillikite, a type of ultramafic lamprophyre (Rock et al., 1991; Tappe et al., 2005). They typically have low silica contents, and experimental evidence suggests that they represent very small partial melts of carbonated peridotite source rocks that compositionally can be gradational to Group I kimberlite (Dalton and Presnall, 1998).

Everywhere within the Sokli complex, and also up to several kilometers away from it, ultramafic lamprophyre dikes occur. They are generally dark rocks varying from reddish- to greenish-gray, occur

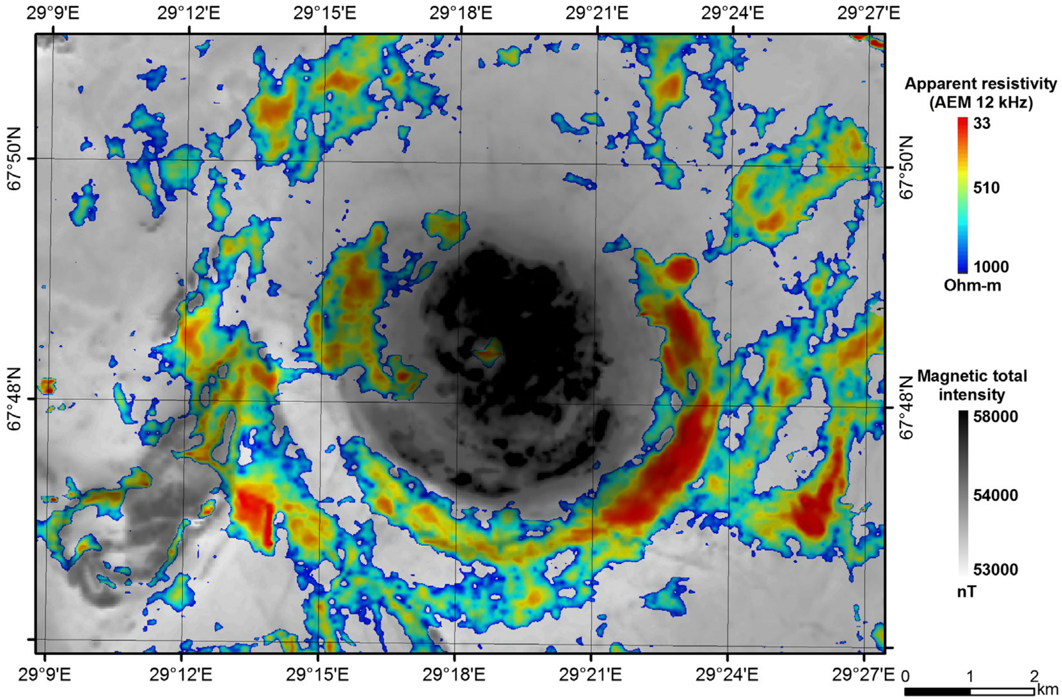

FIGURE 4.2.5 Aeroelectromagnetic map of the Sokli complex showing frequencies 12 kHz and 25 kHz overlain with the geological map of Vartiainen (1980).

These frequencies reveal shallow conductors, mainly as the result of weathering, and demarcate the transition-zone rocks rather well.

as swarms with different orientations, and, according to drilling results, average about half a meter in thickness. Vartiainen et al. (1978) divided the dikes into four subgroups based on texture: porphyritic, xenolithic (= autolithic), massive, and mica-rich. The last two groups dominate, while the first two groups occur mainly within the fenite zone and the bedrock area outside of the carbonatite proper. A typical example of a Sokli aillikite is shown in Fig. 4.2.6.

The mineralogy of the Sokli lamprophyres varies considerably. In the porphyritic group, the proportion of phenocrysts varies between 27 and 37%. Typically, olivine is strongly altered and is absent from the groundmass. The groundmass is very fine-grained (~0.1 mm) and crystallized in the following order: opaques, phlogopite-calcite, and richterite. Xenoliths in the xenolithic variety within the carbonatite complex include rock types of the complex itself and include phoscorite, carbonatite, and fenite.

Weak magnetic, dike-like anomalies radially surround the complex, and, as mentioned, seem to be both older and younger than the transition-zone rocks, based on crosscutting relationships. Lee (2002) also documented evidence that some lamprophyre dikes are affected by, and even cut by, carbonatites from the magmatic core. Hence, combining all observations described points to the existence of multiple generations of lamprophyre dikes, intruded at all stages of the development of the Sokli complex, from the very earliest stages to the very latest.

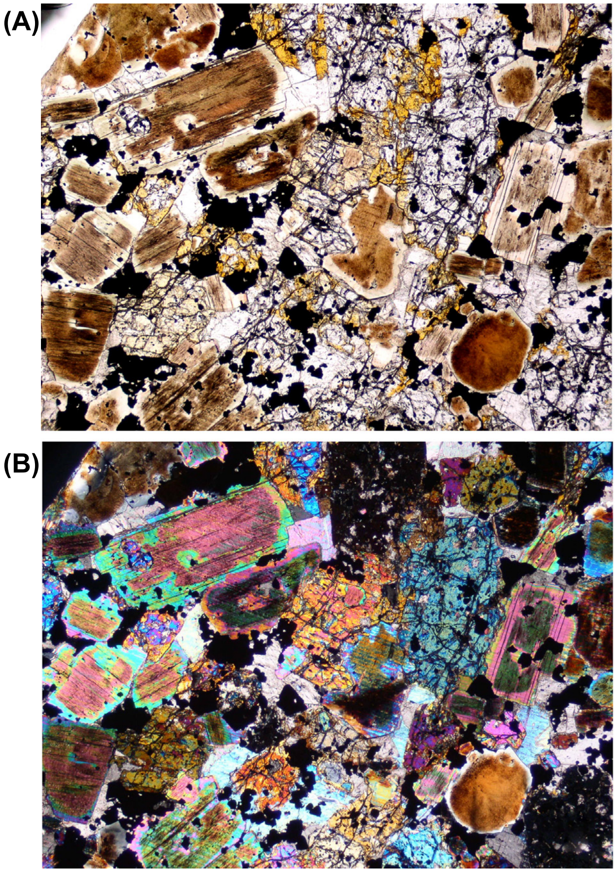

FIGURE 4.2.6 Photomicrographs of Sokli aillikite in thin section.

(A). Olivine is mostly fresh, but approximately 20% has been converted to alteration minerals, in this case predominantly iddingsite. The phlogopite shows systematic zoning from a cloudy core to clear subhedral mantles, to very late discontinuous tetraferriphlogopite rims (see large grain, middle-right). Calcite was late to crystallize, but is abundant. The remaining minerals include magnetite, apatite, and richterite. Plane-polarized light, width of field is 5.0 mm. (B). Same as A, polars crossed.

MINERALOGY

The following overview section on the mineralogy of the Sokli complex relies heavily on the comprehensive work undertaken on Sokli by H. Vartiainen (1980) and by further detailed studies made by Lee (2002, 2005) and Lee et al. (2003, 2006).

OLIVINE

Olivine is dominant in the Tulppio olivinite where it forms nearly monomineralic bodies up to several hundreds of meters in size, accompanied essentially only by magnetite. Within the Sokli complex, forsterite is also relatively important and occurs in blocks of metasomatic phoscorites, within the phoscorites proper of the magmatic core, and as phenocrysts in the aillikite dikes of the complex. In many cases, the existence of olivine in Sokli rocks can only be inferred from alteration minerals, clinohumite being the most typical alteration product.

Microprobe analyses (Vartiainen 1980; Lee, 2002) show that the olivine in the Tulppio olivinite and phenocrysts in the aillikites have similar compositions, with high Ni (0.2–0.45 wt%) and low Ca and Mn (<0.2 wt% both elements), whereas the olivines in the carbonatites and phoscorites are unsurprisingly just the opposite, with low Ni (<0.2 wt%) and high Ca and Mn (up to 0.46 and 1.26 wt%, respectively). This relationship holds, despite the fact that the carbonatite olivines have higher Fo content (Fo88–95) than the aillikite/Tulppio olivines (Fo83–92), presumably due to the relatively high mg# of the Sokli carbonatite magmas. Importantly, some of the aillikites also contain small olivine microphenocrysts that have Ni-poor, Mn-rich compositions (Lee, 2002) indicative of the fractionated and carbonate-rich nature of the matrix liquid composition, an environment much more similar to that in the carbonatite magmas.

CLINOPYROXENE

As we noted earlier, clinopyroxene was probably quite abundant during the early stages of development of the Sokli magmatic system, perhaps forming large cumulate bodies in a similar way to the KAP complexes of Kovdor and Vuorijärvi. However, with the much larger volume of carbonatite influx at Sokli, pyroxene was mostly transformed into other minerals, especially alkali amphibole and mica. Only small remnants of diopsidic pyroxene exist within blocks in the metasomatic carbonatites, or more rarely with the magmatic core, and these remain the only record of the original pyroxenes.

MICA

Compositions of mica range from slightly eastonite-bearing phlogopite (i.e., Al-Tschermak coupled substitution along the phlogopite-eastonite join) to nearly stoichiometric phlogopite to pure tetraferriphlogopite (Lee et al., 2003). Moreover, this variation is very systematic, with each successive PC stage (from P1C1 to P3C3) showing increasingly Al-depleted phlogopite compositions. Fluorine contents mimic this trend, changing from nearly pure OH-bearing phlogopite to a variety of fluorphlogopite in the D5 dolomite carbonatite.

Despite these overall trends, micas from each PC stage show significant variation in composition due to fractionation effects, and from stage to stage show a partial overlap in composition. This strongly implies a continuous progression of increasingly evolved liquids that formed the magmatic core, possibly all derived from a single parental liquid. Similar trends are seen in phlogopites at Kovdor and Vuorijärvi (Kukanrenko et al., 1965), again indicating similarities in magma compositions and crystallization processes among these KAP carbonatite complexes.

CARBONATES

The dominant carbonate minerals at Sokli are calcite and dolomite, with the ratio of the two being quite variable depending on the rock type considered (Vartiainen, 1980). For example, in the magmatic core rocks, the phoscorites contain a significantly higher ratio of dolomite to calcite (at a total CO_2 content mostly below 5 wt%), and vice versa for the conjugate carbonatites (with total CO_2 contents >30 wt%).

The metasomatically derived phoscorites and carbonatites follow a similar rule, with a few exceptions. The other important consistent carbonate mineral relationship is that the late stages 4 and 5 magmatic carbonatites shift almost completely to dolomite; these rocks crystallized from the last and most evolved liquids that formed Sokli. It is also within these late-stage evolved dolomite carbonatites that less common carbonate minerals become more abundant, for example, strontianite, ankerite, siderite, and several REE carbonate minerals are only reported from the late carbonatites.

FE-TI OXIDES

Oxides at Sokli include magnetite and ilmenite, with magnetite nearly ubiquitous throughout the complex. Magnetite is the main mineral in the phoscorites, ranging from 15–70 modal % and having grain sizes from 1–20 mm, with typically larger amounts in the younger phoscorites. Crystals also tend to be more euhedral in the younger phoscorites. Very similar to the progressive evolution evident in phlogopite compositions, the magnetite compositions also vary systematically from stage 1 to stage 5, with constantly decreasing mg# and decreasing concentrations of Mg, Al, Mn, and Ti due to depletion of these elements in the evolving melt. The end result of this process is the crystallization of nearly pure magnetite in the stage 5 carbonatites.

Ilmenite occurs mostly as exsolution features within the magnetite grains or as grains attached to magnetite grain boundaries. The composition of the ilmenite is very much in line with ilmenite from other carbonatites, with high MgO (up to 11.4 wt%) and diagnostically high MnO (up to 14.2%), the combination being the hallmark of carbonatite-related ilmenite (e.g., Mitchell, 1978). However, similar to magnetite, ilmenite compositions show a complete and consistent path toward Fe- enrichment, crystallizing as nearly pure $FeTiO_3$ in the latest magmatic stages (Lee, 2005). This decrease in MgO in the oxides occurs as the equilibrium carbonate phase shifts toward Mg-rich compositions, potentially explaining the MgO depletion in other minerals due to stronger partitioning of Mg into dolomite.

PYROCHLORE

Pyrochlore is the third mineral at Sokli providing evidence of a progressively fractionating system (Lee, 2006). Pyrochlore did not crystallize at Sokli until the magmas evolved to P2C2 compositions, but then it occurs in all later carbonatite magma types. Compositionally, the P2C2 pyrochlores are relatively U- and Ta-rich, but later P3C3 pyrochlore instead contains higher Ce and Th, while the pyrochlores from the latest carbonates are nearly end-member pyrochlore $(Ca, Na)_2Nb_2O_6F$. Further detail provided by Lee et al. (2006) shows that the pyrochlores within a given phoscorite have the same starting composition but a distinctly longer crystallization history than those from the conjugate carbonatite. This strongly suggests that the conjugate pairs formed by liquid immiscibility, with initially identical mineral compositions that then followed distinct fractionation trends after separation.

APATITE

Apatite occurs in all rock types of the Sokli carbonatite complex. Modal values of apatite range from up to 50% in some of the phoscorites, down to tens of percent in the late dolomite carbonatites, with respective grain sizes of millimeter to micrometers. Compositionally, the apatites are all fluorapatites (i.e., Cl is nearly nonexistent). As in many of the other minerals studied, the apatites show a progressive increase in elements such as F, Sr, Na, and light rare earth elements (LREE) from early P1C1 to late C5 carbonatite host rocks. However, such enrichments are even evident on the rims of some P2 phoscorite apatite grains, likely indicative of late-stage magmatic fluids migrating through the already crystallized carbonatite complex rocks.

OTHER MINERALS

Although baddeleyite was originally thought to be absent from the magmatic inner core carbonatites, as opposed to the metasomatized carbonatites where it occurs in trace amounts (Vartiainen, 1980), Lee (2002) reported small amounts of baddeleyite from magmatic core rocks. Rare zirconolite occurs in C2 carbonatite, P2, and P3 phoscorite and in the ultramafic lamprophyres, typically in contact with pyrochlore or baddeleyite, but also as tiny, late-crystallized grains.

GEOCHEMISTRY AND ISOTOPES

Given that the emphasis in this chapter is on petrology and mineralogy and its relevance to the Sokli geophysical signature, we do not discuss in detail the geochemistry of the complex. The average composition of magmatic carbonatite, metasomatic carbonatite, and metasomatic ultramafic rock are listed in Table 4.2.2. Of note are the following points: (1) the magmatic carbonatites are extremely depleted in Al_2O_3, yet contain significant K_2O, explaining the high modal abundance of tetraferriphlogopite in the system; (2) the average MgO content of the metasomatic carbonatites and the transitional zone rocks is roughly the same despite nearly three times the silica content in the latter. This might indicate

Table 4.2.2 Average chemical composition (wt%) of Sokli rocks

	Transition zone	Metasomatic	Magmatic
	metasomatites	carbonatites	carbonatites
SiO_2	29	10.5	2
TiO_2	1	1	0.1
Al_2O_3	6	2	0.4
Fe_2O_3	9.5	9	4.5
FeO	5	4	0.5
MnO	0.3	0.5	0.5
MgO	11	10	5
CaO	20	34	47
K_2O	3.5	1.5	0.5
P_2O_5	5	4	3.5
CO_2	9	23	34
S	0.7	0.5	0.5
Nb	0.01	0.02	0.15

Source: *Data from Vartiainen (1989).*

a significant magnesiocarbonatite component in the metasomatizing melts and fluids that affected the metasomatic carbonatite zone; and (3) as the carbonatite component decreases from the magmatic core to the transition zone, the average phosphorus content increases.

A very comprehensive geochemical dataset on the Sokli complex can be found in Lee (2002); it includes 225 whole-rock samples analyzed by X-ray fluorescence (XRF) and 21 repeat analyses using inductively coupled plasma mass spectrometry (ICP-MS). A number of important observations made by Lee are summarized in the following:

1. The types of magma evolution described by the mineral compositional variations, and summarized above, can also be traced in the whole-rock data.
2. The mineralogically described phoscorite-carbonatite conjugate pairs have parallel trace element patterns, albeit at significantly lower enrichment levels for the phoscorites of each pair.
3. Trace element data show that the calciocarbonatites at Sokli are very much average on a worldwide basis for most elements.
4. In terms of REE contents, however, the Sokli calciocarbonatites are relatively REE-poor, similar to contents in the Siilinjärvi carbonatites (see Subchapter 4.3).
5. A relatively clear compositional gap exists between calciocarbonatites and magnesiocarbonatites, implying that the former are predominantly cumulates without significant trapped evolved magnesiocarbonatite liquid.

The available isotope data comprise a few Sr and Nd analyses reported by Kramm (1993). The two data points plot in the depleted mantle field along with young carbonatites and near the Siilinjärvi composition, and implicate an Ocean Island Basalt (OIB)-type mantle source (see Subchapter 4.1 and figure 4.1.3). Primary carbonatite carbon and oxygen isotope data for Sokli, reported in Demeny et al. (2004), are all close to the values from the other KAP intrusions and well within the “mantle box” of Taylor et al. (1967). For the P1C1 through C3 stages, the values range from $\delta^{13}C = -3.0$ to $-4.2‰$, $\delta^{18}O = 7.1$ to $7.5‰$. However, P3, C4, and the metasomatic carbonatites show a well-defined array away from these mantle values toward $\delta^{13}C = -2.6‰$, $\delta^{18}O = 10‰$. Demeny et al. (2004) suggest that this trend could represent crystallization-induced Rayleigh fractionation, implying crystallization in a relatively shallow subvolcanic magma chamber.

GENESIS OF THE CARBONATITE

The fact that aillikite, a carbonate-rich ultramafic lamprophyre, formed dikes at Sokli that intruded before, during, and after the carbonatite, implies an important role for this magma type in the formation of the Sokli complex. Relatively low LREE enrichment, compared to other carbonatites in the world, appears to be a trademark of carbonatites derived from aillikite magmas (Hornig-Kjarsgaard, 1998). We suggest that the Sokli intrusion likely started as dominantly olivine and clinopyroxene cumulates, quite similar to what is seen at the Kovdor and Vuorijärvi complexes, from ascending and pooling aillikite magmas.

The Tulppio olivinite quite probably represents a remnant from that stage, but different interpretations have been presented (see Maier et al., 2013, who interpreted the Tulppio olivine rich rocks as being of komatiite affinity). Carbonatite magma, derived from an aillikite parental liquid, then intruded into the system, first forming a central core as in the ideal model shown earlier in Fig. 4.2.1. However, in the case of Sokli, an unprecedented volume of carbonatite magma continued to ascend into the system, causing pervasive carbonate overprinting of all previously formed rocks, including the magma chamber cumulates and the first intruded carbonatites and phoscorites. Subsequent erosion has brought these magma chamber rocks to the surface. This evidence suggests that the present level of erosion at Sokli is probably no more than a kilometer below the now-eroded volcanic edifice.

ORE DEPOSITS

WEATHERED CAP

All of the Sokli area is covered by weathered bedrock of variable thickness. It is likely that this thick layer of weathered material has been preserved due to the fact that Sokli is located in a glacial ice divide, the locus of least erosion under a large continental ice sheet.

The most important mineralogical changes associated with weathering are the partial dissolution of carbonates, local replacement of phlogopite by vermiculite, intense alteration of olivine, the partial replacement of magnetite by hematite (martitization), alteration of pyrochlore, and the total removal of sulfides.

ORE TYPES

The phosphorus ore developed from the carbonatite and underwent complex weathering, leaching, recrystallization, and lithification processes (Nuutilainen, 1973), driven by the prevailing tropical climatic conditions (Finland lay on the equator ~400 Ma ago). The end product is a reddish brown layer, averaging 26 m in thickness, which varies from solid rock to a soil in which the carbonate has been totally dissolved. Apatite, magnetite, hydrated mica, and patchy pyrochlore occur as restite minerals. Recrystallized phases include francolite (carbonate-fluorapatite), goethite, and manganese oxides (Vartiainen et al., 1990). Owing to this process, the P_2O_5 values have been elevated from the original 4–5 wt% to up to 30 wt%.

There are three main types of residual phosphorus ore at Sokli: lateritic phosphate ore, silicate-apatite ore, and apatite residue on the carbonatite ring dikes intruded into the region of fenites outside the carbonatite (Vartiainen, 1989). The lateritic ore is located above the magmatic carbonatite, while the silicate-apatite ore is located above the transition-zone rocks that contain significantly more silicate minerals (and thus silica; see Table 4.2.2).

GEOPHYSICAL MAPPING OF ORE TYPES

From the aeroradiometric data (Fig. 4.2.7), it is apparent that the carbonatite contains elevated levels of thorium and uranium relative to the surrounding country rocks, whereas it is depleted in potassium, consistent with the geochemistry of the rocks. In the overburden overlying the complex, thorium and uranium are adsorbed onto iron oxides. In detail, thorium concentrations in the overburden over the transition zone and well into the fenite zone are relatively higher than uranium. This is due to the greater extent of alteration of the overburden above the magmatic and metasomatic carbonatite zones, and the greater leaching of thorium downward. The niobium-rich mineral deposits have a high concentration of both uranium and thorium in the middle of the massif, whereas potassium is enriched along the outer edge of the massif.

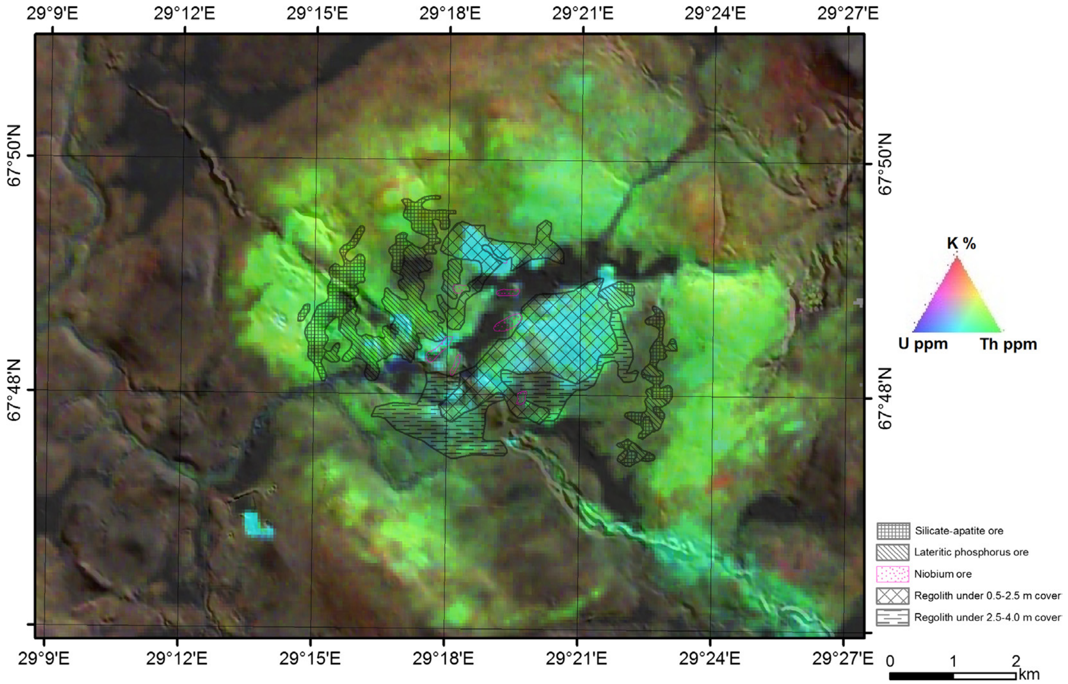

FIGURE 4.2.7 Aeroradiometric map of the Sokli complex overlain with the various surface ore types.

Water attenuates gamma rays significantly and, therefore, wet areas appear as black in the map.

The carbonatite contains abundant magnetite, which affects the negative response to the low-frequency AEM data. The reddish colors in Fig. 4.2.8(A) indicate rock units rich in magnetite, where the magnetic susceptibility is high and the electrical conductivity is low. This negative AEM response outlines the carbonatite core well. The innermost core also has a higher concentration of thorium and uranium so that the highest values are correlated with the lowest AEM-negative response (Fig. 4.2.7). The negative AEM response was roughly divided into two categories, which are thought to result from grain size variation of magnetite causing variation in the magnetic susceptibility (Fig. 4.2.8(A)). The silicate-apatite ore deposits are located in the surrounding weathered transition zone and they follow high-frequency conductivity anomalies represented with bluish colors in Fig. 4.2.8(B).

ORE RESERVE ESTIMATES

Vartiainen (1989) reported the ore reserves of the various residual phosphate ore types at Sokli to be approximately 110 Mt in total, at a P_2O_5 content of 16.5%. In the environmental impact statement prepared for Yara International ASA (Pöyry Environment Oy, 2009), the reserves reported are very similar to the earlier estimates, and are broken down by ore type in Table 4.2.3.

Ores based on the weathered crust of the carbonatite (regolith) were discussed by Vartiainen (1989) with an ore reserve estimate of ~200 Mt at a grade of 4.5% P_2O_5. The Pöryr EIS (Pöyry Environment

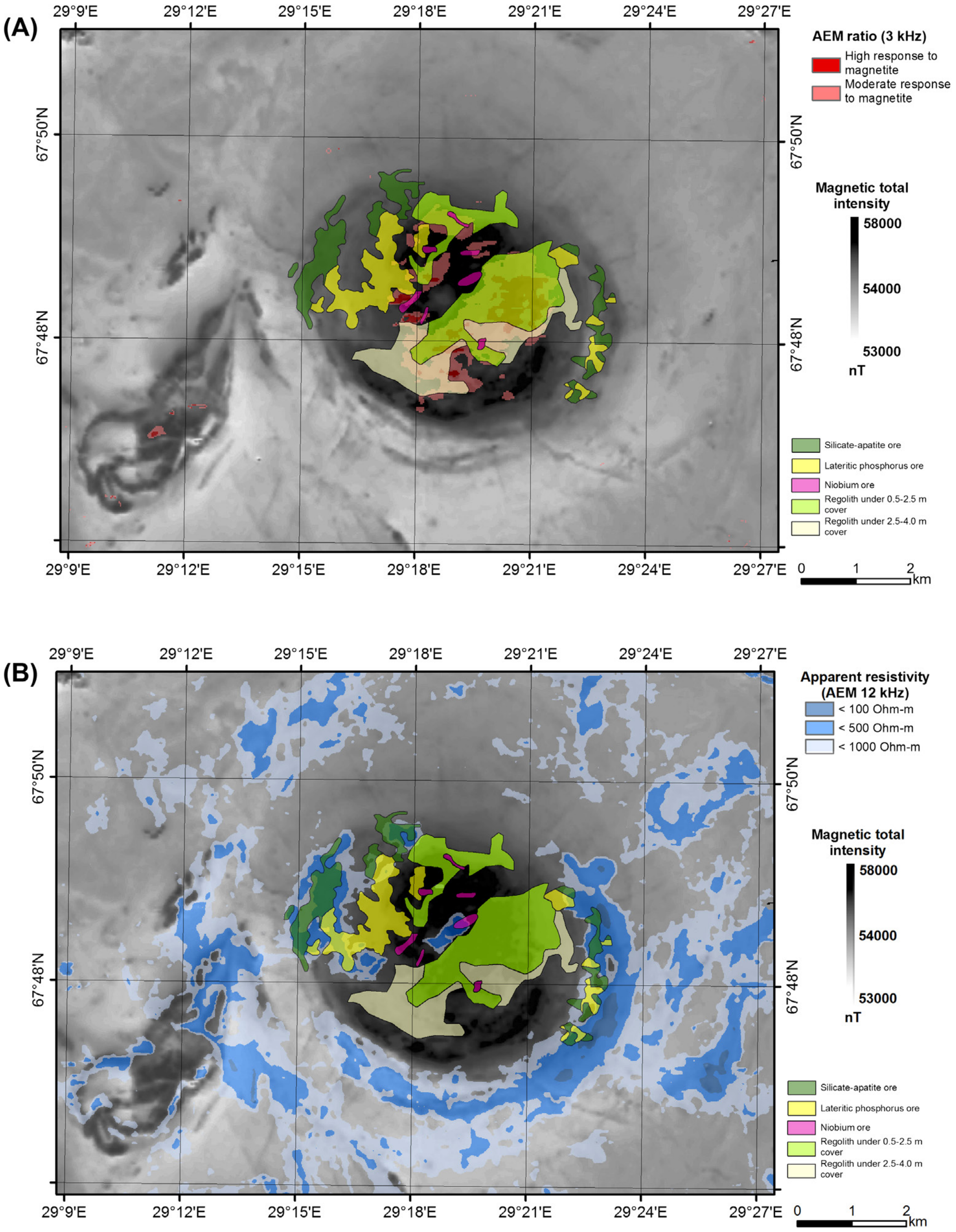

FIGURE 4.2.8 (A) Combined apparent resistivity and classified AEM ratio image compared to location of the various surface ore types. (B) Classified apparent resistivity compared to location of the various surface ore types.

Table 4.2.3 Sokli ore reserves by type

	Amount (Mt)	P_2O_5 wt%
Lateritic ore	36.7	18.7
Silicate-apatite ore	19.3	11.0
Other phosphorus ore	4.4	10.9
Ores in weathered rock	53.1	14.1
Subtotal/average	113.6	14.9
Regolith ores	75.2	5.6
Nb ores	1.9	6.7
Total/average	190.6	11.2

Source: *From Pöyry (2009), a JORC compliant report.*

Oy, 2009) puts the regolith ore reserves at 75 Mt by limiting the reserve to areas under the thinnest overburden, in the Kaulusrova area, with a grade of 5.6 wt% P_2O_5, and Nb content 0.2 wt% (Table 4.2.3). Other ores include the niobium ore, localized within several small areas in the carbonatite core area (see Fig. 4.2.8A) with a grade of 6.7 wt% P_2O_5, and Nb content 0.6 wt%. The grade of the unweathered carbonatite is on average 3.5% P_2O_5, with huge resources given the size of the complex. However, on a global scale, this is very low-grade ore.

ONGOING MINE PREPARATION

Yara International ASA is presently going through the processes necessary for establishing a phosphorous mine at Sokli. Commissioning an environmental impact assessment, completing further definition drilling, and spending a large effort negotiating with the government of Finland and the local population about acceptable plans for a new phosphorus mine are all activities currently underway or recently completed. Mine development plans are proceeding, and CTS Engtec reported completion of the definitive feasibility study for the mine in October 2013. As of this writing the mine decision is still pending.

SUMMARY

1. Sokli is a member of the Devonian Kola alkaline province. At the early magmatic stage it may have resembled the Kovdor and Vuorijärvi complexes in terms of rock types, zoning, and general layout. However, at Sokli, the later carbonatite magma overprinted the early silicate cumulates to such an extent that the latter are now rare, and studying them is difficult. The Tulppio olivinite, if proven to be related to the same magma system, may be the only real remnant from these early stages, and deserves further scrutiny.
2. Magnetic properties of the complex are distinct for each of the rock types described by Vartiainen (1980). Nevertheless, there has not been sufficient study of the metasomatic carbonatites, and particularly the transition-zone rocks, to fully illuminate the details of the processes by which they formed, including time sequencing and the geochemical mass balance. The

geophysical properties of these rocks can help map the distribution of rock types for these calculations.

3. Research by Lee (2002 and subsequent papers) concentrated on the magmatic carbonatites and showed quite convincingly how the phoscorite-carbonatite conjugate pairs were formed, documented both in terms of mineral and whole-rock chemistry. Valuable information remains to be gleaned from this extensive geochemical database.
4. Textures consistent with immiscibility, although rare, are known from a number of the KAP carbonatites, and although this process was almost certainly active at Sokli, modern methods of investigation have not been carried out on these spectacular samples.
5. Aillikite dikes were intruded throughout the development of the Sokli complex, and although it is difficult to prove, evidence including moderate REE enrichment, and the relatively high K_2O contents of the Sokli carbonatites point toward some type of aillikite magma as parental to the system.
6. The ore deposit is composed mostly of laterized materials at the top of the complex. The bulk of the ore is derived from weathering of the metasomatic carbonatite and the transition-zone rocks. It is an interesting observation that the rocks formed by metasomatism apparently have higher average P_2O_5 contents than the magmatic carbonatite core.
7. Geophysical mapping of ore deposit types is best accomplished with resistivity measurements at high frequency that show the strongest response to near surface, conductive features.
8. The Sokli ore reserves of “soft-rock” phosphate-rich materials are about 114 Mt with 15 wt% P_2O_5, with an additional approximately 75 Mt of weathered bedrock ore with about 5.6 wt% P_2O_5.

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