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Geological Characteristics of the Sokli Carbonatite Complex, Finland

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Abstract

The characteristic features of the Sokli carbonatite complex are given by describing the geology, structure, and mode of emplacement of the complex. Four units are discernible in the carbonatite complex surrounded by a large fenite aureole: (1) the magmatic core, which is thought to have formed in five stages; (2) the metacarbonatite area, whose rocks seem to have been generated mainly through the action of metasomatic processes; (3) the metaphoscorite zone, in which the primary rocks, i.e., the magnetite-bearing olivinites and pyroxenites, have altered into metaphoscorites; and (4) a disrupted transition zone between (2) and (3) and the surrounding fenites. Here metasomatic amphibole rocks, mica amphibole rocks, and metasilicosövites predominate. In structure the complex is thought to be a downward-tapering cone with a magmatic core.

Studies are still underway; hence, the ores and mineral occurrences associated with the complex are only briefly described. The weathered surficial parts of the complex consist of apatite-francolite regoliths, hydromica-apatite residues, and, in the fenite area, apatite residue. The U-Ta-pyrochlore mineralization and apatite-magnetite occurrences in the fresh rock are described; all seem to have a geologic control within the complex.

The position of the Sokli complex in the Kola alkaline rock province is discussed. The conclusion is reached that its emplacement was controlled mainly by the long, active Kandalaksha deep fracture.

Introduction

THE carbonatite complex at Sokli in eastern Finnish Lapland (Fig. 9) was discovered by airborne geophysical survey carried out by the Mining and Steel Company of Rautaruukki Oy. Exploration was centered on weathered phosphorus ores and complicated pyrochlore mineralization in fresh rock. The carbonatite is covered by glacial drift 0.5 to 60 m thick (Fig. 1), and hence the main investigation methods were geophysical survey and geochemical sampling. An area of 50 km^2 was covered by airborne geophysical survey, and about 30 km^2, comprising the carbonatite complex and part of the fenite aureole, was studied systematically by ground geophysics including magnetic, gravimetric, galvanic, electric, electromagnetic, radiometric, and emanometric methods. Also shallow seismic sounding, vertical seismic sounding, and deep seismic sounding were carried out along 72, 10, and 33 profile kilometers, respectively, in addition to some special surveys.

In addition to Rautaruukki Oy, numbers of other organizations also took part in the exploration of Sokli: these included, the Geological Survey of Finland, the University of Oulu, the University of Helsinki, the Helsinki University of Technology, Suomen Malmi Oy (Helsinki), Georesearch Company (Helsinki), the Leningrad Mining Institute (Leningrad), the Geological Department, Ministry of Geology of the U.S.S.R. (Leningrad), the British Museum (Natural History) (London), and the Institute of Geological Sciences (London).

The environment of the Sokli complex is mainly composed of Archean gneisses, gneissic granites, amphibolites, and ultramafic rocks. The Sokli carbonatite is a part of the alkaline rock province of Kola (Fig. 9). According to Heinrich's (1966) classification, the Sokli carbonatite complex belongs to the carbonatite group, which is "not directly associated with any alkalic complex" and is a rather rare type of carbonatite complex.

The fenite aureole has been described in detail by Vartiainen and Woolley (1976). According to the same authors (1974), the age of the carbonatite ranges from 334 to 378 m.y. Papers dealing with the complex include a brief account by Paarma (1970), interpretations of air photographs (Paarma et al., 1968, 1977), the results of geochemical survey reviewed by Nuutilainen (1973), heavy mineral prospecting of stream beds by Vartiainen (1976), and a description of sulfur isotopes of magmatic carbonatites by Mäkelä and Vartiainen (1978).

In this paper the geological setting, structure, and mode of emplacement of the complex is briefly described, an account of mineral deposits in the complex is given, and the structural position of the Sokli complex in the alkaline rock province of Kola is discussed.

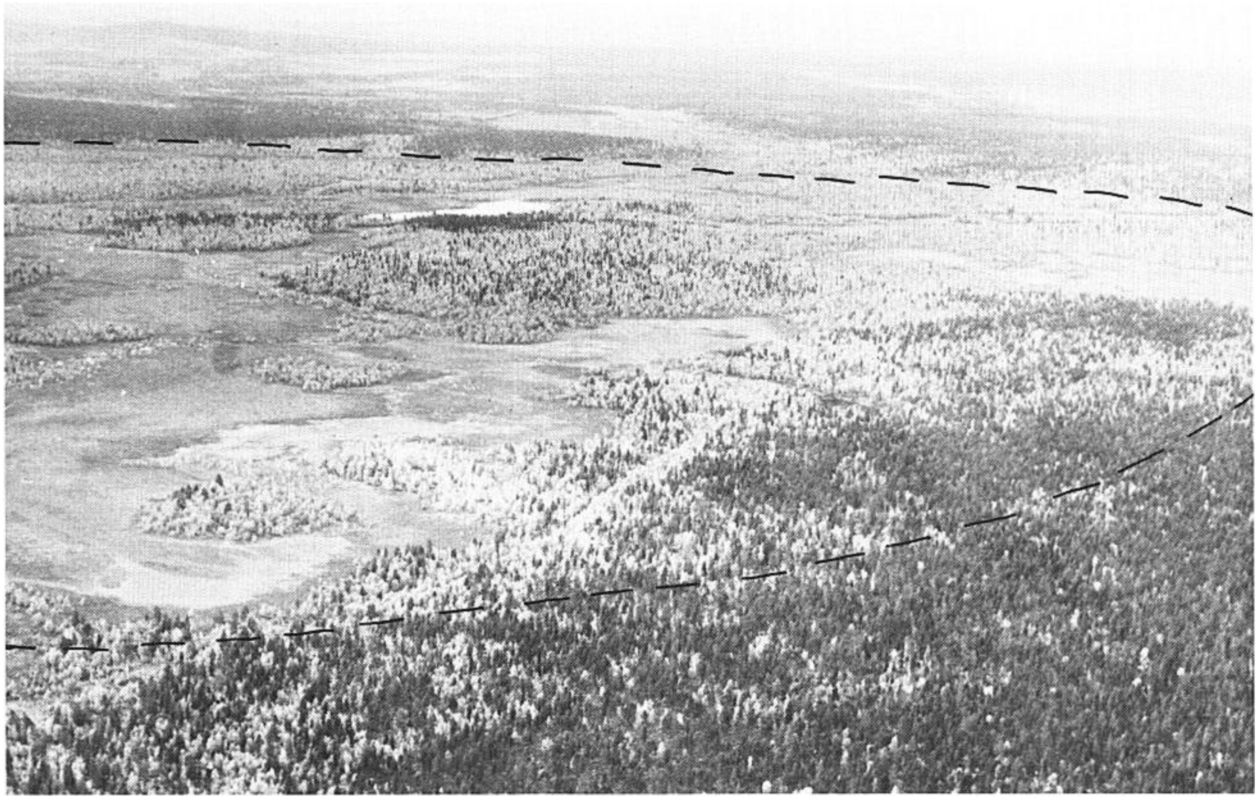

FIG. 1. Aerial view southwestward showing the western part of the Sokli complex. Broken line marks the contact between the carbonatite body and the fenite aureole. Light birches prevail on the carbonatite body and dark pines on the fenite aureole. Swamps are widely spread. Length of the lake in the middle is 0.5 km.

Geological Setting, Structure, and Mode of Emplacement of the Complex

The carbonatite body, which appears oval on the map (Fig. 2), covers an area of about 20 km^2. Topographically it forms a depression surrounded by hills of fenite aureole (Fig. 1). The upper part of the carbonatite body is weathered down to a depth of 10 to 100 m. Intensive drilling and geophysics, especially seismic soundings, have provided a good basis for establishing the structure of the Sokli complex. On the geological map the complex can be divided into five geological units (Fig. 2): (1) magmatic core, (2) horseshoe-shaped metacarbonatite area, (3) metaphoscorite zone, (4) collarlike transition zone between fenite and metacarbonatite area, and (5) fenite aureole. Calcitic, dolomitic, and numerous kimberlitic dikes and veins form an irregular stockwork, but they cannot be mapped on the scale used.

The geological interpretation (Fig. 3) of the structure of the complex is based on gravimetric data and deep seismic soundings. Gravimetric interpretation, corroborated by geological data, indicates that the complex plunges southward. The southern part of the fenite aureole is more intensely fenitized, and carbonatite dikes and veins are more numerous than on the northern side. The Sokli complex is cone-shaped.

The nomenclature by von Eckermann (1948) has been adopted here for magmatic carbonatites rich in calcite (sövite) or dolomite (rauhaugite). As suggested by Verwoerd (1967), the name metacarbonatite has been used for rocks which are the products of "a replacement process by which preexisting rocks of diverse compositions are wholly or partially transformed to carbonate or carbonate-silicate rocks" (Verwoerd, 1967, p. 13). According to Russell et al., (1954), carbonate-poor rocks mainly consisting of magnetite, apatite, olivine (mostly altered), and micas are called phoscorite if the rocks are of magmatic origin, but metaphoscorite if the metasomatic processes have produced similar mineral compositions.

Magmatic core

The magmatic carbonatite forms the core of the cone-shaped complex. On the present erosion level

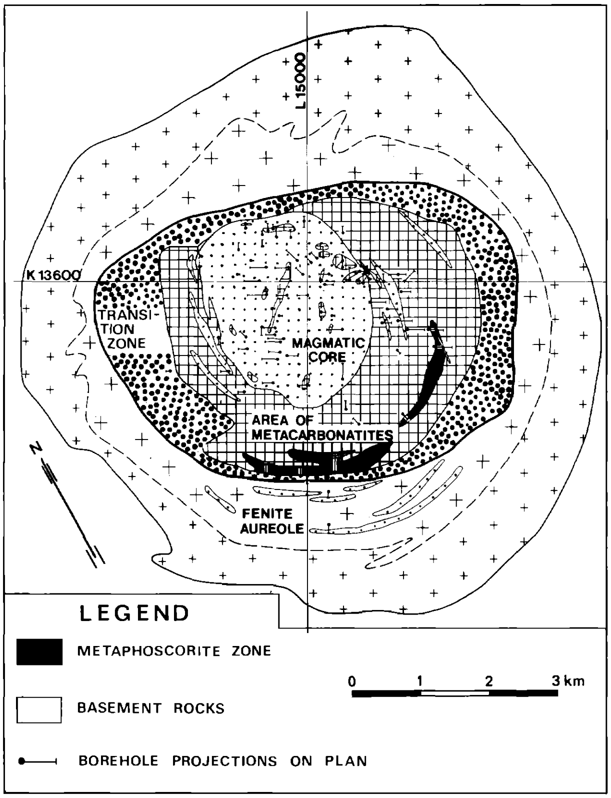

FIG. 2. Geologic map of the solid rock surface of the Sokli carbonatite complex.

the diameter of the core is 2.5 km. Deep seismic reflections suggest that at the depth of 5 km the diameter is about 1 km. Seismic reflections in the core at depths of 2.5 and 4 km are possibly caused by fragments of metacarbonatite and fenite wall rocks, although they may also indicate heterogeneity in the central core proper. The area of the core on the surface is 5 km^2. It can be distinguished from its surroundings by magnetic and gravimetric anomalies, and by acoustic properties. The velocities of the solid rock are higher, and the seismic character is by and large more heterogeneous than in the environment (Fig. 5). The contacts of the core with the metacarbonatite area are partly intrusive and partly gradational breccia type. Fragments of metacarbonatites, amphibole rocks, and mica-amphibole rocks, from some centimeters to hundreds of meters in size, indicate magmatic stoping (Fig. 3). The internal structure of the core is very highly complicated and composite.

Magmatic carbonatites have developed successively and pulsatively in five stages; first, by direct crystallization from carbonatite magma and later through hydrothermal processes. The evolutionary succession of the magmatic carbonatites is tentatively as follows:

Stage	Process	Rocks
I	Segregation from carbonatite magma	Medium to coarse-grained, massive phoscorite; occur as fragments in sövite and silicosövite (Fig. 4A)
II	Slow intrusion and crystallization from carbonatite magma	Fine- to medium-grained massive sövite and silicosövite; occurs as bodies, lenses, and fragments, also assimilated by younger rocks (Fig. 4a and B)
III	Hydrothermal activity: alteration of minerals, deposition of sulfide, apatite, dolomite, tremolite, pyrochlore	Host rocks, mainly phoscorite of stage I and silicosövites of stage II; also metacarbonatites
IV	Rapid intrusions of mobile fluidal magma	Fine- to medium-grained, banded dolomite-bearing sövite and silicosövite, and rauhaugite, which are distributed irregularly throughout the core
V	Crystallization of residual melt of carbonatite magma	Medium- to coarse-grained porous veins containing dolomite, Ln-, and Sr-carbonates, barite, etc., in cavities; occur mostly in the vicinity of fracture zones

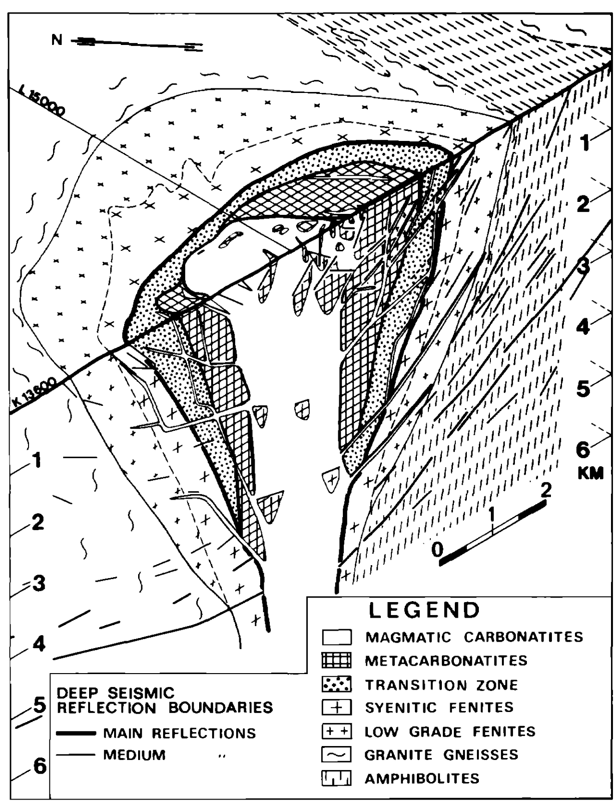

FIG. 3. Orthogonal-isometric structural model of the Sokli carbonatite complex.

Table 1 shows the mineralogical compositions of magmatic carbonatites.

Shallow seismic soundings revealed the central core as the most fractured part of the carbonatite body. The seismic map (Fig. 5) depicts the strikes of fracture zones. Vertical seismic profiles prove that the fracturing reaches a depth of at least 0.5 km. The concentration of fractures in the central core indicates cooling and contraction of the magmatic rocks. The fracture zones are characterized by intense breccia structures. Numerous dikes and veins of several stages show renewed activities in the fracture zones. The mineral banding and rock units of the central magmatic core mainly display vertical structures.

Metacarbonatite area

The metacarbonatites occupy an area fairly distinctly outlined against the central core, whereas the contacts with the surrounding transition zone are gradual. The main rock types of the metacarbonatites are metasilicosövites, which were formed by metasomatic replacement from unidentifiable rocks and by CO_2-rich fluids derived from carbonatite magma. On a small scale the rocks show magmatic carbonatite injections. Banded structures are typical of the metasilicosövites (Fig. 4C). The metaphoscorites form a fairly uniform zone in the southeastern part of the area (Fig. 2); elsewhere they occur as fragments in the metasilicosövites. The primary rock types of the metaphoscorites can sometimes be identified as magnetite-bearing olivinites and pyroxenites in which the primary minerals are replaced by amphibole, mica, and carbonate. There are, however, also mica-amphibole and amphibole rocks that seem to have obtained magnetite and apatite, and thus to have achieved the mineral assemblage of phoscorite. Table 1 shows the mineralogical compositions of metacarbonatites.

The evolution of the metacarbonatite area was as follows:

1. The original rocks were ultrabasic magnetite-bearing olivinites and pyroxenites or mica-amphibole and amphibole rocks formed earlier by metasomatic processes from fenites and amphibolites.
2. The metaphoscorites developed from the ultrabasic rocks by metasomatic formation of amphibole, mica, apatite, and carbonate. Likewise, some of the metaphoscorites were generated from mica-amphibole and amphibole rocks by formation of magnetite, apatite, mica, and carbonate.
3. From earlier rocks high grade CO_2-metasomatism produced metasilicosövites, which mobilized and brecciated the metaphoscorites, especially in the inner part of the area.

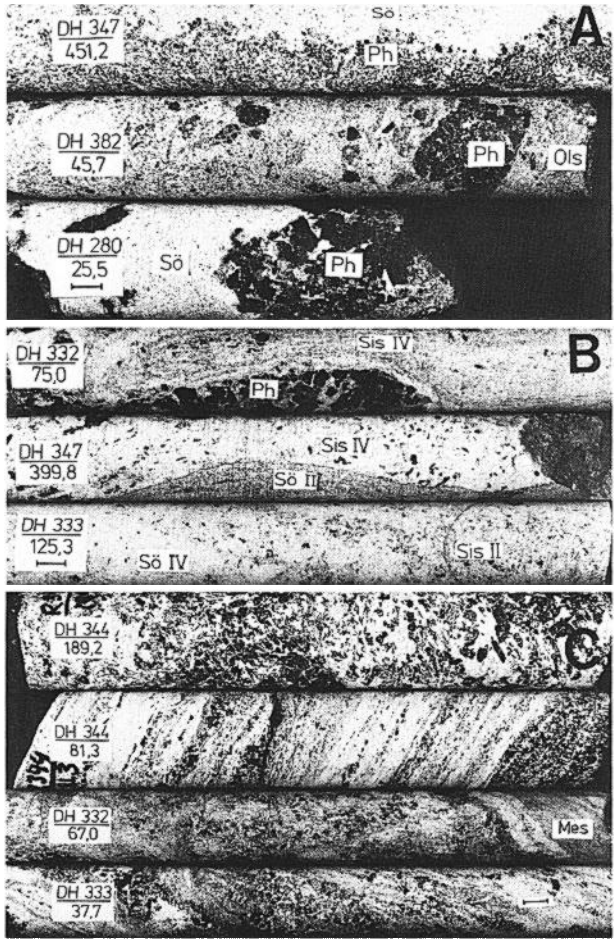

FIG. 4. A. Contact relationships between stage I phoscorite and stage II sövitic rocks. DH 347/451.2, irregular contact of fine to medium-grained phoscorite (Ph) with olivine-bearing sövite (Sö). DH 382/45.7, medium-grained phoscorite (Ph) fragments in olivine-sövite (Sö). DH 280/25.5, coarse-grained, partially altered phoscorite fragment (Ph) in sövite (Sö); scale line, 1 cm.

B. Relationships of stage IV sövites and silicosövites to earlier magmatic rocks. DH 332/75.0, dolomitized stage III phoscorite fragment (Ph) in stage IV silicosövite (Sis IV); note flowlike structure in silicosövite. DH 347/399.8, sharp contact of stage II sövite (Sö II) with stage IV silicosövite (Sis IV). DH 333/125.3, spotted texture due to assimilation of stage II silicosövite (Sis II) by stage IV (Sö IV); scale line, 1 cm.

C. Typical metasilicosövites of the metacarbonatite area. DH 344/189.2, massive, medium-grained amphibole-sövite; medium green amphibole laths are discerned against white calcite; magnetite (M) occurs as strongly resorbed, mealy grains. DH 344/81.3, distinct banding with highly variable mineral compositions in colored bands; calcite/dolomite ratios vary in white carbonate bands; some of them may be magmatic injections. DH 332/67.0, spotted texture developed by magmatic calcitization of rock cut by banded metasilicosövites (Mes). DH 333/3.7, irregularly banded rock. Texture is developed by mobilization and uneven distribution of carbonate; scale line, 1 cm.

4. Magmatic carbonatite dikes intruded the metasilicosövites.

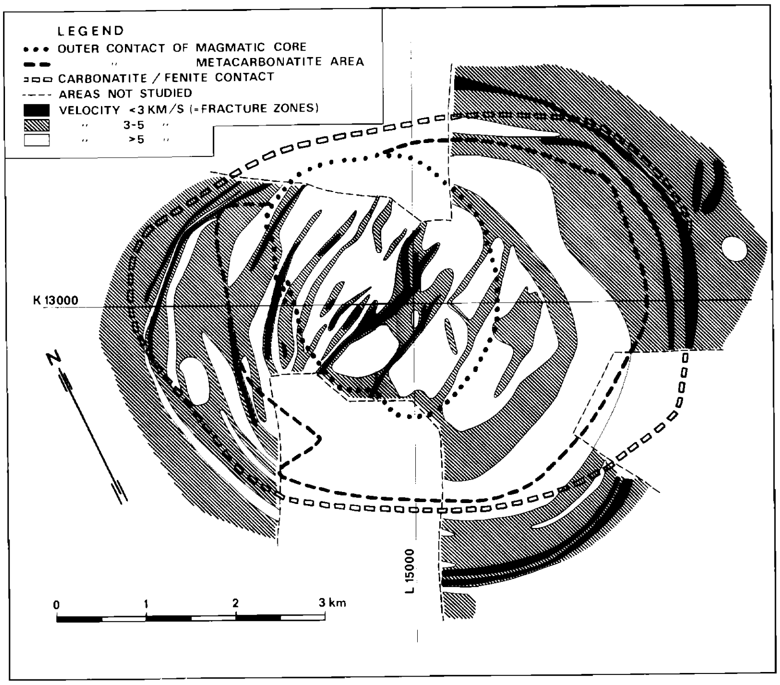

FIG. 5. Seismic velocities on the hard rock surface of the Sokli carbonatite complex.

Owing to metasomatic processes the metacarbonatites are plastic rocks. They are, therefore, not so intensely fractured as the carbonatite core (Fig. 5), whose somewhat regular concentric and conical fractures demark the metacarbonatite area. These fractures offered channels for the magmatic carbonatite which occurs as ring-, cone-shaped, and irregularly trending dikes of variable size (Fig. 2). The deep seismic reflections in the area are possibly due to these magmatic carbonatite dikes (Fig. 3).

Metaphoscorite zone

An arcuate, partly broken zone of metaphoscorite, occurs between the metacarbonatite area and the transition zone. The zone is 4 km long, 100 to 300 m wide, and the deepest drilling sections reach a depth of 200 m. Metaphoscorite occurs in the zone as fragments ranging in size from some centimeters to tens of meters. The zone was initially composed of ultrabasic rocks: magnetite-bearing olivinites (partly of pegmatoidal grain size), pyroxenites, and amphibole rocks. Originally, the zone was possibly continuous but later movements combined with carbonatite emplacement fragmented it, and mobilized metasilicosövites as well as, to a lesser extent, magmatic carbonatite injections brecciated the zone. During these processes the initial rocks were converted metasomatically into metaphoscorites. Primary olivine

TABLE 1. Mineralogical Compositions of Carbonatites

Minerals	Magmatic carbonatite stages				Metacarbonatites					
	I	II	III	IV	Metaphoscorites			Metasilicosövites		
Carbonates	10.0	83.0	9.0	84.0	15.0	40	7.5	50.0	66.0	70
Olivine	8.0	1.0	3.0							
Clinohumite	3.0		8.0							
Serpentine	6.0		0.5		25.0					
Pyroxene						9				
Tremolite	1.0		1.0		15.0				5.0	5
Hornblende						30	20.0	15.0		
Phlogopite	7.0	3.5					32.0	24.0		10
Tetraferriphlog.	2.0	0.1	27.0	4.0	10.0				10.0	
Apatite	26.0	7.5	29.0	8.0	4.0	16	24.0	8.5	15.0	9
Magnetite	33.0	4.0	17.0	3.0	30.0	4	14.0	1.7	4.0	6
Sulfides	3.5	0.7	5.0	0.5			2.0	0.5		
Pyrochlore	0.3	0.1	0.4	0.5						
Baddeleyite	0.2	0.1	0.1							
Zircon					1.0	1	0.5	0.3		

and pyroxene occur occasionally as relicts, but magnetite is well preserved. On the other hand, the amphibole rocks have achieved phoscoritic mineral composition by metasomatic formation of magnetite. Variations in the composition of metasomatic fluids, initial rocks, and deformative effects have produced very diverse mineral compositions. This variation in composition is gradational. Metasomatism has generated apatite, phologopite, and carbonate. Zircon, a mineral typical of metaphoscorites, is also possibly of metasomatic origin.

The disrupted transition zone between the fenite and the metacarbonatite area/metaphoscorite zones

Roughly between the carbonatite body and the fenite aureole there is a conspicuous, deformed zone, circular in shape and 100 to 300 m wide, which can be recognized as a gravimetric minimum, very low frequency anomaly, and low seismic velocity zone (Fig. 5). The zone is dominantly composed of fenites which are intensely brecciated, fractured, and in part weathered down to a depth of over 100 m. The zone also contains carbonatite veins and dikes. It is possible that the upward movement of the complex has gradually developed the deformed zone. The same movements have also influenced the transition zone, although the abundance of carbonate solutions and fluids has maintained the rocks in a more plastic state; thus tectonic effects appear as banding, flow structures, and shear planes and not as intense brecciation and fracture zones as in the more rigid fenites.

The transition zone, which forms a girdle between the fenite aureole and the metacarbonatite area, tapers downward like a wedge (Fig. 3), but on the surface its width varies. The contacts of this zone with the fenites are of intrusive breccia type due to mobilization and movement of the carbonatite body in relation to the fenites. The contacts with the metacarbonatite are gradational and obscure; and only in the southeastern part are these geological units clearly separated by the metaphoscorite zone (Fig. 3). In spite of the narrow magmatic carbonatite dikes the rocks of the transition zone can be shown to have developed metasomatically in two steps; the fenites and amphibolites were altered into mica-amphibole rocks, and these were then transformed into metasomatic silicosövites.

The internal structure of the transition zone is complicated. Fragments of fenites, and mica-amphibole and amphibole rocks, some centimeters to tens of meters in size, are embedded in altered, banded silicosövites. On a small scale, the contact relations between the metasomatic rocks are sharp or gradational, but the magmatic carbonatites display sharp contacts with the metasomatites throughout.

The fenite aureole

The petrography, mineralogy, and geochemistry of the fenite aureole have been described in detail by Vartiainen and Woolley (1976). The high-grade, syenitic fenitization extends up to 2 km south and southeast of the carbonatite contact, i.e., farther than was supposed earlier. Wide carbonatite ring dikes that occur in the same area have been traced for several kilometers by magnetic and very low frequency measurements. A phosphorus mineralization is associated with these dikes. The deposits have been enriched by weathering processes. The latest data permit the fenite aureole to be divided on the map into syenitic and low-grade fenite areas (Figs. 2, 3). The contact relations of the fenite aureole with the carbonatite body have been discussed before. The contacts with the gneiss granite host rock are gradational and the incipient fenitization is only microscopically discernible. The boundary between syenitic and low-grade fenites is undulating. The degree of deformation varies in the fenite aureole. In places it is weak and only microscopically visible as bent, broken, and displaced twin lamellae in plagioclase, bent cleavages in biotite, and mortar texture. More intense deformation has produced fractures coated by dark alkali minerals (aegirine, Na-amphiboles). Intense fracturing can be seen outside the fenite aureole (Fig. 3), indicating that the tectonic impact of the complex extends for several kilometers beyond the complex. The fractures may be postfenitic but precarbonatitic or contemporaneous with carbonatite intrusion. The most intense fracture zones in the fenites are filled with carbonatite intrusions (Fig. 2). The original, foliated structure of the gneissic host rock is preserved in the low- and medium-grade fenites, whereas the syenitic fenites are totally recrystallized, massive rocks.

Mineral Deposits

The Sokli carbonatite complex contains several mineral occurrences which may be of economic importance, and which can be divided into two main types on the basis of their mode of occurrence. Phosphorus ores occur in the weathered upper part of the complex and pyrochlore and apatite-magnetite occurrences in the deeper parts of the massif. Geological studies on all these mineralizations are still underway, and only preliminary information can be given.

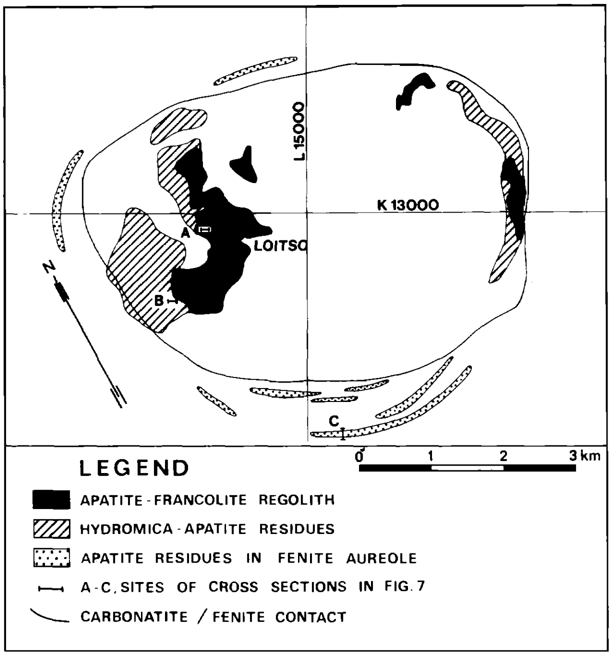

FIG. 6. Locations of some phosphate deposits in the Sokli complex.

Apatite-francolite regolith

The most important prospect explored to date in the Sokli area is an apatite-francolite regolith located in the western and eastern part of the carbonatite massif (Fig. 6). Francolite is secondary carbonate fluorapatite. The deposit is covered by an overburden of glacial debris (average thickness, 5 m) and underlain by weathered carbonatite crust. The thickness of the deposit varies, the maximum being 72 m and the average 25 m. Reserves, although not yet fully evaluated, are believed to be 80 to 100 million tons. About 80 to 90 percent of the volume of the deposit is beneath the ground-water table. The mechanical properties, and mineralogical and chemical composition of the regolith vary.

The color of the regolith varies from light to dark brown, being nearly black in the manganese-rich parts. The brown colors are due to fine-grained goethite. The deposit consists mainly of three fractions: slimes, <0.1 mm; silt/sand, 0.1 to 2 mm; and hard fragments, 2 to 1,000 mm in size. As a whole the regolith is a loose, wet, and ferruginous earthy-stony material, which is made up of a random mixture of all of these fractions (Fig. 7A). The density of the deposit is not more than 1.76.

The constituent minerals fall into two groups: residual primary minerals derived from carbonatites and secondary minerals of supergene origin:

Residual primary minerals		Secondary minerals
Apatite	Ilmenite	Francolite
Magnetite	Pyrochlore	Goethite
Amphiboles	Zircon	Siderite
Micas	Baddeleyite	Mn-oxides
Clinohumite	Niobozirconolite	Hematite
Dolomite	Rutile	Rhabdophane

The quantitites of apatite and francolite are nearly equal, and together they comprise about 50 percent of the volume. Apatite occurs as separate or aggregated rounded grains, or rounded, elongated prismatic crystals (0.1 to 1.0 mm) which are usually water clear but may be coated by iron oxides (Fig. 8B). Francolite has crystallized as several generations, and it occurs mainly in hard, lithified phosphorites. During the first stage, francolite crystallized simultaneously with geothite as microcrystalline intergrowths which cemented the primary minerals. The earliest lithified generation occurs as fragments in a later stage francolite-rich matrix which is composed of finely columnar to fibrous radial growths in which

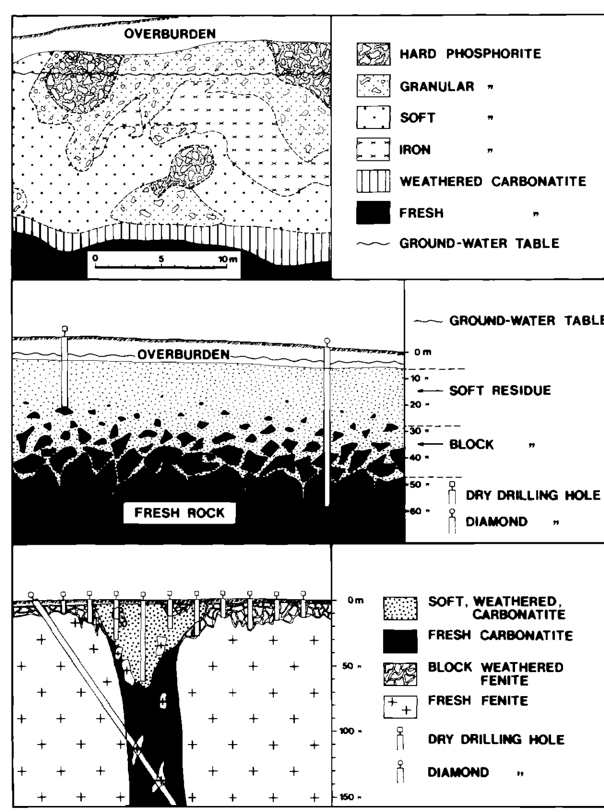

FIG. 7. Cross sections of some phosphate deposits in the Sokli complex. A, apatite-francolite regolith; B, hydromica-apatite residue; and C, apatite residue in the fenite aureole.

the individual francolite grains are less than 0.02 mm (Fig. 8B). This generation constitutes the bulk of the hard and granular ore types. The third francolite generation was precipitated out of the last phosphorus-bearing solutions that circulated in fissures, cracks, and cavities of lithified phosphorites. Brushlike francolite, which occurs as several layers in the cavities, varies in color from pale brown or pink to milk-white. The colored varieties contain abundant dustlike inclusions.

The hydromica-apatite residues

The hydromica-apatite residual deposits are located in the margin of the carbonatite massif within the distributed transition zone (Fig. 6). These deposits were formed as a result of the weathering of carbonates and the hydration of micas in the underlying rocks, such as mica-amphibole and apatite-bearing amphibole rocks, and metasilicosövites. Practically the only secondary minerals deposited were manganese oxide nodules. The phosphorus-poor fenites and sövites underwent weathering in the same areas and have turned into soft regoliths.

The hydromica-apatite residues are dark green-brown in color. Drilling and seismic sounding have demonstrated that within the area occupied by these residues the deposits invariably have an intensely weathered soft upper layer and a partly weathered lower blocky formation (Fig. 7B). The latter is composed of partly weathered or almost fresh and hard fragments, 0.1 to 2 m in diameter, and of powdered weathering products that fill the spaces between the fragments (Fig. 7B). Only the upper soft weathered rock is interesting in terms of phosphorus ore.

The hydromica-apatite residues are more simple in composition than the apatite-francolite-regoliths; their apatite content is lower, 30 to 35 percent at the most, and secondary minerals are sparse. An inventory of the hydromica-apatite residues is being made, and mineralogical studies are underway.

The apatite residues in the fenite aureole

As a result of detailed exploration, apatite occurrences have also been found in the southern parts of the fenite aureole (Fig. 6). Preliminary studies indicate that they are associated with the discontinuous arcuate carbonatite veins that conform with the shape of the carbonatite massif. Apatite is enriched in the upper parts as a result of intense weathering. The weathering of the carbonatites is largely restricted to the dissolution of carbonates. In fresh rock, apatite amounts to 5 to 8 percent. On account of weathering, however, the abundance of apatite has increased to 20 to 50 percent, with hardly any secondary minerals

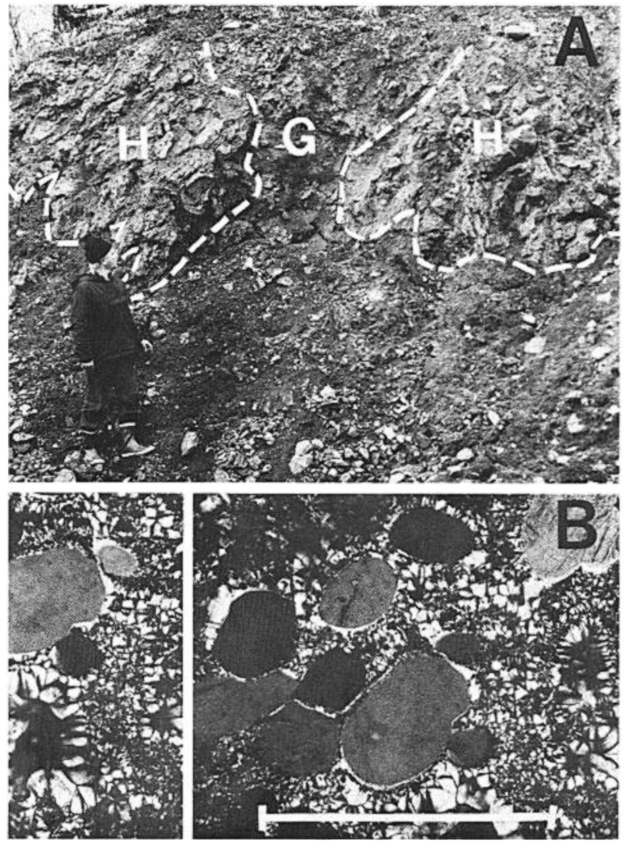

FIG. 8. A. Hard and granular apatite-francolite regolith in test pit 4. B. Lithified apatite-francolite regolith. Subround apatite grains are embedded in fine-grained francolite matrix. Crossed polarizers; drill hole 23 at 25.5 m; scale line, 1.0 mm.

formed. The quantity of apatite residues is not likely to be very high, because even though the formations are several kilometers long they are narrow, and generally only 10 to 20 m thick. The thickest deposit encountered so far is 70 m deep (Fig. 7C).

Mineralizations in carbonatites

The overburden on the carbonatite massif and the thick weathering crust on the carbonatite have made it difficult to explore the fresh rock. Mineral occurrences in the fresh rock have been found not only by weathered crust studies but also by magnetic, gravimetric, very low frequency, radioactivity, and seismic surveys. Humus and peat geochemical investigations are underway to localize new ore showings. On account of the great number of showings and the large size of the area favorable for the occurrence of ores, the diamond coring employed has been on a trial basis. No ore showings have been submitted to inventory so far. Drill core and geophysical data made it possible to establish the internal geological control of the massif for the different ore mineralizations.

Pyrochlore mineralization with U-Ta enrichments

The U-Ta-pyrochlore mineralization is related only to magmatic carbonatites, primarily to the rocks of the two first stages. Therefore, the mineralization occurs mainly within the magmatic core, where it forms low-grade zones of diverse rock types. Fission track studies on the distribution of uranium have shown that uranium is almost completely incorporated in pyrochlore (Rehtijärvi 1978, pers. commun.). It is highly probable that the same also holds for tantalum and niobium. The bulk of the U-Ta-pyrochlore occurs in the phoscorites of the first stage and in the olivine sövites of the second stage. In thin section this mineral is orange-brown in color and typically corroded along its margins; its grain size fluctuates between 0.2 and 0.5 mm.

Pyrochlore-baddeleyite intergrowths are common. Preliminary electron microprobe studies show that the U-Ta content varies considerably from one grain to the other, even within a single polished thin section. In some spots, the highest UO_2 contents reach 20 to 25 percent, although typical abundances are between 1 and 10 percent. The tantalum contents are slightly lower than that of uranium. The U-Ta-Nb zones contain apatite and magnetite as well as minor baddeleyite. The magnetite exhibits rather high titanium and zinc contents.

Pyrochlore mineralization with thorium

This mineralization seems to be related to hydrothermal activity, which is considered as the third stage in the evolution of the magmatic carbonatites, and to the magmatic carbonatites of the fourth stage that were intruded during or after the third stage. To date, the most promising mineralization, in which the Nb_2O_5 content averages 0.4 to 0.6 percent, is closely associated with the fractures in the core that were identified by seismic sounding. These fractures are considered to be genetically related to the pyrochlore mineralization and to have controlled its deposition. Several pyrochlore occurrences have been encountered within the core.

The host rocks of the Th-pyrochlore vary more in composition than do those of the U-Ta-pyrochlore. The richest Th-pyrochlore occurrences are encountered in intensely altered phoscorites. They occur in breccia fragments, from 0.1 to 10 m in size, in the carbonatites of the fourth stage. The silicosövites richest in apatite and tetraferriphlogopite are also richest in pyrochlore. The Th-pyrochlore occurrences are diluted by rocks that are practically devoid of pyrochlore, such as sövites, kimberlitic, dolomitic, and calcitic veins, and the dike rocks of the fifth. magmatic stage.

In thin section, the Th-pyrochlore varies from almost colorless to pink and orange. In the phoscoritic host rocks, some cores of the pale pyrochlore grains may be reddish-brown in color, indicating that when the phoscorites underwent hydrothermal alteration, possibly the primary U-Ta-pyrochlore altered into Th-pyrochlore. In texture the altered Th-pyrochlore is even more corroded and worn than the primary U-Ta-pyrochlore. Another bigger grained and euhedral pyrochlore is encountered in phoscorites and silicosövites and presumably represents a later hydrothermal Th-pyrochlore generation. In the silicosövites of the fourth intrusion stage the Th-pyrochlore is invariably euhedral and often intensely zonal. According to some analyses, the ThO_2 contents seem to vary between 1 and 7 percent, and the Nb_2O_5 contents from 50 to 62 percent.* The apatite, baddeleyite, and magnetite abundances are similar to those in the U-Ta-Nb zones.

The apatite-magnetite mineralization

The metaphoscorites in the metacarbonatite area, as well as the entire metaphoscorite zone (Fig. 2), have been studied as likely apatite-magnetite ores. It is probable that the majority of the metaphoscorites were primarily coarse grained magnetite-rich olivinites and pyroxenites which attained their present composition through metasomatic processes. The primary macrograined magnetite, of which grains 10 to 20 cm in diameter are still visible, was granulated and corroded in metasomatic and deformational processes and was replaced by other minerals. Therefore the magnetite abundance decreased from its original value, until, in the present metaphoscorites, it is mainly 15 to 30 percent.

The apatite in the metaphoscorite is partly primary and occurs as individual angular, prismatic, or subrounded grains or incoherent aggregates. Broken grains with abundant fractures are typical of the primary apatite generation. The apatite that was formed during metasomatism is less broken and the grains are more rounded. The metaphoscorite zone is the most coherent metaphoscorite formation. Nevertheless, it too is broken owing to the action of mobilized metasomatic silicosövites and the variety of magmatic dike rocks. Hence, the metaphoscorite zone has comparatively low magnetite and apatite abundance.

Discussion of the Structural Position of the Sokli Complex

Doig (1970) has described an extensive and complex rift system that extends from east Canada to

* According to the International Mineralogical Association (Hogarth, 1977), the two types of pyrochlore described above are largely pyrochlore (strictly so called), only a small proportion of the U-Ta-pyrochlore being true uranpyrochlore.

the Kola peninsula, and which is called the "North Atlantic alkaline igneous province." In this system the alkaline rocks of Kola have partly intruded along the margin of the Kandalaksha graben. The evidence for a rift valley system closely related in space and time with alkaline rocks and carbonatite in Canada and East Africa (Kumparapeli and Saull, 1966) is not as convincing in the alkaline rock province of Kola. According to Kukharenko (1967), the alkaline massifs of Kola, Finland, Sweden, and Norway are associated with a major fault which joins the Rhine graben and intercontinental Mediterranean rift belt. Paarma (1963) had earlier shown interest in the correlation between alkaline rocks and this zone of tectonic disturbance. Vartiainen and Woolley (1974) have noted the possibility that the "North Atlantic alkaline igneous province" is not a rift system but has a close temporal relationship with successive major orogenic events, and that these relationships can be explained in terms of a plate tectonic model. The Kola rocks belong to the intrusions of Caledonian-Appalachian age that ran in a relatively narrow zone on either side of the orogenic belt before continental drift started. Belyaev et al., (1976A) have suggested a ring and radial fault system for the emplacement of the massifs of central type in the Kola peninsula (Fig. 9). The structural system around the large magmatic center in the Khibina area was caused by internal tensions and high stresses. The carbonatite massifs are located at the intersections of the ring and radial faults (Fig. 9). According to Perevozchikova (1974) the numerous igneous ring complexes in the Eastern Fennoscandian shield intruded active deep fractures oriented east-west or nearly so, which joined deep fractures oriented north-south, northwest, and northeast (Fig. 9).

The tectonic structure that controls the location of the Sokli complex is the so-called Kandalaksha deep fracture (Fig. 9, Paarma and Talvitie, 1976). On the Finnish side of the alkaline rock province of Kola, it is clearly visible in Landsat imageries as a lineament over 150 km long and 10 to 20 km wide (Fig. 9). Geophysical data indicates that the Kandalaksha deep fracture runs through the White Sea and the Timanski ridge up to the Polar Urals. It constitutes an ancient rift zone (Belyaev et al., 1976b), which is one of the largest deep fractures in the eastern part of the Fennoscandian shield (Perevozchikova 1974). According to Petrov (1970), its history dates back to late Archean and early Proterozoic time. Bylinski et al. (1976) have studied the Kandalaksha deep fracture in detail, and emphasize its importance throughout geological history as the basic stem structure of the Kola-Karelia geoblock. The Tulppio olivinite 1 to 3 km southwest of the Sokli complex may represent ancient igneous activity within the Kandalaksha deep fracture. Despite the great age of the fracture zone, it is still seismically active (Talvitie, 1977). The west-east-oriented deep fracture that tangentially passes the Khibina massif on its northern side (Fig. 9) joins up with some gravimetric (Paarma and Talvitie, 1976) and magnetic anomalies on the Finnish side, and probably indicates the continuation of the deep fault zone. It is suggested that the Sokli complex is situated structurally at the intersection of this west-east-oriented fracture and the Kandalaksha deep fracture. There is no evidence of the Khibina concentric ring fracture (Belyaev et al., 1976a) in the Sokli region. Accordingly, the crossing point of the deep fractures has long been active and the channel for the Sokli carbonatite intrusion has long been under preparation. Similarly, Rodriques (1972) explains the distribution of alkaline complexes in Angola and Brazil (50 to 220 m.y.) as being the outcome of a reactivated Precambrian system of fractures.

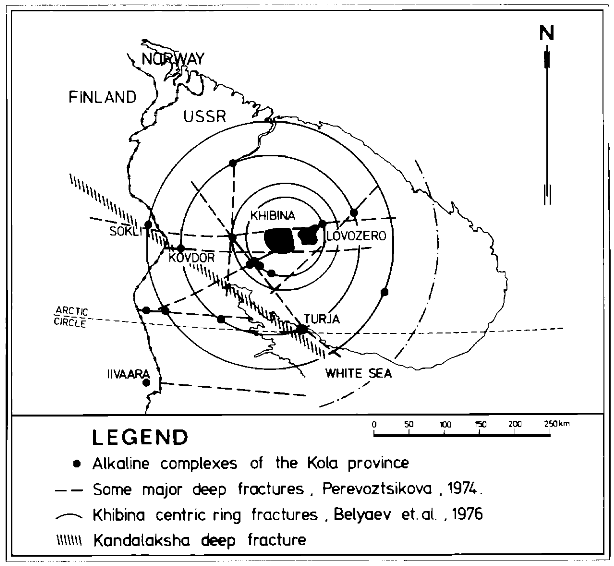

FIG. 9. Structural position of the Sokli carbonatite complex in the alkaline rock province of Kola.

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