GEOLOGIAN TUTKIMUSKESKUS — GEOLOGICAL SURVEY OF FINLAND

Opas — Guide 28

KOITELAINEN INTRUSION
AND
KEIVITSA - SATOVAARA COMPLEX

Excursion guide

5th International Platinum Symposium

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INTRODUCTION

In 1969, Quaternary geologists of the Geological Survey of Finland (GSF) reported a find of nickeliferous soil south of Lake Rookkijärvi, northern Sodankylä. As the area had been known, since the general geological mapping of the 1920s and 1930s, to be part of the Koitelainen mafic intrusion (Mikkola, 1937, 1941), the Exploration Department of the GSF promptly undertook detailed geological mapping and exploration at the Koitelainen intrusion. The initial excitement soon died down when it turned out that the nickeliferous sample came from weathered dunite. Then, however, field teams discovered boulders of sulphide-disseminated pyroxenite which, although low in Ni, showed somewhat elevated contents of Pd.

After a pause of four years, exploration was reactivated in 1973. The main target was still nickel, but we were already aware of the possibility that the intrusion might host deposits of PGE. However, finds of V-rich magnetite, which compared quite favourably with the ore of the new Mustavaara mine, shifted priorities to the uppermost cumulates of the intrusion. Extensive drilling in the eastern part of the intrusion in 1976–77 established a thick V-rich gabbro unit; however, most of the original magnetite had been altered during regional metamorphism into hornblende and biotite, making the bulk of the rock´s V unextractable.

At an early stage microscopic studies of ultramafic cumulates had demonstrated that the magma had attempted incursions into the chromite liquidus field and thus, on petrological grounds and relying on analogies, it was boldly forecast that the intrusion might hide chromite ores. The prediction proved correct in a quite unexpected way, when, in June 1977, an exploratory drill hole intersected 1.15 m of chromitite only 160 m below the base of the magnetite gabbro. Follow-up drilling confirmed that this Upper Chromitite (so named in anticipation of more chromitite layers lower down) was a laterally continuous and compositionally homogeneous layer, with promise of large tonnages. The presence of PGE was an extra favour.

Up to this point Koitelainen had disguised itself as an ordinary layered intrusion, with the exemplary succession of ultramafic cumulates, gabbros, anorthosites, magnetite gabbros and granophyre. The Upper Chromitite (UC) layer, in an improbable stratigraphic setting and with perplexing mineralogical and geochemical features, was the first major aberration from the orderly picture. It was followed by many other findings that challenge common sense, conventional textbook wisdom and also recent hypotheses and models constructed to explain layered intrusions and associated ore deposits.

By means of pedogeochemical sampling of till and grussified subdrift bedrock, chromitite layers were pinpointed in the lower part of the intrusion in 1980. In 1981–82, the layers were intersected by five drill holes. While the setting of these Lower Chromitites (LC), among pyroxenitic cumulates of the uppermost lower zone, was just within "normal" chromitites, the low Mg of the chromite, as well as the potassic composition of the melt inclusions in chromite and of the matrix (features shared by UC), implied that the chromite had crystallized and equilibrated in an environment very poor in Mg and rich in K.

Meanwhile, exploratory drilling continued in the lower and main zone, and follow-up drilling of UC was being done in southern and western parts of the intrusion. Although no new ore layers were encountered, the drilling revealed long stretches of unexposed stratigraphy and, on the side, provided more mineralogical and geochemical evidence for the important, at times even dominant, effect of contamination on the crystallization of cumulus phases. To take an example, loveringite was found to be common in the lower zone — in pyroxenites it even occurs as cumulus crystals — and to persist at least up to the upper main zone. In particular, "granitic" melt inclusions, ubiquitous in cumulus olivine of dunites and peridotites, explicitly suggested that olivine had crystallized only when (and where) the magma was strongly contaminated by alkalies (see Kushiro, 1974).

But there was more to these melt inclusions: dauhter crystals of chlorapatite, along with the high overall Cl content, pointed to a heavy intake of Cl. Later on, primary Cl minerals would turn up on many occasions, most conspicuously in association with PGE.

A hole drilled through the lower main zone intersected a peridotite underlain by 4 m of rock with anomalous Pt values. In peridotite and in its constituent salic-ultramafic "mixed rock" parts, chlorapatite occurs as large cumulus crystals. This peridotite revealed many other intriguing mineralogical and geochemical features. It is regarded as a relative (albeit a poor one) of the Stillwater PGE Reef.

Exploration had been focused on chromite and vanadium, but prospects of other kinds (chalcopyrite veins with Au, magnetite-ilmenite-rich pegmatoid pipes with Pt, vermiculite) were also explored by geophysical techniques, pedogeochemical sampling, trenching and drilling.

Althouh no drilling has been done in Koitelainen since 1982, re-examination of old outcrop and drill-core samples brought to light two occurrences of PGE. A routine sample taken in 1974 from an upper main zone gabbro outcrop, and with meagre sulphide dissemination, was assayed and found to contain fair grades of Pt, Pd and Au. So far, only outcrop sampling using a portable drill has been made on the site.

The other PGE-Au deposit which we have been nurturing in recent years is located in the magnetite gabbros which failed to qualify as vanadium ore. After PGE–Au were detected in a quartz vein, we speculated that the metals might have derived from surrounding altered magnetite gabbro. Tentative assays of various gabbro types duly showed PGE–Au grades ranging from anomalous to encouraging. Continuous assays of two drill holes established a layer, 75 m thick, averaging 0.5 ppm PGE+Au. Although not exactly a bonanza economically, the deposit represents a challenge to the established models of PGE ore genesis; also, it may well be a harbinger of similar (and perhaps better) deposits waiting to be found in the future.

The Keivitsa – Satovaara complex lies 1.5 km south of the Koitelainen intrusion. Earlier exploration efforts by Outokumpu Oy and the GSF were repeatedly discouraged by dismally low Ni in sulphide segregations in peridotites. More of this same stuff was found during a field trip in 1983, which was extended from Koitelainen to Satovaara. However, unassuming disseminated sulphides in another type of peridotite proved rich in Ni, Cu and PGE–Au. Despite low metal values in rock, the type was seen as a good omen, as it suggested that a viable sulphide phase, rich in Ni and PGE–Au, could coexist with Ni–PGE-poor sulphides. Later, this was found to be the case in the Keivitsa intrusion.

The Keivitsa – Satovaara complex and adjoining areas have been covered by systematic geophysical (gravity, magnetic, inductive electromagnetic) surveys. The Keivitsa area, being more accessible by forest truck roads, has been subjected to closely spaced pedogeochemical line sampling, and several prospects have been drilled. In the more remote Satovaara area, only limited till sampling has been done, and no drilling at all.

These intrusions share some prominent features with the Koitelainen intrusion. Choice granitic melt inclusions in olivine, with chlorapatite daughter crystals, attest to the role of salic contamination. Primary Cl minerals — cumulus chlorapatite and intercumulus dashkesanite — are associated with PGE-rich sulphides. Common to both the Koitelainen and the Keivitsa – Satovaara intrusions is the fact that the PGE show little respect for stratigraphy or sulphides. But then the Keivitsa – Satovaara complex also has some idiosyncracies, for example, a "hanging" deposits of Ni-rich sulphides high up in the intrusion, cumulus graphite in a gabbro interlayer, and a "chondritic" hydrothermal PGE mineralization in the silicified roof dunite.

Exploration continues in the Keivitsa – Satovaara complex.

THE 2.45 b.y. AGE GROUP LAYERED INTRUSIONS OF THE FENNOSCANDIAN SHIELD

The Koitelainen intrusion and the adjacent Keivitsa – Satovaara complex lie 150 km north-northeast of Rovaniemi, in a wilderness between the rivers Kitinen and Luiro (Figs. 1, 2). They belong to the northernmost group of Lower Proterozoic mafic layered intrusions in northern Finland. The intrusions of this group form a nothwesterly belt, 180 km long and about 50 km wide. The biggest are Särkijärvi in the nortwest, Koitelainen, Keivitsa – Satovaara, Särkivaara and the tectonically dismembered intrusion complex of the Lokka area in the central part, and the intrusions of Tanhua and Akanvaara in the southeast.

The southwestern group of intrusions includes the truncated intrusions and intrusion blocks of Tornio (with an extension on the Swedish side of the international border), Kemi and Penikat and the intrusions of the Portimo complex (see, e.g., Veltheim, 1962; Kujanpää, 1964; Söderholm & Inkinen, 1982; Alapieti & Lahtinen, 1986).

In the southeast, the Koillismaa group comprises several intrusion blocks, the biggest being Syöte, Porttivaara and Kuusijärvi, and the layered feeder of Näränkävaara. A hidden connecting feeder dyke occurs between Porttivaara and Näränkävaara (see Juopperi, 1977; Piirainen & al., 1977; Alapieti & al., 1979; Alapieti, 1982).

Most of these intrusions were emplaced roughly between the Archaean basement and the overlying Lapponian metasediments and greenstones; these are interpreted variously as Archaean or Proterozoic in age, depending on the author. The layered feeder of Näränkävaara, the connecting dyke, as well as the feeder dykes southeast of the Kemi and Penikat intrusions (Seppo Elo, 1979, unpubl. report), typically trend northwest; this

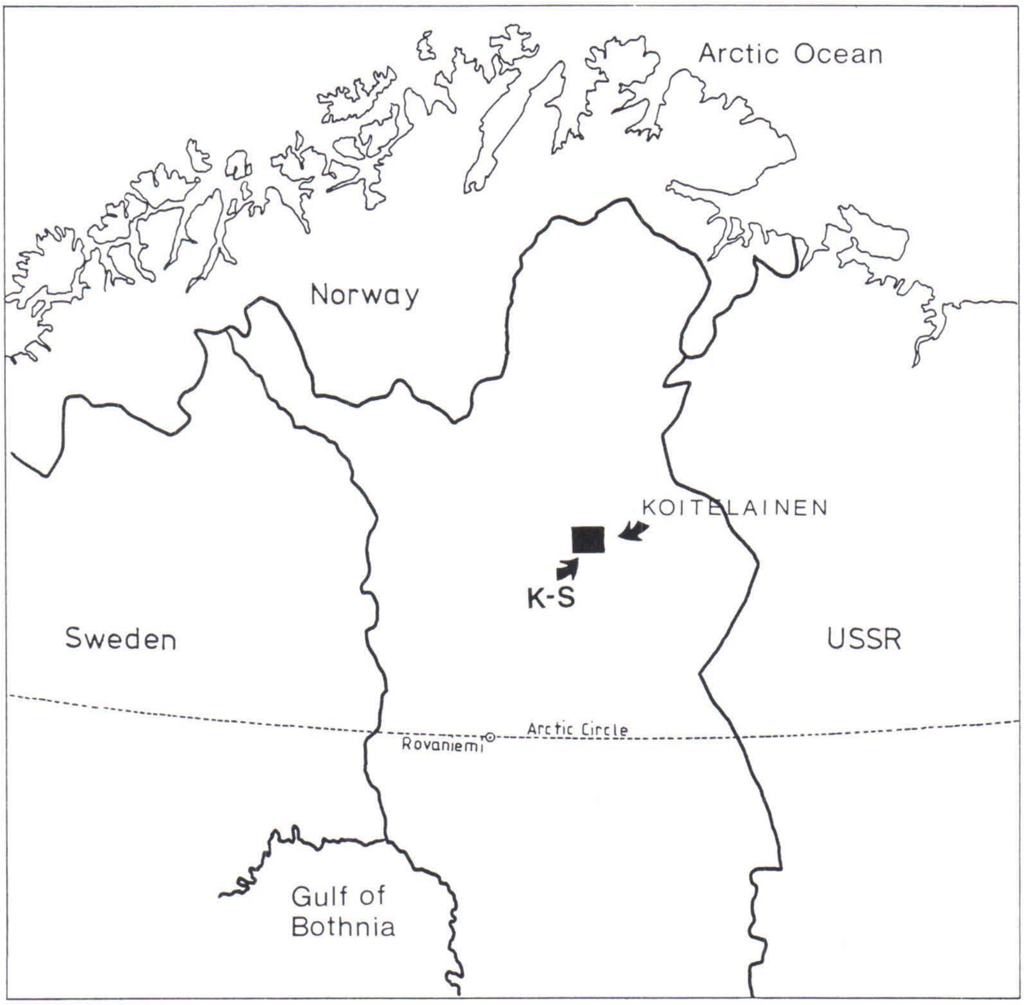

Fig. 1. Location of the Koitelainen intrusion and the Keivitsa–Satovaara complex (K-S).

trend is also seen in the overall distribution of the intrusions of the northern group (Fig. 2).

An age of 2.435 b.y. for the Koitelainen intrusion was yielded by zircon of the pyroxenitic pegmatoid pipes, interpreted to represent an immiscible melt from the the intercumulus liquid (Mutanen, 1976). Although virtually the same age was found for the zircon of granophyre (Mutanen, 1989), and the dating procedures were technically impeccable, the ages aroused suspicion, particularly as their acceptance would have called for a painful re-structuring of the customary stratigraphic divisions. Later, ages similar to those of Koitelainen were obtained from the other layered intrusions of northern Finland (Alapieti, 1982; Alapieti & Lahtinen, 1986).

There is quite a number of large mafic layered intrusions in the Kola Peninsula and Soviet Karelia, including the Burakovsk intrusion, the biggest in the Fennoscandian Shield. These have the same general characteristics as the intrusions in northern Finland, and are obviously of the same age (see, e.g., Kozlov & al., 1967; Proskuryakov, 1967; Bogachev & Lavrov, 1971; Sharkov & Vaskovskii, 1973; Kozlov, 1973; Kozlov & Yudin, 1974; Stepanov, 1975; Batashev & al., 1976; Bogachev & al., 1976; Sokolova,, 1976, 1979; Rundkvist & Sokolova, 1978; Lavrov, 1979; Sharkov & Sidorenko, 1980;

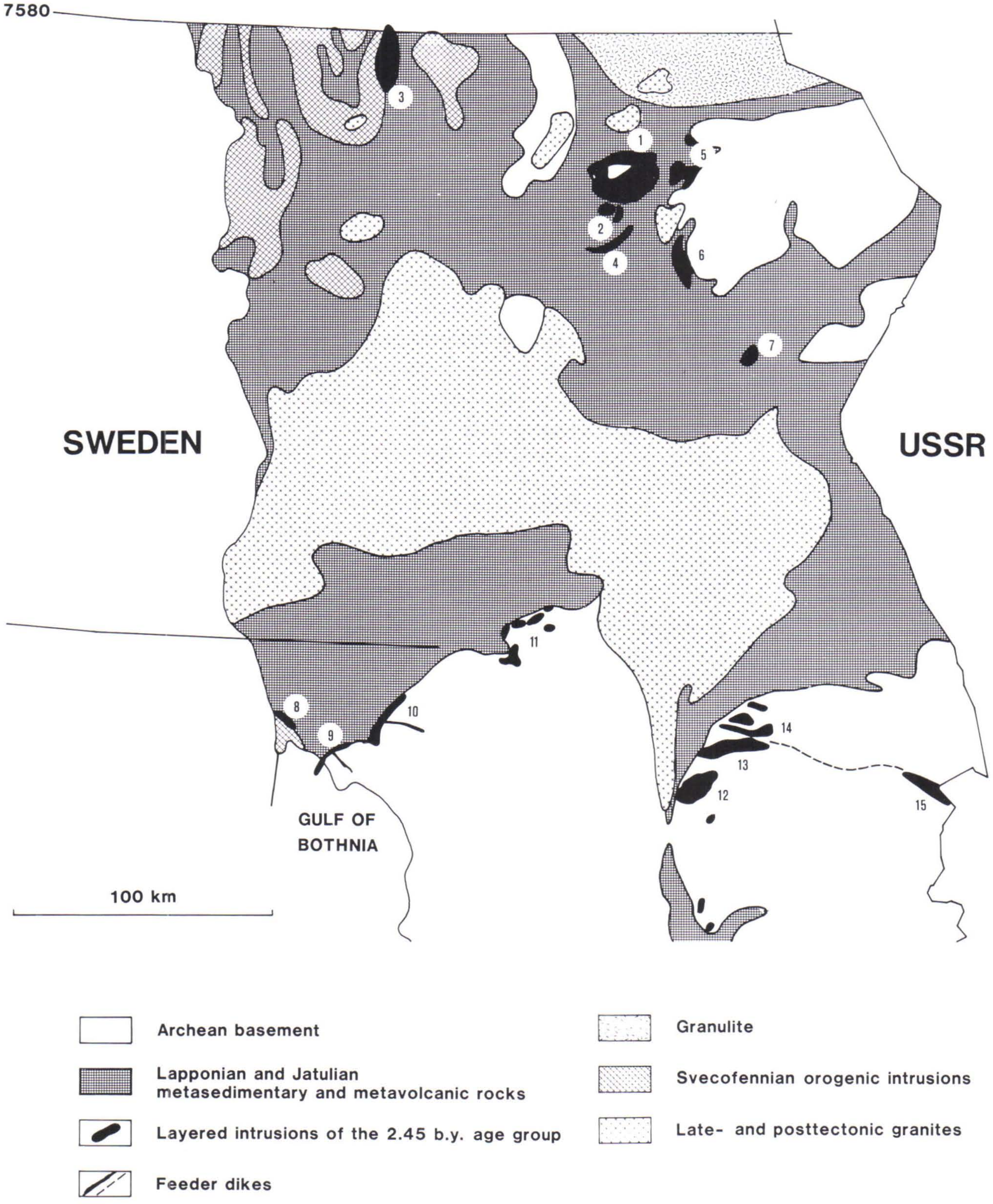

Fig. 2. Geological setting of the mafic layered intrusions in northern Finland. Intrusions: 1 – Koitelainen, 2 – Keivitsa–Satovaara, 3 – Särkijärvi, 4 – Särkivaara, 5 – Lokka, 6 – Tanhua, 7 – Akanvaara, 8 – Tornio, 9 – Kemi, 10 – Penikat, 11 – Portimo complex, 12 – Syöte, 13 – Porttivaara, 14 – Kuusijärvi, 15 – Näränkävaara.

Sidorenko & Shurkin, 1980; Dokuchaeva, Zhangurov & Fedotov, 1982; Dokuchaeva & al., 1982; Lobach-Zhuchenko & al., 1986; Distler & al., 1988).

Also widespread in the eastern part of the Fennoscandian Shield, and about the same age as the mafic intrusions, are acid igneous rocks, including charnockites, granites, alkali granites and quartz porphyries, (e.g., Kratts & al., 1976; Batieva, 1976; Tugarinov & Bibikova, 1980; Shemyakin, 1980; Kratts & al., 1984; Luukkonen, 1988). The mafic intrusions seem to represent an integral phase, generally the final one, of the volcanic and intrusive activity that produced the piles of eruptive rocks of the Late Archaean – Early Proterozoic greenstone belts.

After formation, before and during the Jatulian time (ca. 2.3–2.0 b.y.), the intrusions of the southwestern group were tilted, faulted and truncated by erosion to varying depths; elsewhere, the intrusions were spared pre-Jatulian denudation. Diabase dykes of Jatulian age have been found cutting most of the intrusions.

During the Svecokarelian orogeny, the intrusions were folded, sometimes into upright and even overturned positions. The intrusive rocks were altered by regional metamorphism to a varying degree. The intrusions are split and often dismembered into separate blocks by faults. Evidently, faulting accompanied folding, but some occurred later, too.

Various ore deposits are associated with the layered intrusions; at present, however, only the huge chromite deposits of the Kemi intrusion are being mined. A short-lived vanadium mine was operated at Mustavaara (Porttivaara intrusion). Chromitite layers are known from the Tornio, Penikat and Koitelainen intrusions (Kujanpää, 1964; Mutanen, 1981; Söderholm & Inkinen, 1982). Vigorous PGE exploration has been going on in many intrusions, so far without definite success. In the Kola peninsula, Ni-Cu ores were once mined from the Monchegorsk intrusion. Judging from recent reports of chromitite layers in many intrusions in the USSR, the Kola – Karelia region has huge resources of low-grade chromite ores (e.g., Kozlov & al., 1975; Dokuchaeva, Zhangurov & Fedotov, 1982; Dokuchaeva & al., 1982; Lavrov & Pekki, 1987).

PHYSIOGRAPHY AND SURFICIAL GEOLOGY

The area is part of a south-sloping peneplain, with a mean height of 260 m a.s.l. in the north and 220 m a.s.l. in the south. This flat country is covered with great expanses of interconnected bogs. The presence of bog pools, treacherous watery reaches and meandering brooks makes the terrain negotiable only with difficulty; many stretches are impassable. The least fractured and chemically the most resistant rocks stand up from the flats as low, smoothed ridges and mesa-like hills. The highest point is the summit of the Koitelainen tunturi (fell), 408 m a.s.l. Dry moraines are covered with spruce forest; pine grows on craggy ground and in reforested clear-cut areas in the western parts. The highest summits are almost bare, supporting only sparse stunted birches. Most of the area of the intrusion lies within the planned Koitelaiskaira Wilderness Preserve area.

The bedrock is unevenly, rock-selectively and, on the whole, poorly exposed. Apart from rare solid, glacially polished outcrops alongside streams, the exposures are frost-shattered outcrops and boulder fields, most often only groups of solitary, frostheaved boulders.

All rocks containing biotite or phlogopite were deeply grussified before the Quaternary glaciation, and are exposed only by chance, as in periglacial landslide gorges. Unfortunately, such rocks include chromitites as well as rocks and layered portions associated with ore layers such as pyroxenites, anorthosites, stratigraphic reversals and compositionally contrasted layered cumulate sequences. Such rocks have been encountered only by percussion drilling and trenching; during diamond drilling the grussifield rocks are usually flushed away. The presence of supergene minerals (violarite, marcasite, hydromica, maghemite, goethite) indicate that weathering processes have reached deep into hard rocks, in some cases down to 120 m or more.

As part of the ice divide belt, the Koitelainen area did not suffer unduly from glacial erosion. Locally, however, erosion and transport were surprisingly strong, as indicated by roches moutonnées, grooves, striations and associated crescentic fractures. The erosional features indicate glacier advance from the north-northwest; the ice movement was not affected by bedrock relief. Till, with an average thickness of about 5 m, covers the bedrock, and is in turn buried under peat deposits in boggy areas.

Throughout postglacial time the area has been supra-aquatic. Right in front of the receding glacier, periglacial landslides occurred in places, typically on northern (proximal) slopes. Periglacial processes, such as frost-shattering, frost-heaving and solifluction, are still active.

THE KOITELAINEN INTRUSION

Geological setting

The intrusion is a flat, oval-shaped brachyanticline structure, ca. 29 by 26 km (see Geological map, Applendix 1). The interior is made up of footwall rocks of the intrusion — Archaean granitoid gneisses, overlying Lapponian supracrustal rocks, pre-Koitelainen gabbroic intrusions and ultramafic dykes.

The Archaean gneisses form two domes. The smaller dome, immediately west of the peridotitic basal cumulates of the Koitelainen intrusion, consists of tonalites, trondhjemites and granodiorites (Peltonen, 1986).

Zircon from these rocks yields a U–Pb discordia age of 3.1 b.y. (Kröner & al., 1981); however, Sm–Nd isotopic ratios suggest a prior crustal residence of about 250–500 m.y. (Jahn & al., 1984). The few exposures of the much larger easterly Kiviaapa dome are all located near the base contact of the Koitelainen intrusion. The eastern contact of the Kiviaapa dome gneisses with the Koitelainen intrusion has been intersected by two drill holes. Zircon fractions from slightly hornfelsed gneisses from the Kiviaapa dome give U–Pb discordia ages between 2.765 and 2.820 b.y. (Mutanen, 1989).

A deep gravity low occupies the core of the Kiviaapa dome, with distinct gradient boundaries against surrounding gneisses. Only 'a granite mass of great depth could conceivably account for the gravity low.

The lower Lapponian supracrustal rocks around the Archaean gneisses (but beneath the intrusion) include arkosic quartzites, various acid and intermediate volcaniclastic rocks and diamictites, tuffs and tuffites, and basaltic lavas and tuffs.[1]

The most common, but rarely exposed, rock type is a biotite-plagioclase mica gneiss that contains varying amounts of felsic volcanic material.

Rocks adjacent to the base contact of the Koitelainen intrusion display thermal metamorphic effects. Because of hornfelsing, incipient and, ultimately, wholesale melting of the basement rocks, it is often difficult to distinguish between the Lapponian and Archaean acid rocks.

A U–Pb discordia age of 2.526 b.y. (± 46 m.y.) has been obtained from a rhyolite (Peltonen 1986); thus, the lowermost Lapponian rocks, at least in this area, straddle the established Archaean/Proterozoic boundary.

The Koitelainen intrusion is overlain by a thick succession of volcanic and sedimentary Lapponian rocks. In the roof, within reach of severe thermal effects of the intrusion, high-aluminous schists and komatiitic volcanic rocks, accompanied by lesser amounts of basaltic lavas and tuffs and subarkosic quartzites, predominate. Farther up, there are chlorite–sericite schists, micaceous arkosic quartzites and calcareous rocks, intercalated by extrusive sheets of basaltic komatiite. These are overlain by a thick and extensive unit of laminated mica schists containing felsic volcaniclastic material and interbeds of black schists. At about the level of emplacement of the Keivitsa intrusion the mica schists are succeeded by sulphide-bearing felsic rocks, probably of volcanic origin.

Emplaced among the volcanic-sedimentary rocks are several mafic and ultramafic intrusions and mafic sills. Some of these are older than, and obviously unrelated to, the Koitelainen intrusion; these include "komatiite gabbros" and ultramafic intrusions of the komatiite affinity, and a differentiated mafic sill immediately beneath the Koitelainen intrusion. Some of the differentiated sills between the Koitelainen and Keivitsa intrusions are interpreted as contemporaneous and consanguineous with the Koitelainen intrusion. The layered intrusions of the Keivitsa–Satovaara complex were most likely emplaced just before the Koitelainen magma.

The status of most of the peridotite bodies outside the layered intrusions is not clear. Apart from a few occurences of komatiitic pillow lavas, agglomerates and tuffs, there is no unambiguous evidence for the volcanic nature of the numerous lenses and sheets of peridotites/serpentinites.

Countless diabase dykes (only the thickest are shown on the map), probably of Jatulian age, cut the basement, the intrusion and the Lapponian supracrustal rocks. During the Svecokarelian folding the intrusion behaved mainly as a brittle body and broke along NE and N faults. Plastic deformation is evident in the foliated to schistose granophyres near the upper contact and throughout the tectonically thinned western limb of the intrusion; plastic deformation, even folding, also occurred in the broad fault zones that cut gabbros. Younger NW by NNW fault and fracture zones also occur.

The intrusion and the diabase dykes are metamorphosed to varying degrees, most heavily along fault zones and near the upper contact. Original magmatic minerals are

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[1] The prefix meta- is generally omitted from metamorphosed rocks in the following.

never preserved in granophyres and only occasionally in magnetite gabbros. The metamorphic grade of the area corresponds to that of lower and middle amphibolite facies.

Emplacement and contact effects

The Koitelainen magma intruded through the Archaean basement and lowermost Lapponian rocks. The intrusion was formed essentially as a single cast. The lower contact is transgressive, climbing the stratigraphy away from the feeder assumed to be located in the western part of the intrusion beneath the deep basin filled with thick olivine cumulates. A gabbro dyke projecting northwest from this basin may be an extension of the feeder.

The upper contact is roughly conformable. Nowhere does the intrusion breach the high-aluminous schists, which evidently controlled the ascent and lateral spreading of the magma.

Fine-grained chilled rocks of silica-saturated, low-Ti tholeiitic composition formed against the wall rocks. Mostly, however, this lining did not resist for long but, loosened by the melting of the support rocks, was transported and fragmented by magma currents. Thus, the rocks of the lower chilled margin are generally found as microgabbro autoliths amongst the lowermost cumulates, along with refractory xenoliths of pre-Koitelainen rocks. Subsequently, chilled linings were formed continuously on exposed cooler wall rocks, where they substituted for former chilled rocks which had been peeled off and picked up by convection currents or stoped from the roof. Microgabbro autoliths in the upper zone bear evidence of having been formed against anatectic roof melt. Stepwise chill renewal from continuously fractionating magma may give a deceptive impression of successive magma pulses. Later, we shall see how the reversals in the layered sequence, which are generally (and too casually) ascribed to new magma pulses, might be explained by contamination.

As the inner marginal sheathing was intermittently stripped off, heat was transferred readily to the roof, causing widespread melting. This is a characteristic feature of convective intrusions (Kadik, 1970). With the advance of melting, refractory volcanic rocks were detached and fell onto the cumulate pile. Now they are found in their correct stratigraphic order as xenoliths, mainly in the lower part of the upper zone. The consolidated roof melt formed the granophyre cap. Roof melting continued after the solidification of the main intrusion (see Kadik, 1970).

The granophyre melt adjusted to the underlying hotter mafic magma by exchanging components with it, and by digesting refractory minerals from partially melted felsic rocks. Minerals insoluble in the granophyre magma settled down through it and reacted with the main mafic magma.

Contrary to most layered intrusions, where marginal chill and the growing cumulate pile shielded the floor rocks from melting, large-scale floor melting occurred beneath the Koitelainen intrusion, particularly under the deep cumulate basin in the west. Melt pockets that formed from Lapponian and Archaean felsic rocks coalesced and ascended diapirically through the cumulates, eventually reaching the main magma. Some diapirs evidently escaped to the roof as "melt balloons", but others were arrested below a ceiling chill, a blanket formed through interaction of the diapir and the main magma. The diapir melts combatted overheating by exchanging components with the intercumulus liquid of the cumulates surrounding the diapirs and eventually acquired a syeno-monzonitic composition.

The country rock melted in two main stages. The first was water-saturated melting of granitic constituents during the early stages of consolidation in the course of which unmelted country rocks turned to dry hornfelses. The second, "dry granitic" melting, occurred much later and at a much higher temperature.

The layered structure

The lower contact is disconformable to the layering of the intrusion. Measured across the most complete cumulate section the intrusion is about 3.2. km thick.

The general stratigraphy is presented in Fig. 3. The intrusion is divided into an ultramafic lower zone, a gabbroic main zone and a gabbroic upper zone (with anorthosites and magnetite gabbros). Granophyre forms a continuous cap above the mafic succession. All standard types of layering occur. Fine scale layering has been noted in anorthosites and chromitites and, rarely, in magnetite gabbros. Igneous lamination is present in all gabbros of the main and upper zones, but it has not been observed in gabbroic interlayers of the lower zone.

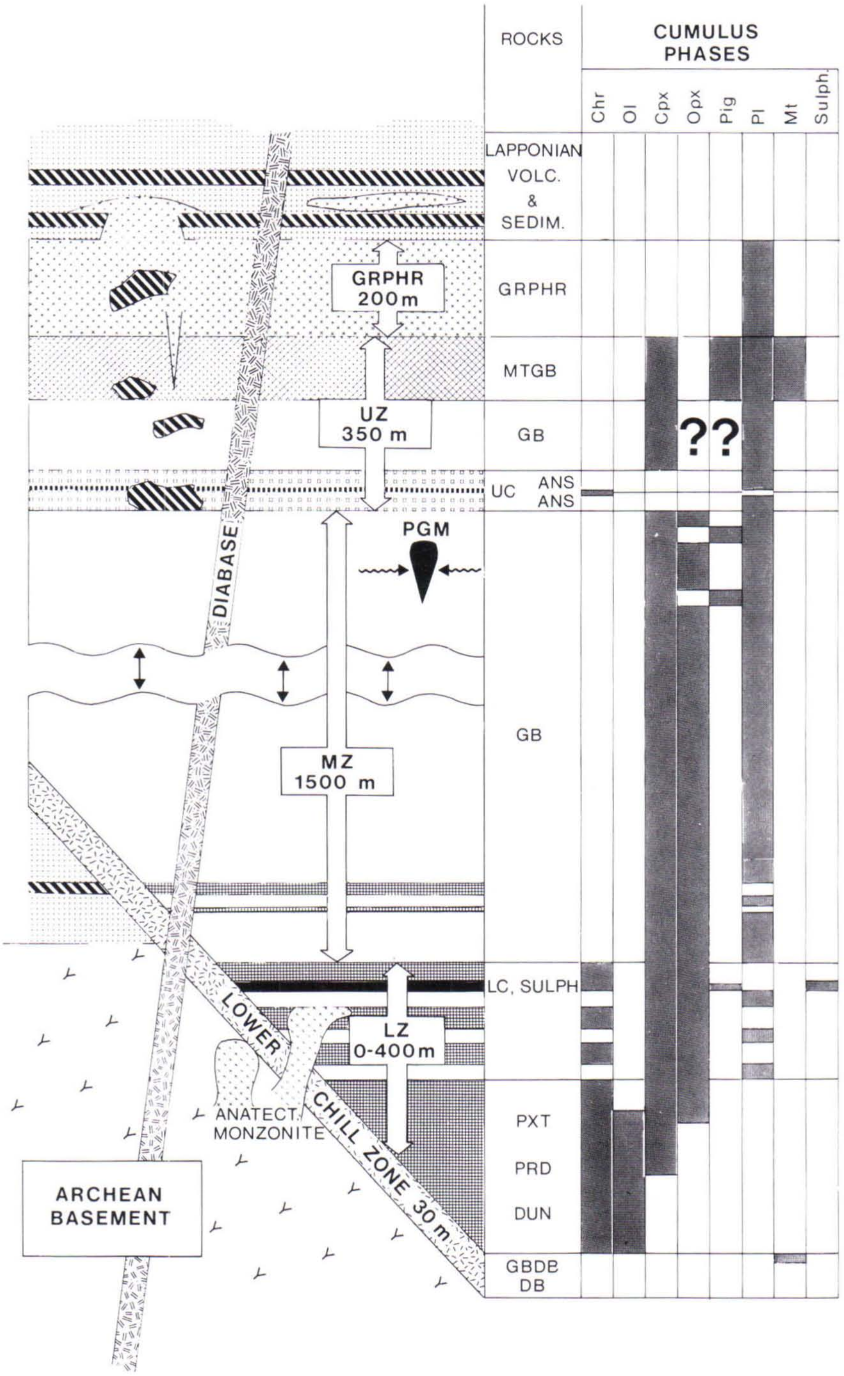
The lower part of the lower zone consists of two peridotite layers separated by a gabbro-pyroxenite interlayer. However, there is evidently more than one peridotite-gabbro rhythmic unit. Peridotites are olivine-chromite cumulates, with varying amounts of intercumulus orthopyroxene, augite, plagioclase, potassium feldspar and minor primary phlogopite. Potassium feldspar is largely altered to secondary phlogopite. The gabbros are plagioclase-orthopyroxene-augite cumulates, with olivine in places.

Owing to the presence of monzonitic diapirs and faults and the lack of outcrops, relations between the peridotitic lower part and the pyroxenitic upper part of the lower zone are obscure. The pyroxenites, which have been intersected by several drill holes east of the Kiviaapa dome, are orthopyroxene-chromite cumulates, with intercumulus plagioclase, augite, primary phlogopite, potassium feldspar, quartz and accessory zircon, chlorapatite and fluorapatite. Loveringite is ubiquitous, often occurring as fair-sized, roundish cumulus crystals (Tarkian & Mutanen 1987).

There are several chromitite layers (LC chromitites) among the pyroxenites, and in the uppermost part of the pyroxenite unit there are interlayers of gabbro.

The main zone consists chiefly of gabbros. In the lowermost part there are interlayers of feldspathic pyroxenite. About 250 m above the base of the main zone there is a 2.5 m-thick layer of feldspathic pyroxenite (orthopyroxene-augite cumulate), with a 5 cm-thick chromitite layer at the base. About 60 m above this, there is a 13 m layer of peridotite (olivine-chromite cumulate), underlain by 4 m of pyroxenite. Among the peridotites there are feldspathic patches (the "mixed rock"). Thin layers of feldspathic pyroxenite occur about 13 m above the peridotite-mixed rock sequence.

The gabbros of the main zone are plagioclase-orthopyroxene-augite cumulates with some plagioclase-orthopyroxene cumulates. In the upper main zone the Ca-poor pyroxene is inverted pigeonite, with one, possibly two reversals back to "normal" orthopyroxene.



KOITELAINEN INTRUSION

ROCK UNITS AND CUMULATE STRATIGRAPHY

LZ	Lower Zone
MZ	Main Zone
UZ	Upper Zone
GRPHR	Granophyre
DUN	Dunite
PRD	Peridotite
PXT	Pyroxenite
LC	Lower Chromitite layers
SULPH	Sulphide-rich layers
GB	Gabbro
ANS	Anorthosite
UC	Upper Chromitite
MTGB	Magnetite gabbro
PGM	Pegmatoid
GB(DB)	Gabbro(Diabase)
Chr	Chromite
Ol	Olivine
Cpx	Clinopyroxene
Opx	Orthopyroxene
Pig	Pigeonite
Pl	Plagioclase
Mt	Magnetite
Sulph	Sulphide liquid

Fig. 3. Rock units and igneous stratigraphy of the Koitelainen intrusion. Zone thicknesses are estimated averages.

Aside from the pigeonite gabbros, all the other main zone gabbros contain intercumulus quartz. Loveringite occurs in all the fresh gabbros in small amounts.

The upper zone begins with a 40 m-thick succession of anorthosites. The UC layer is located in the middle of this unit. The anorthosites are overlain by gabbros and anorthosites, the amount of anorthositic layers decreasing upwards. The upper zone gabbros are plagioclase-pyroxene cumulates; the pyroxenes are completely uralitized. The uppermost unit of the upper zone is magnetite gabbro, about 100 m thick, underlain by a 10 m-thick spotted anorthosite gabbro. The relations between the magnetite gabbro and the overlying granophyre are not quite clear. In some parts of the intrusion the magnetite gabbros seem to grade into granophyre with the increase in interstitial granophyric material; in others an anorthositic layer separates the magnetite gabbros from granophyre.

The thickness of the granophyre in the best exposed (and the least tectonized) parts is 200–400 m. Plagioclase was the first mineral to crystallize from the granophyre melt. The euhedral to subhedral plagioclase crystals are always completely altered to albite + epidote. The mafic minerals, hornblende and biotite, are secondary (metamorphic). The lowermost granophyres are often medium- to coarse-grained, but upwards the grain size decreases. Some of the granophyres in the southern part of the intrusion resemble plagioclase-phyric lavas.

Granophyre also occurs as dykes in the upper zone, mostly in magnetite gabbros, as pockets trapped beneath autoliths and xenoliths, and as small patches in anorthosites.

As a general feature, non-cotectic cumulates (chromitites, pyroxenites, dunites, peridotites and anorthosites) are orthocumulates. Anorthosites generally contain poikilitic hornblende (after original pyroxene), which gives a spotted or mottled appearance to the rock. The gabbros are mesocumulates.

Xenoliths of intrusive and extrusive rocks, and also chill-autoliths occur here and there near the basal contact of the intrusion. Neither autoliths nor xenoliths have been found among the main zone gabbros, but in the upper zone and granophyre they are common once again, particularly in basal parts of the anorthosite and the magnetite gabbro.

Phenomena that might be characterized as magmatic-diagenetic were associated with the consolidation of the cumulus pile. They include the diapirs of anatectic melt mentioned earlier, ultramafic pegmatoid pipes and veins in the main zone and granophyre dykes in the upper zone. The ultramafic pegmatoids are bodies of clinopyroxenites (now meta-pyroxenites) rich in ilmenite and magnetite. Their contacts with the surroundung gabbros are always sharp. They have been interpreted as contraction openings and crevices, filled by lateral secretion with mafic residual liquid. Crystal fractionation continued in pegmatoid magma bodies.

Representing the last eutectic liquids of the granophyre magma, granitic dykes, projecting downwards from the granophyres into the magnetite gabbros, were driven into contraction crevices opened in consolidated gabbros. They might be called "magmatic clastic dykes" or, more appropriately, "magmatic frost wedges".

No evidence for any large-scale upwards migration of intercumulus liquid has been found.

PGE occurrences

Several occurrences of PGE–Au are known from the Koitelainen intrusion, but the grades are always too low to be economically interesting. During the exploration stage base metals were analysed by AAS in the GFS laboratories in Espoo and Rovaniemi, and sulphur was determined (LECO) in the GSF laboratory in Kuopio. Pd and Au were analysed in Rovaniemi (graphite furnace AAS; see Kontas & al., 1986), and Pt–Pd–Au (fire assay) in the Espoo laboratory. In addition, 57 samples from eight types of PGE occurrence from Koitelainen and Keivitsa – Satovaara were analysed for Au, Os, Ir, Ru, Rh, Pd, Pt and Re (Ni sulphide/NAA) by Nuclear Activation Services (NAS) Ltd., Canada. The chondrite-normalized concentrations were calculated using the chondrite values reported by Taylor & McLennan (1985). Concentrations in 100 percent sulphides (sulphide phase) were calculated on the basis of the S content of 37 wt % for the sulphide phase.

At *Rookkijärvi*, pyroxenites of the lower zone, with weak sulphide dissemination, contain traces of PGE. Two samples analysed by NAS had total PGE of 860 and 1295 ppb, with Pt/Pd of 0.18 and 0.12. Au is very low (max. 36 ppb), and the chondrite-normalized graph has a steep positive slope (Fig. 4). PGMs have not been found. The host rock is a feldspathic pyroxenite (orthopyroxene-augite cumulate), with abundant intercumulus quartz, potassium feldspar and biotite. The pyroxenite grades into quartz-rich gabbros, which also contain sulphide blebs and dissemination. An autolith of microgabbro has been found in the pyroxenite.

This sulphide PGE occurrence is located in the northern part of the belt of anatectic diapirs. Syeno-monzonite occurs in close proximity to sulphide-bearing rocks. Sulphide separation is thought to have been provoked by salic material fed by the felsic diapirs to the mafic magma.

The LC layers. These have been intersected by four drill holes in the Porkkausaapa area, east of the Kiviaapa dome. Subdrift bedrock samples obtained by percussion drilling indicate that the layers are continuous over a minimun distance of 13 km. In the investigated area, pyroxenites rest upon older rocks, being separated from them by microgabbros of the chilled margin. The dip of the contact and of the igneous layering is about 10° SE (Fig. 5). The UC layers occur among pyroxenites within a vertical span of 37-59 m. The distance from the uppermost chromitites to the base of the main zone ranges from 30 to 55 m. It is difficult to connect individual chromitite layers between drill holes, but as an estimate, there would seem to be four to six layers more than 0.3 m thick with chromite as the sole cumulus mineral. The longest chromitite intersection was 2.9 m. The Cr_2O_3 content of individual layers ranges from 10.6 to 32.2 wt %. The basal contact of the layers is generally sharp; the hanging wall contact is gradational, passing from massive chromitite to net-textured ore to rich disseminated rock to normal pyroxenite with a few vol.% chromite. Besides the thick layers, there are numerous thinner bands, net-textured schlieren and disseminated layers.

According to electron microprobe analyses, the composition of chromite varies

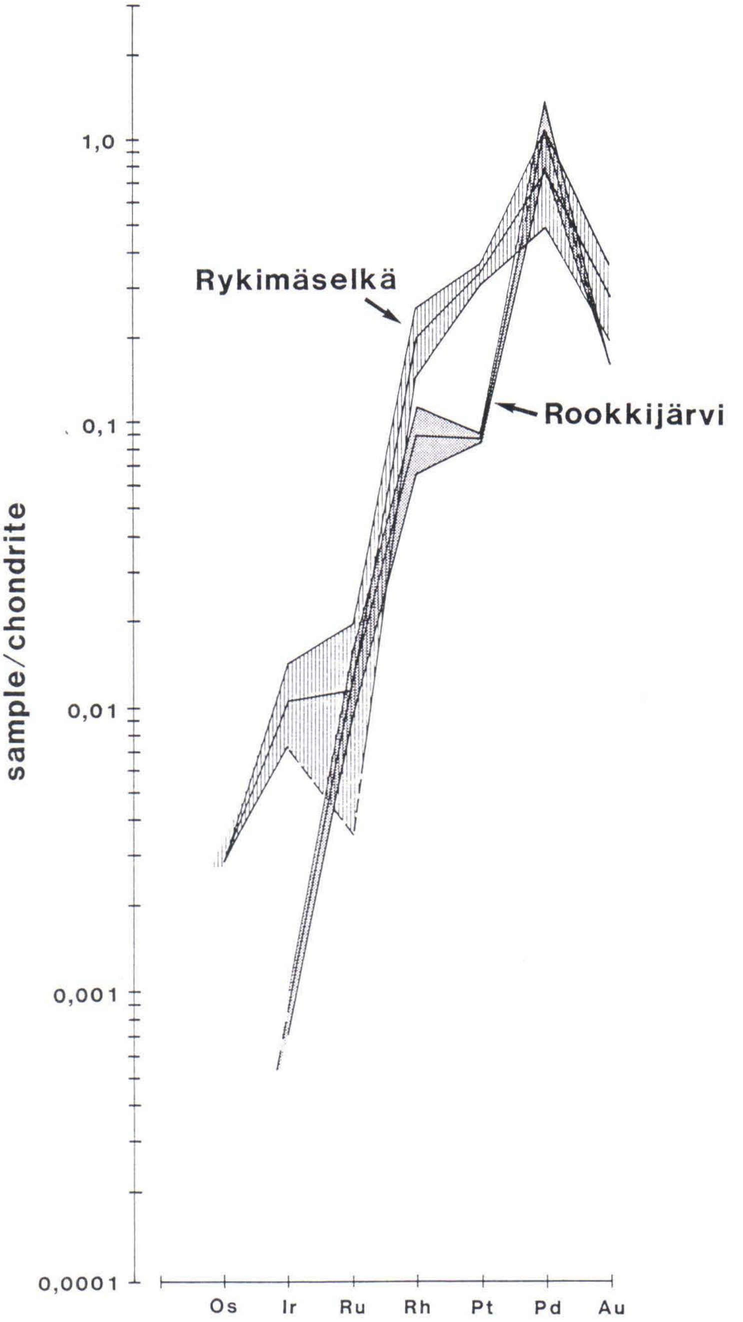


Fig. 4. Chondrite-normalized PGE-Au concentrations of disseminated sulphides of Rookkijärvi (lower zone) and Rykimäselkä (upper main zone), Koitelainen intrusion.

somewhat between the layers. Typical compositions of chromites from the LC and UC layers are given in Table 1. The LC layers have an average total PGE concentration of 1.4 ppm. The highest content of Pt+Pd is 3.4 ppm. Four samples, each representing the whole intersection of an individual layer, were analysed by NAS for PGE-Au. The chondrite-normalized graphs of LC samples are presented in Fig. 6, along with graphs for UC samples. The PGE-contents and chondrite-normalized patterns are similar in different LC layers. The graph for UC cannot be distinguished from that of LC. Koitelainen

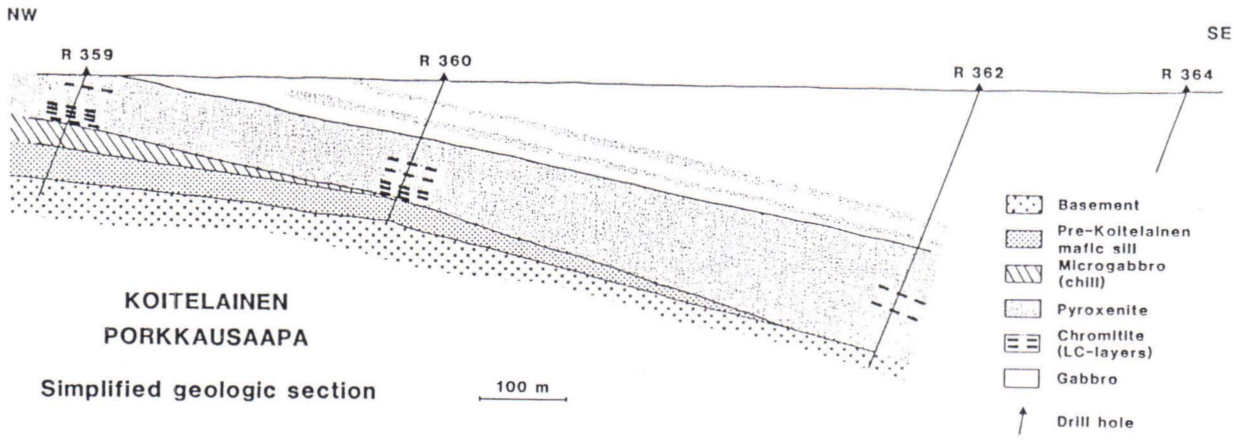


Fig. 5. Geological section of the Porkkausaapa area, Koitelainen, showing the intersected LC layers.

chromitites have chondrite-normalized graphs with a characteristic M shape, with peaks at Rh and Pd.

The chromitites of the LC layers do not contain any primary sulphides. PGMs have not been found.

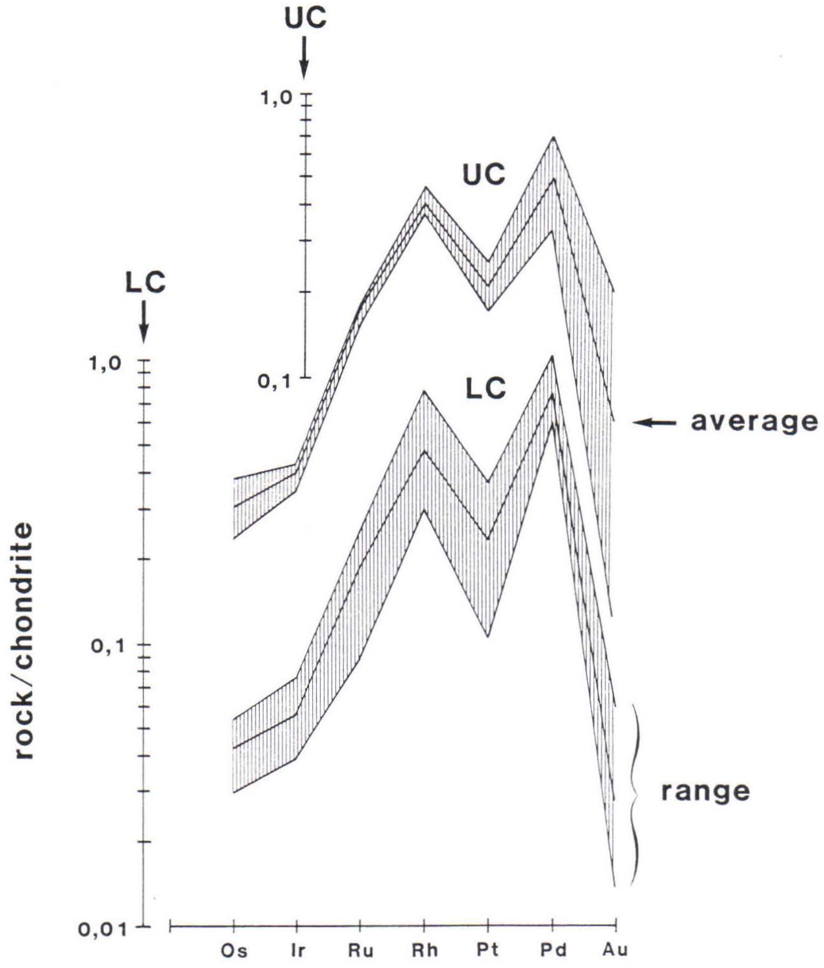


Fig. 6. Chondrite-normalized PGE-Au concentrations of LC and UC chromitites, Koitelainen.

The pyroxenites associated with the LC layers have been systematically analysed for Pd and Au (each length ca. 0.5 m). All the samples were well below the economic threshold; Au, however, exceeded 20 ppb in a combined core length of 80 m (with 13 m containing more than 40 ppb). Pd was very low, exceeding 20 ppb across a total length of 19 m. Disseminated and massive sulphides 1 m thick are associated with a pyroxenite-chromitite breccia. The disseminated rock, with 1.1 % Cu and 0.08% Ni, contained 0.13 ppm Pt+Pd, the massive sulphides (with 0.3 % Cu and 0.34 % Ni) had a mere 0.1 ppm Pt+Pd.

The peridotite - mixed rock. This complex layer, at about 340 m above the base of the main zone, has been intersected by one drill hole. The layer is underlain by 4 m of pyroxenite and alternating layers of gabbro and feldspathic pyroxenite. The pyroxenites contain about 0.1 ppm Pt. The Pt-anomalous zone contains no sulphides. The characteristics of the peridotite - mixed rock are discussed later.

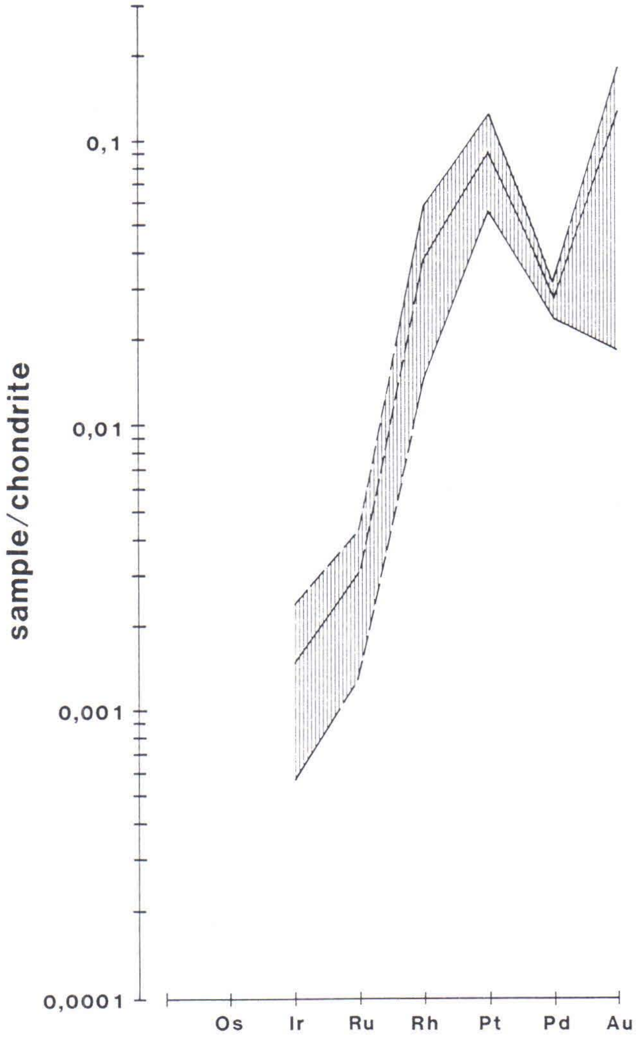


Fig. 7. Chondrite-normalized PGE-Au concentrations of pegmatoids in the Lakijänkä area, Koitelainen.

Ultramafic pegmatoids occur among the gabbros of the main zone. A swarm of pegmatoid pipes and veins occur in the Lakijänkä area in the Koitelainen fell; a big pegmatoid pipe, about 200 m in diameter, has been intersected by drilling at Mukkajärvenaapa, in the southwestern corner of the intrusion. The pegmatoids were originally clinopyroxenites rich in magnetite and ilmenite, but clinopyroxene (augite) is almost completely altered to hornblende. The parts rich in magnetite and ilmenite generally have Pt grades of 0.1 - 0.2 ppm. Pt is enriched in magnetite; a magnetic concentrate contained 2.3 ppm Pt. Sulphides are lacking in the pipes, but some vein pegmatoids contain disseminated Fe-Cu sulphides; in such rocks Pd dominates over Pt.

Chondrite-normalized graphs of two pegmatoid samples from Lakijänkä show a steep positive slope, with a peak at Pt (Fig. 7).

Rykimäselkä. This PGE occurrence is associated with the reversal of pigeonite gabbro to "normal" pyroxene gabbro in the upper main zone. The distribution of PGE-Au is irregular, but the highest grades seem to correlate with the abundance of Fe-Cu sulphides. The chondrite-normalized pattern (Fig. 4) has the expected positive slope. The calculated PGE+Au contents of the sulphide phase range from 56 to 1532 ppm. The reversal zone is regarded as potential for PGE ores.

A distinct pedogeochemical Pd anomaly coincides with the upper main zone rocks (see Kontas & Niskavaara, 1989), but we do not yet know whether the anomaly is due to PGE-enriched layers or to a general increase in PGE in the upper main zone.

The Upper Chromitite constitutes a distinct layer,1.3 m thick on average, situated on the 86 PCS level of the intrusion (Figs. 8, 9). The chromitite usually rests directly on mottled anorthosite, but in some drill hole sections a succession of alternating gabbroic and anorthositic rocks occurs between the UC and the footwall anorthosite.The UC is always separated from the hanging wall anorthosites by a layer of homogeneous medium-grained gabbro 0.7-1.0 m thick. A similar gabbro sometimes occurs in the middle of the UC (seam splitting). The overlying anorthosites are mottled and spotted types. Higher up, gabbroic interlayes appear, and from 20 m above the UC upwards, gabbros dominate over anorthosites.

The base of the UC is sharp, with the top normally consisting of a chromite-banded zone 5-10 cm thick . In places the banded part is missing, and a thin anorthosite layer separates the UC from the hanging wall gabbro. In this anorthosite, small chromitite fragments, eroded from the upper part of the UC, show scouring by magma currents. Strong convection and concomitant magmatic erosion preceded, accompanied and succeeded the accumulation of the UC.

The grain size of chromite decreases upwards from the base contact. In the middle of the layer, there is a size reversal back to coarser chromite; this reversal coincides with the level of the intervening gabbro layer.

The ore contains 21 wt % Cr_2O_3, 0.4 wt % V and 1.1 ppm total PGE. The chondrite-normalized PGE pattern is identical to that of LC (Fig. 6).

Euhedral, unchained chromite crystals constitute 39-47 vol.% of the ore. Sulphides occur in very small amounts. The PGMs encountered are ruarsite, sperrylite, a Pt-Pd bismuth telluride and a Rh sulphide. The gangue consists mainly of biotite and hornblende, in various proportions, and sodic plagioclase. Besides chromite the cumulus

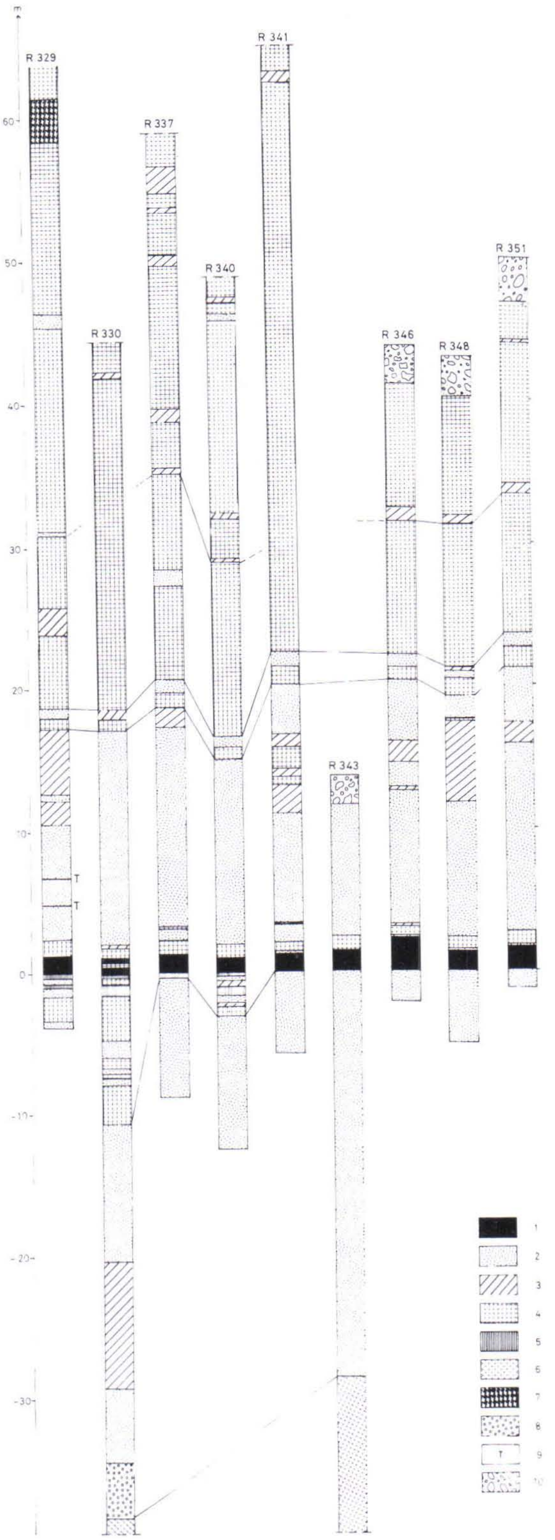


Fig. 8. Drill hole sections of the lower part of the upper zone, Koitelainen intrusion. 1 - UC layer; 2 - mottled anorthosite; 3 - gabbroic anorthosite; 4 - uralite gabbro; 5 - microgabbro; 6 - main zone gabbros; 7 - komatiite (xenolith); 8 - amygdaloidal basalt (xenolith); 9 - tourmaline; 10 -Quaternary deposits (till).

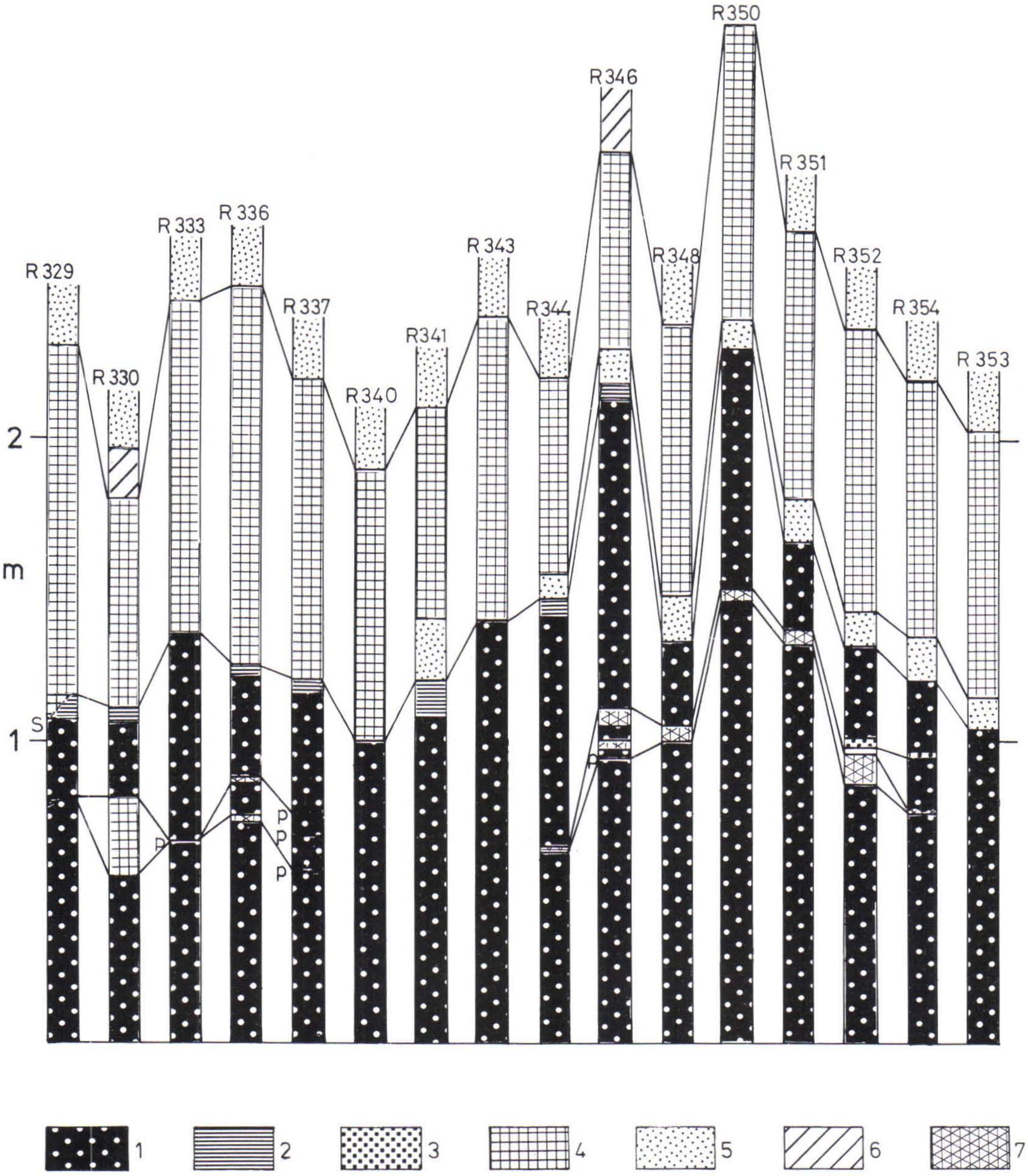


Fig. 9. Drill hole sections of the UC layer, Koitelainen. 1 - massive chromitite; 2 - banded chromitite; 3 - chromite-plagioclase cumulate; 7 - plagioclase-hornblende pegmatoids (=P); S = fault.

minerals are rare orthopyroxene (now cummingtonite) and plagioclase.

The composition of chromite is unique among ore chromites (Table 1), being fairly high in Cr and very high in Fe, Ti and V, but without Mg. Ti is incorporated in tiny exsolved ilmenite grains partly replaced by metamorphic titanite and biotite (Fig. 10). Fossil melt inclusions, indicative of rapid crystal growth in a viscous medium, are common in chromite (Fig. 11).

Magnetite gabbros. The PGE-Au enrichment in these rocks is one of the most conspicuous geochemical features of the Koitelainen intrusion. The magnetite gabbros

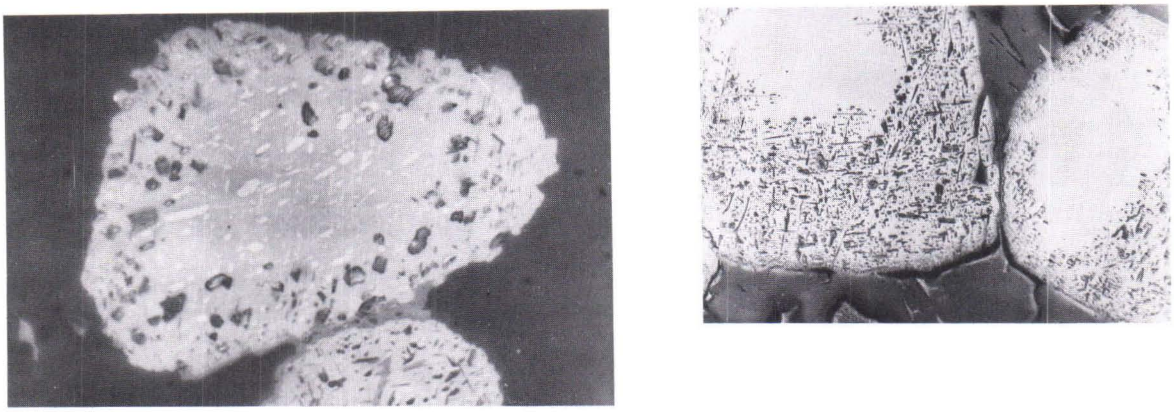


Fig 10. Exsolved ilmenite in chromite (left); chromite crystals with exsolved ilmenite partly replaced by secondary (metamorphic) silicates (right). UC layer, Koitelainen. Reflected light. Photomicrograph by Erkki Halme.

form a tripartite unit (Fig. 12). The lowermost part, about 45 m thick, is rich in V (0.14-0.25 wt.% V) and poor in Cu; near the top of the division Cu increases about tenfold, and remains high, even increasing towards the end of the unit. The Cu hike marks the level of terminal saturation of sulphides in the Koitelainen magma, with the separation of a Cu-rich sulphide liquid.

The gabbros immediately above the sharp base contact against the underlying spotted anorthosite gabbros are enriched in Cr.

Table 1. Electron microprobe analyses of chromites from chromitite layers of the Koitelainen intrusion

	1	2
SiO_2	1.0	-
TiO_2	0.4	0.9
Al_2O_3	9.3	11.9
FeO^{tot}	41.1	42.6
MnO	0.3	0.8
MgO	0.0	1.2
Cr_2O_3	47.5	41.6
ZnO	0.2	0.47
V_2O_3	0.8	0.32
CoO	-	0.12
NiO		0.0
Total	100.6	99.91
Cr/Fe	1.02	0.86

1 - UC sample, drill hole R329, by Jaakko Siivola, GSF

2 - LC, R359/ 42.07 m, by Tuula Hautala, GSF

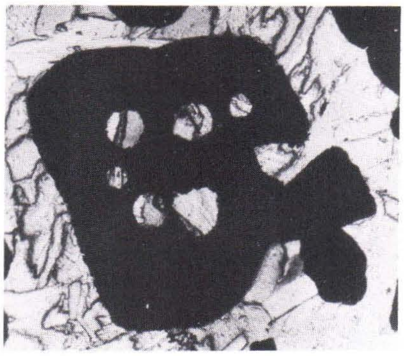


Fig. 11. Fossil melt inclusions in chromite. UC layer, Koitelainen. Transmitted light. Photomicrograph by Erkki Halme.

The 20 m-thick middle part consists of plagioclase-rich gabbros poor in V (0.03 - 0.07 wt % V). The top part, with a thickness of 35 m, is rich in V (0.2-0.3 wt % V).

The magnetite gabbros are cotectic plagioclase-pyroxene-magnetite cumulates (Fig. 13). During metamorphism, the plagioclase was largely albitized, and the pyroxenes (augite and probably also pigeonite) were uralitized. The magnetite of the composite magnetite-ilmenite grains has mostly been altered to hornblende and biotite (Fig. 14).

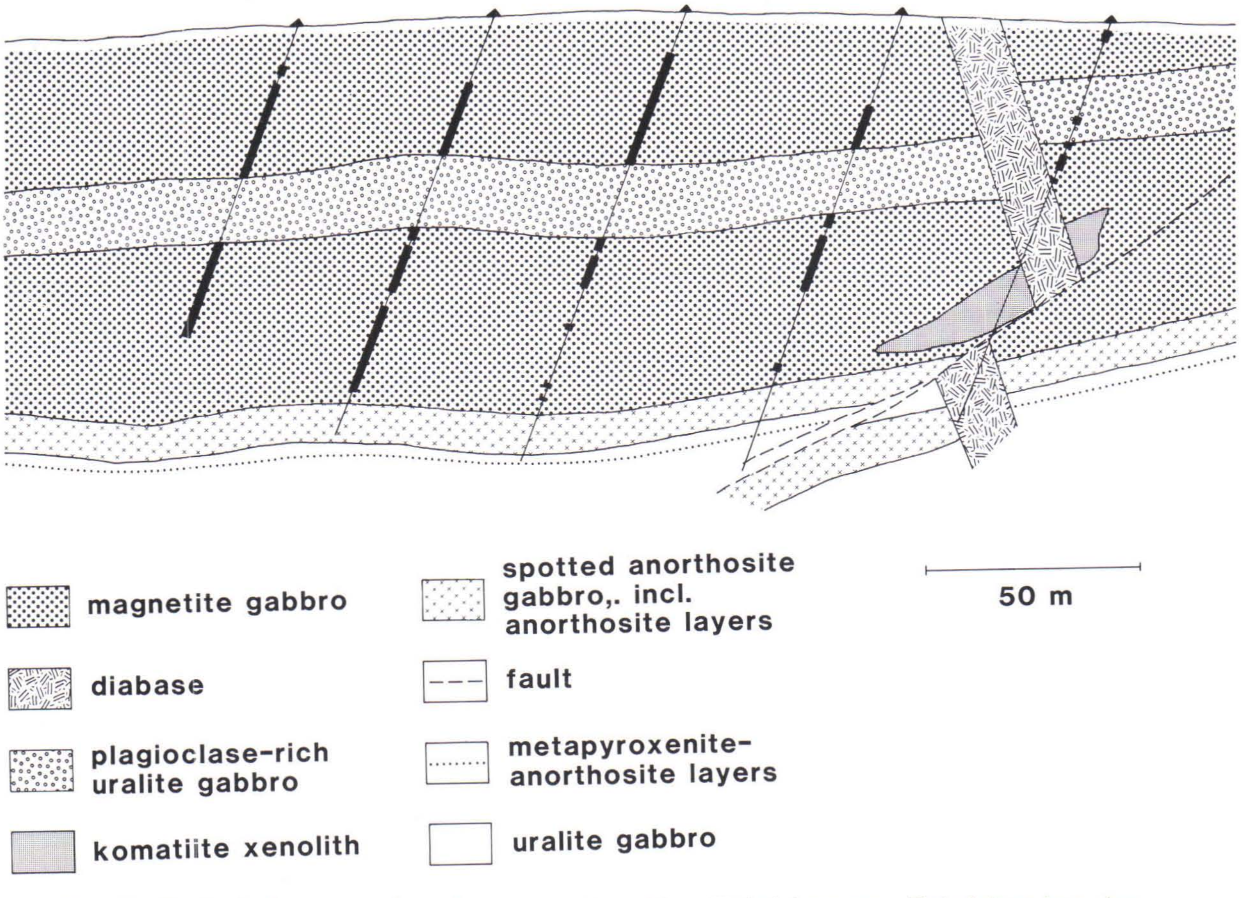


Fig. 12. Geological cross section of the magnetite gabbro, Koitelaisenvosat, Koitelainen intrusion.

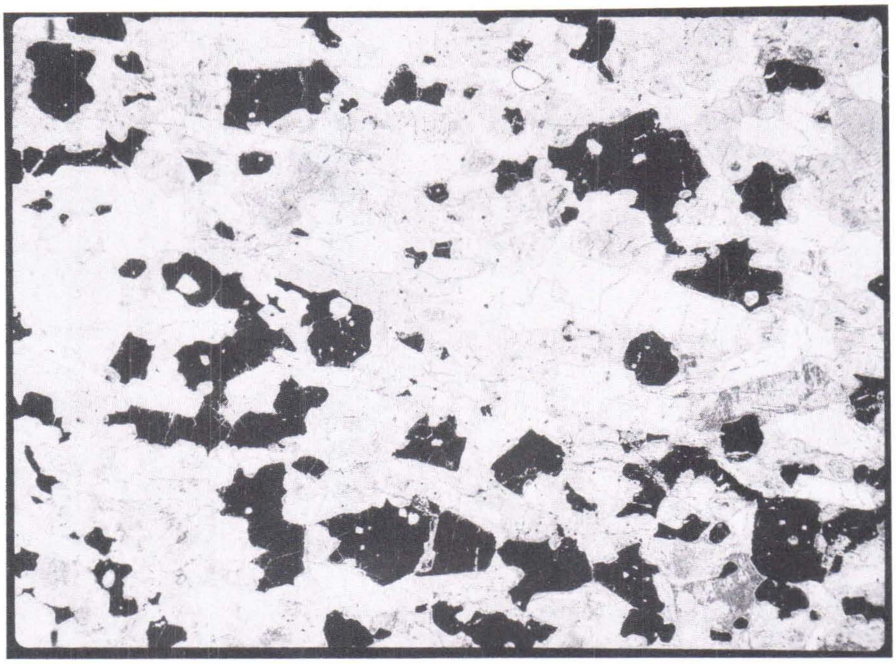


Fig. 13. Magnetite gabbro. Black – magnetite and ilmenite, grey – augite and uralite, white – plagioclase. Koitelaisenvosat, Koitelainen. Transmitted light. Photomicrograph by Erkki Halme.

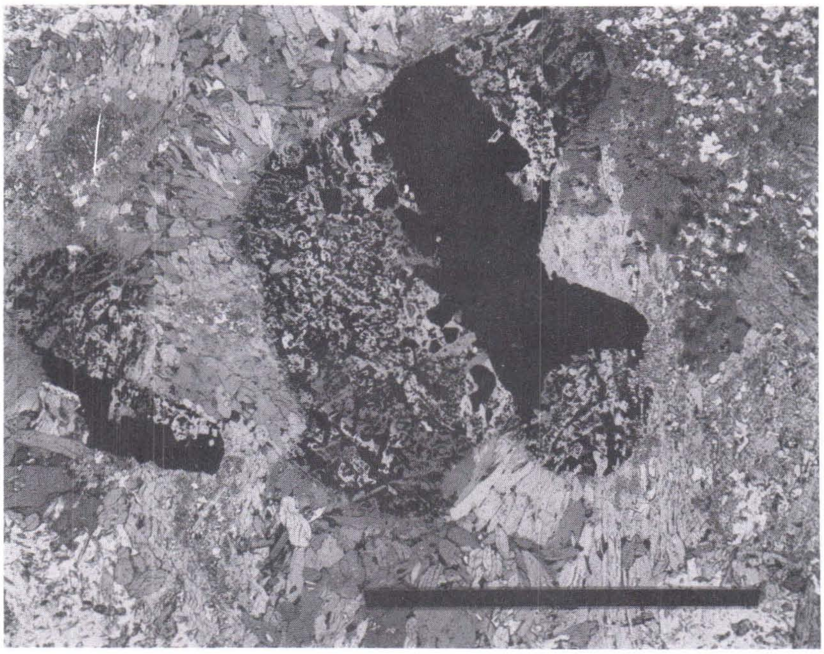


Fig. 14. A composite ilmenite-magnetite grain, magnetite completely silicated. Early exsolved granule ilmenite and later exsolved lace-like ilmenite have remained intact. Transmitted light. Photomicrograph by Erkki Halme. Scale bar 2 mm.

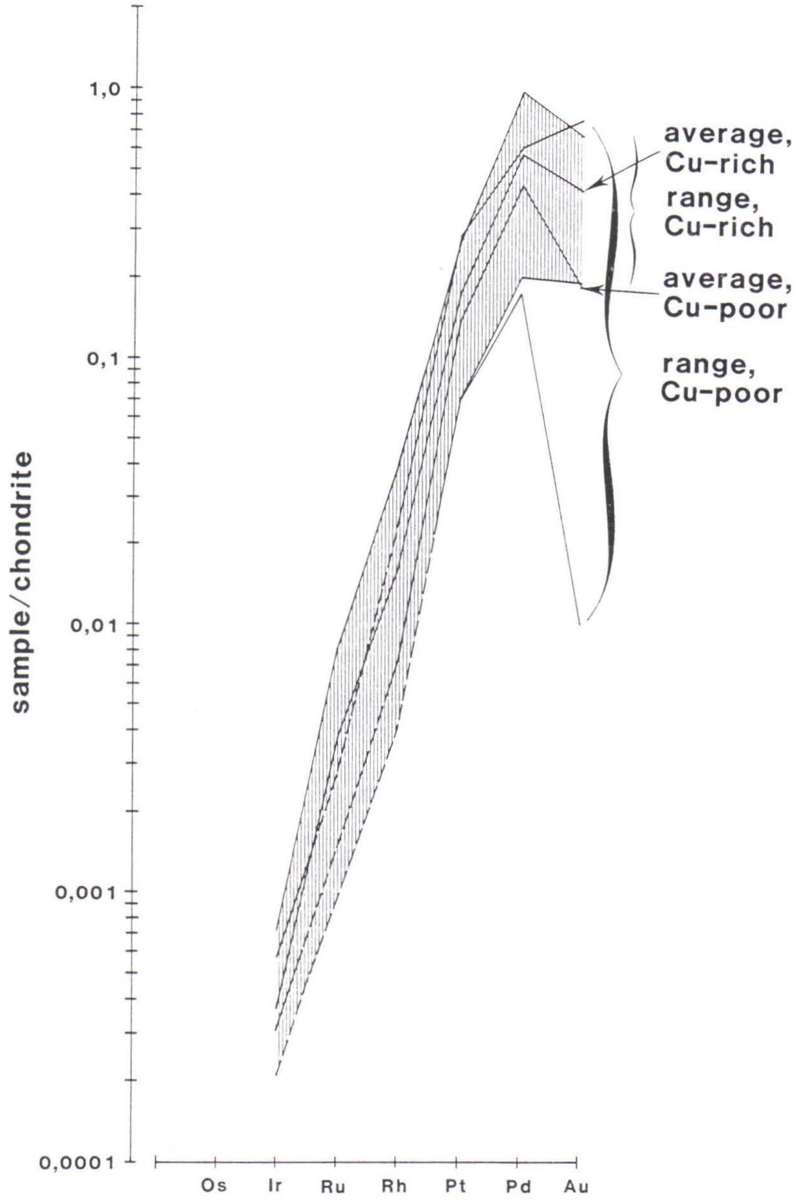


Fig. 15. Chondrite-normalized PGE-Au concentrations of magnetite gabbros, Koitelaisenvosat, Koitelainen.

Continuous assays of the cores from two drill holes (R318 and R319; see Figs. 16 a–c) show a distribution of Pt, Pd, Au and V. The grades are low in the the V-poor middle part, and finally die out rapidly at about 75 m above the base of the magnetite gabbro. The weighted average Pt+Pd+Au grade of the lowermost 75 m of magnetite gabbro is 0.5 ppm. The peak total assays are 1.17 ppm/2.0 and 1.21 ppm/2.35 m.

There is no correlation between PGE-Au and Cu, except for the highest value of Au, which coincides with the first Cu hike, i.e., with the first sulphide liquid separated from magma. The PGMs (cooperite, Pt tellurides, Pt-Fe alloys) do not follow sulphides, not even in the Cu-rich part, but occur as separate grains, mostly in magnetite. The PGE-Au correlate very well with V, i.e., with the abundance of original cumulus

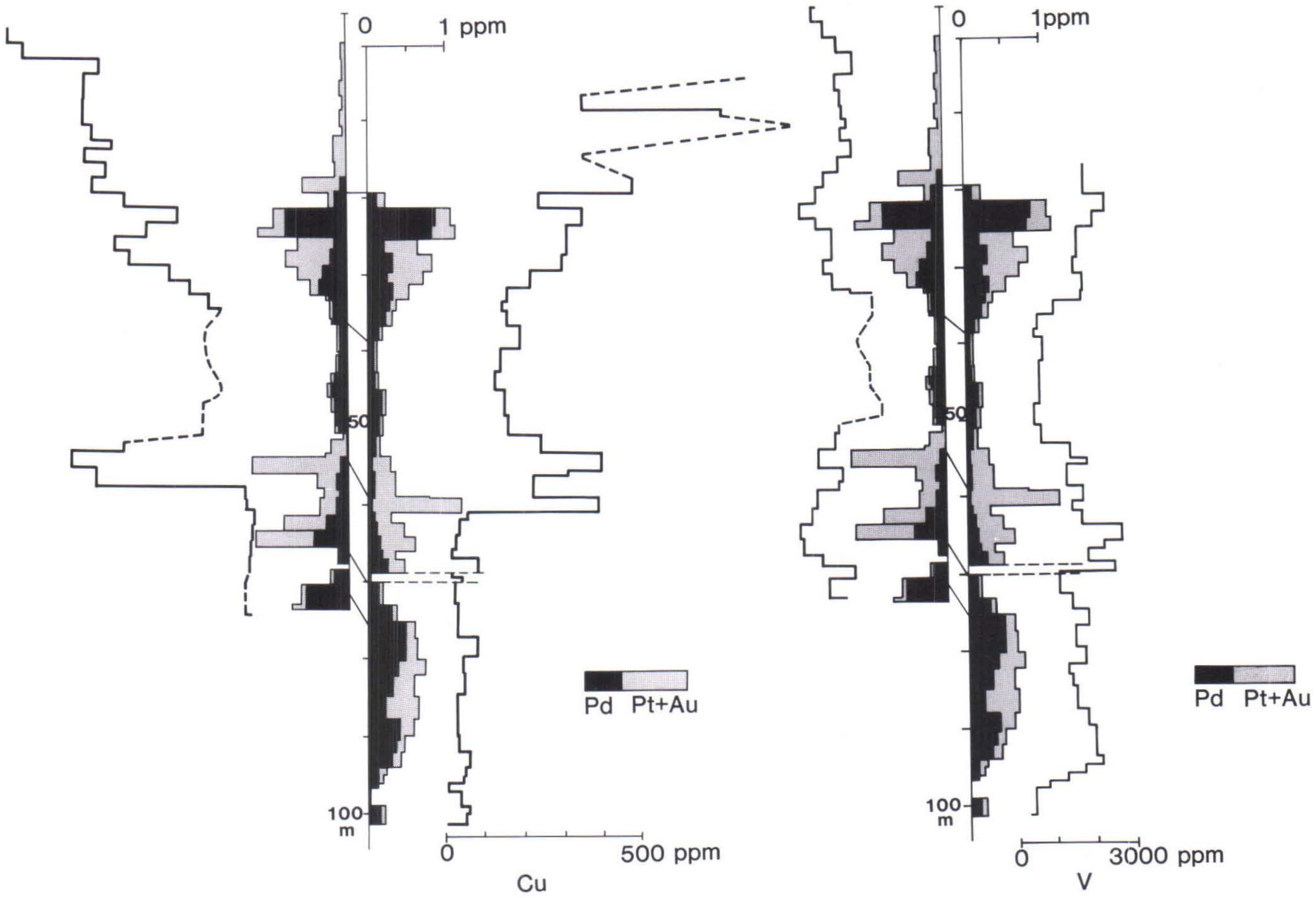


Fig. 16 a and b. Chemical variation in two drill holes across magnetite gabbro. Koitelaisenvosat, Koitelainen. Drill hole R318 (scale to the left) failed to reach the base contact, which is indicated by the sudden increase in V in drill hole R319 (scale to the right). Variation in Pd, Pt+Au and Cu (Fig. 16 a), Pd, Pt+Au, and V (Fig. 16 b) and Pd, Pt+Au, Pt/Pd and Au (Fig. 16 c) .

magnetite (see Fig. 16 b). The Pt/Pd ratios fluctuate within wide limits, even in successive core samples (Fig. 16 c). However, the vertical patterns of the ratio are similar in the two drill holes assayed. The average Pt/Pd in the Cu-poor lower part is 0.32, and 0.51 in the upper, Cu-rich part . The chondrite-normalized graphs of the Cu-poor and the Cu-rich parts are similar to each other (Fig. 15). Os, Ir and Ru are strongly depleted; curiously, however,the values Ir, Ru and Rh are higher in the upper magnetite gabbros than in the lower part. The PGE-Au allotted to sulphides is 870 ppb (max. 4321 ppb) in the Cu-rich part and 2234 ppb (max. 11626 ppb) in the Cu-poor part.

Discussion: petrology of the Koitelainen intrusion

The cumulate stratigraphy reflects normal, cotectic fractional crystallization, and superimposed contamination. The main contaminant was the salic roof melt, now granophyre, which formed through anatectic melting of the Lapponian schists. The most intense contamination coincided with episodes of melting and intermittent bursts of

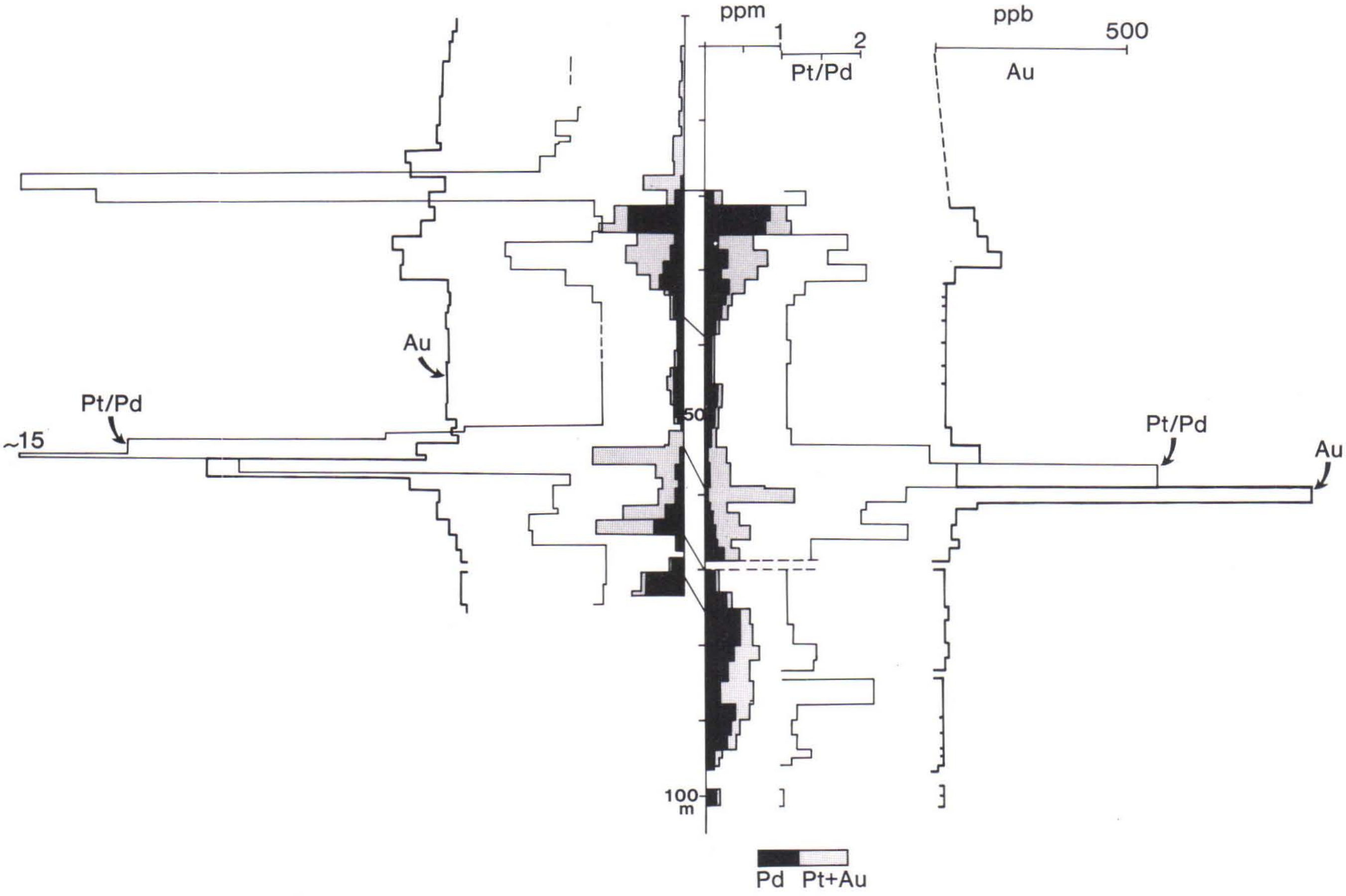


Fig. 16 c

convection but, never involved wholesale mutual mixing or solution of the anatectic salic melt and the mafic melt. The processes associated with contamination occurred basically in a vertically restricted mixing zone between the light, viscous salic roof melt and the underlying, convecting mafic magma. The buoyancy of the roof melt and the kinetic difficulty of mixing the contrasting magmas (Blake & al., 1965); Yoder, 1971; McBirney, 1980) quaranteed the isolation of the melts, and the autonomous evolution of the mafic magma towards iron enrichment. The mixing was evidently occasionally boosted by refractory xenoliths falling from the melting roof; however, it was convection that was principally responsible for the mixing of the salic and mafic ingredients in the mixing zone and for the strewing of crystals along the magma/cumulate interface.

The mafic magma incorporated exotic components through selective diffusion, mixing with anatectic melts and digesting (or reacting with) excess residual phases after partial melting of the country rocks.

Usually, the three processes seem to have acted simultaneously. It is important to note that the effects of contamination were mostly only "catalytic", leaving no readily discernible clues of the contaminant.

It is considered that the cumulus minerals crystallized in the contaminated roof region of the magma, in the mixing zone. This zone consisted of a salic/mafic emulsion

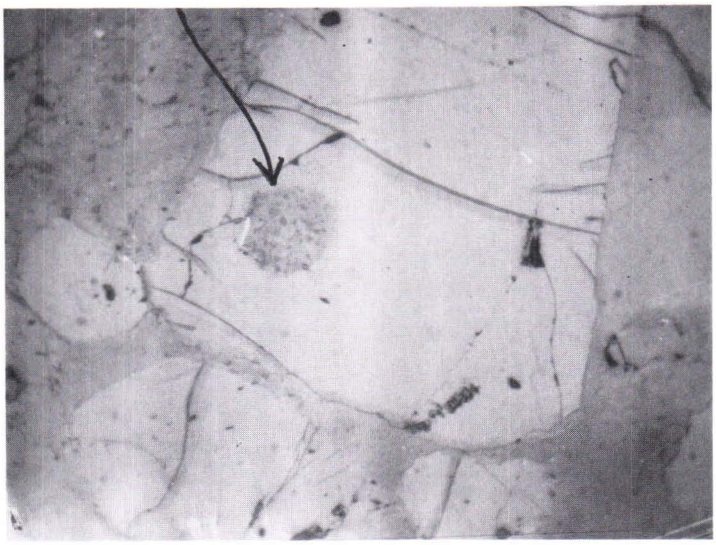


Fig. 17. A melt inclusion in olivine (arrow), with a daughter crystal of ilmenite (white). The diameter of the inclusion is about 20 µm. Dunite, sample 3723/R310 - 82.50 m. Kivelä area, Koitelainen. Reflected light.

and their hybrids, along with residual and newly formed mineral phases. Brought to the mafic magma, the crystals adjusted themselves compositionally and, if not in equilibrium as phases with the mafic magma, either reacted or dissolved altogether.

Towards the end of fractionation of the mafic magma, the salic melt and the residual mafic melt approached an immiscible relationship, and contamination was due to residual phases.

In the following, features are described which could be attributed to contamination.

Table 2. Electron microprobe analyses of olivine melt inclusions, wt. %. Lower zone dunite, Koitelainen. Anal. Bo Johanson, GSF.

	1	2
SiO_2	43.2	59.2
TiO_2	0.35	0.00
Al_2O_3	9.69	16.6
FeO^{tot}	7.09	1.90
MnO	0.05	0.03
MgO	27.10	11.1
CaO	3.34	1.16
Na_2O	0.7	8.83
K_2O	5.61	0.27
Cl_2O	0.45	0.11
Sum	97.58	99.70

1 = K-Ca-type inclusion, 2 = Na-Si-type inclusion.

The massive accumulation of olivine cumulates which launched the formation of the layered succession is in strange contrast to the absence of olivine from the chilled early marginal rocks. Now melt inclusions, abundant in cumulus olivine, provide clues to this puzzle.

The melt inclusions are of the sealed or reentrant type, ranging in size from less than 10 μm to 200 μm (Fig. 17). Some olivine crystals are full of inclusions ("Swiss cheese olivine"). Orthopyroxene usually occurs in inclusions as a reaction rim against the olivine host. Other daughter minerals are phlogopite, brown hornblende, ilmenite and chlorapatite. Most inclusions analysed by electron microprobe are high in K and Ca, others are high in Na and Si (and low in Ca) or compositionally intermediate (Table 2). Obviously, the inclusions do not represent the mafic mother magma but are samples of the salic/mafic emulsion of the mixing zone. The K-Ca type inclusions are interpreted as representing trapped mafic liquid which had gained K from the salic liquid by selective diffusion (or selective contamination; see Watson, 1982); the Na-Si type inclusions are samples of the contaminant melt which had lost K to the mafic melt (op. cit.). The addition of alkalies, and also of H_2O, shifted the composition of the mafic melt into the olivine liquidus field (Kushiro, 1973). Thus, selective contamination is able to change the course crystallization radically from that "predetermined" by the composition of the virgin parent magma (cf. Biggar, 1974)

Similar inclusions occur in olivines of the Keivitsa - Satovaara complex (see later), and also in the Kemi intrusion. Descriptions in the literature (Predovskii & Zhangurov, 1968; Fenogenov & Emelyanenko, 1980) indicate that inclusions of contaminant melt in olivine may be common in layered intrusions.

Besides phase reversals (olivine), the additions of alkalies may produce MgO/FeO compositional reversals in ferromagnesian cumulus silicates, by raising the ferric/ferrous iron ratio of the liquid (see Paul & Douglas, 1965). Thus, olivine crystallized from an alkali-contaminated magma would have a higher Fo content than that crystallized from a virgin melt. The chilled hybrid melt, described by Maury and Bizouard (1974, p. 279), is a case in point.

Daughter crystals of chlorapatite, also found in melt inclusions in olivine of the Keivitsa - Satovaara complex and of the Kemi intrusion, clearly indicate intake of Cl, probably by selective diffusion from metasediments and from anatectic melt. The average Cl concentration of the melt inclusions in olivine is 3000 ppm (max. 6000 ppm), as analysed by electron microprobe from inclusion matrix, avoiding chlorapatite daughter crystals. A big chlorapatite crystal was also found as an occluded mineral in a magma inclusion in cumulus orthopyroxene, in a lower zone harzburgite.

Plagioclase crystals likewise felt the effect of contamination. Plagioclase is typically reversely zoned, with a core more albitic than the surrounding overgrowth zone. In the gabbroic interlayers of the lower zone, areas of potassium feldspar are common in the cores of zoned plagioclase crystals. These features suggest that the plagioclase crystals started to grow in a contaminated, alkali-rich part of the magma chamber.

Intercumulus material rich in alkalies (dunites, peridotites, chromitites) and in silica (pyroxenites) is also interpreted as representing the contaminated environment, caught in the crystal-laden density flow and trapped between cumulus crystals (see Irvine, 1979). Accessory minerals such as loveringite, zircon, baddeleyite, thorite, galena, molybdenite, xenotime, chlorapatite and fluorapatite, which often occur as large, well-shaped crystals, crystallized from the contaminated melt (Tarkian & Mutanen, 1987).

The cohabitation of cumulus olivine and intercumulus quartz in some feldspathic olivine pyroxenites (a feature also noticed in Merensky Reef) indicates that the hybrid melt was compositionally heterogeneous. The resultant rock is a composite of small domains of feldspathic olivine pyroxenite and quartz-bearing feldspathic pyroxenite. The "pitted peridotites" of the Keivitsa - Satovaara complex are a major unit of heterogeneous cumulates of this type.

The peridotite-mixed rock layer of the main zone provides petrographic, mineralogical and geochemical evidence for contamination (Fig. 18) The layer is interpreted as having formed through the combined effects of selective alkali contamination and salic contaminaton. The crystals formed in the contaminated environment deposited from a density flow. The salic portions represent the salic contaminant, modified by selective diffusion (loss of K to, and intake of Na from, the mafic magma). Phlogopite-rich melt inclusions in chromite and in chlorapatite, as well as the phlogopite-rich intercumulus matrix, represent samples of the K-enriched environment which bred the olivine. Contamination is clearly attested to by the range of accessory minerals: chlorapatite, zircon (both as big crystals), baddeleyite, loveringite, thorite and galena. Such would hardly be expected were the peridotite the result of a new pulse of primitive magma. In the drill hole section (Fig. 18) it is seen that peridotite is enriched in both Pb and Zn compared with gabbros below and above it. The peak Pb values, from 4 to 6 times the background concentration in gabbros, occur in the salic parts of the mixed rock. There is no primary sulphide enrichment in the peridotite to explain the Pb-Zn anomaly.

The UC layer presents a paradox which does not yield to conventional genetic explanations. There is no evidence that a pulse of fresh magma supplied the Cr. Just before deposition of the UC, the residual magma contained about 5 ppm Cr. To produce the UC from this magma (and making the rather impossible assumption that any chromite would crystallize from such a dilute magma) would have called for a liquid layer about 35 km thick; at the time of deposition of the UC, however, only some 300 m of magma were available. Moreover, the rocks overlying the UC are as hopelessly poor in Cr as are the footwall gabbros. Whatever the source of Cr, all the Cr supplied to the magma system was deposited as the UC layer.

Instead of the residual liquid (too dilute) or a new magma pulse (nonexistent), an adequate source of Cr was available right in the roof - the high-aluminous schists. It was suggested earlier (Mutanen, 1981), that the Cr was liberated by the melting of these schists. The melting produced about 70 wt % liquid of the present granophyre composition, the rest being refractory phases, mainly Al-rich silicates and magnetite. The topmost granophyre contains up to 2000 ppm Cr, mainly in magnetite. A simple calculation shows that melting of 415 m of schist (with an average of 530 ppm Cr_2O_3) would produce 290 m of granophyre and 1 m of chromitite with 20 wt.% Cr_2O_3. In Koitelainen, the excess alumina was bound to a grossular-almandine garnet, which reacted with the mafic magma to produce plagioclase. Ultimately, the liberated excess alumina formed anorthositic cumulates.

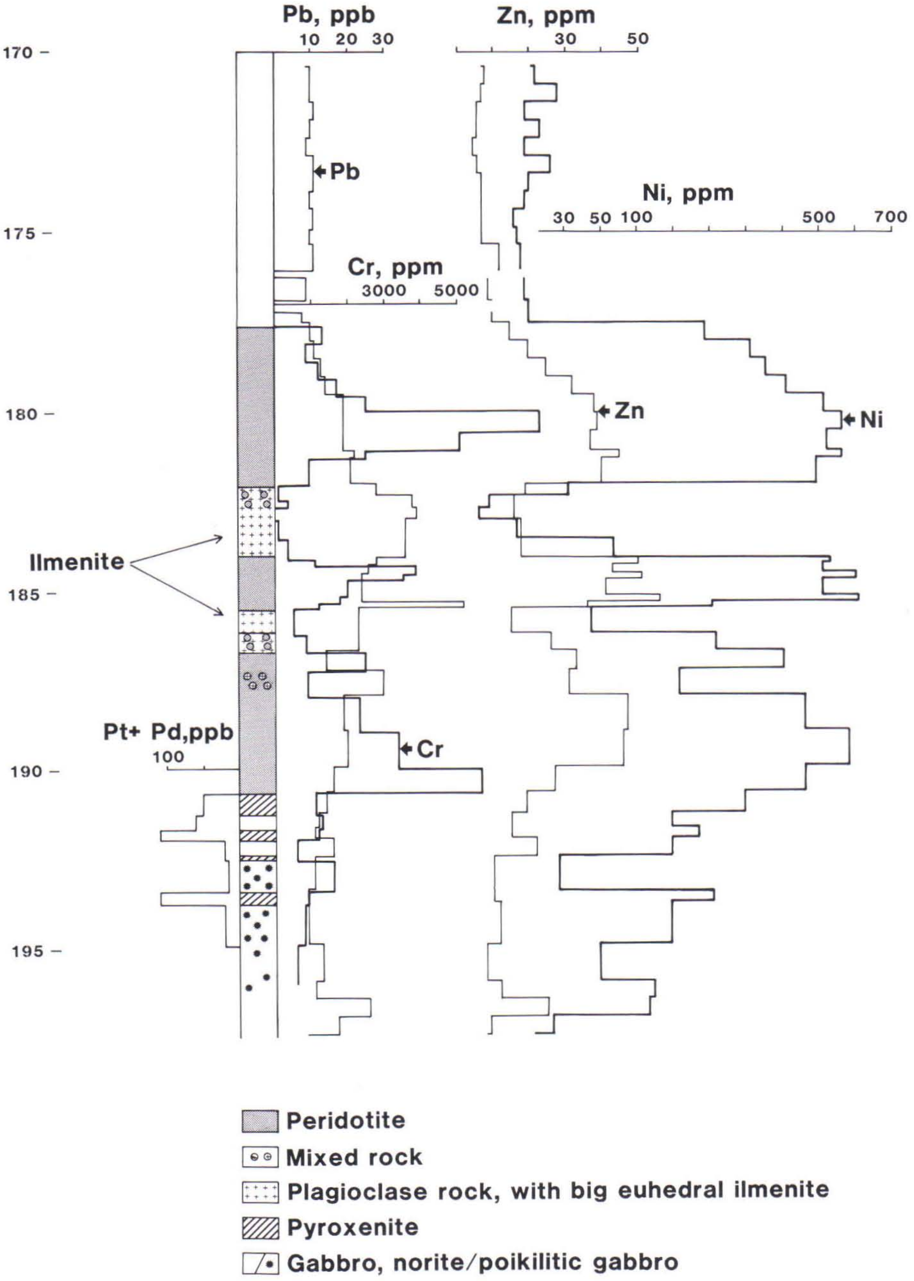


Fig. 18. Columnar section of the peridotite – mixed rock layer (drill hole R365), showing variations in Pt+Pd, Cr, Ni, Pb, and Zn. Note that the scale for Ni is not linear. Keskilaki area, Koitelainen intrusion.

THE KEIVITSA - SATOVAARA COMPLEX

Form and structure

The complex consists of the layered intrusions of Keivitsa and Satovaara and a dunite body inside the Keivitsa intrusion (see Geological map, App. 2). The Keivitsa intrusion (in the west) and the Satovaara intrusion (in the east) probably represent blocks of a single intrusive body, separated by NE faults. The magma is thought to have been emplaced just before the intrusion of the Koitelainen magma.

The Keivitsa intrusion is shaped like a steep-sided basin, with an original thickness of 1–2 km. The dunite body, which is located in the middle of the basin structure, was emplaced before the Keivitsa intrusion, and is not directly related to it. The Satovaara intrusion is a NW dipping sheet with an estimated thickness of 300–500 m. The following description mainly concerns the better known Keivitsa intrusion.

The intrusion is surrounded by a wide aureole of hornfelses. Xenoliths and large roof pendants of schists and volcanic rocks abound in the southern half of the intrusion. Large-scale melting of country rocks is not evident, although granitic melt inclusions in olivine indicate that melting of the country rocks took place. The abundance of primary hornblende and phlogopite, and the occurrence of primary Cl minerals (chlorapatite and dashkesanite) indicate pronounced intake of volatile components from the country rocks. The magma also obtained considerable amounts of exotic sulphur, by direct melting of sulphide-rich schists and by gaseous transfer.

Fine-grained chilled rocks formed against roof pendants, but they are not known from the basal contact. At the base of the intrusion, there is a narrow zone of contaminated, quartz-rich gabbros and feldspathic pyroxenites. In the pyroxenitic lower part, interstitial sulphides are common, typically enveloping and wetting euhedral crystals of cumulus orthopyroxene. Intercumulus dashkesanite and chlorapatite are common but never abundant.

Upwards, with the decrease in the abundance of intercumulus plagioclase and the appearance of olivine, the pyroxenites grade into olivine pyroxenites and peridotites. Intercumulus plagioclase occurs in small amounts in all peridotites of the intrusion. The peridotites grade upwards into "pitted peridotites", the trade mark of the Keivitsa and Satovaara intrusions. These rocks are composed of 5-10 cm domains of wehrlitic and lherzolitic rocks. The postcumulus phlogopite in the lherzolitic domains makes these very susceptible to grussification weathering, resulting in a peculiar pitted surface. The pitted peridotites are interpreted as mixed cumulates; the phlogopite-bearing lherzolitic cumulus assemblage is thought to have formed in a silica-contaminated part of the magma chamber, which mingled with the cumulus assemblage of olivine and augite. The pitted peridotites grade upwards into homogeneous wehrlite which contains sparse grains of orthopyroxene. The uppermost ultramafic rocks are feldspathic olivine pyroxenites and pyroxenites, the majority altered to hornblendites.

The gabbros seem to be confined to the upper distal fringes of the Keivitsa intrusion, but their relations to the peridotitic cumulates are still obscure. Most of the gabbros are thoroughly altered to albite-uralite gabbros. The lower gabbros appears to be

Fig. 19. Euhedral crystals of "cumulus" graphite, Keivitsa intrusion. The rock is partly uralitized augite-pigeonite gabbro. The longest graphite flakes are about 2 mm. Textures indicate that graphite crystallized together with plagioclase and pyroxene. Fine flakes of "intercumulus" graphite occur throughout the rock but are not seen in this picture. Reflected light. Photomicrograph by Jari Väätäinen.

mesocratic, medium-grained rocks in which augite and inverted pigeonite are sometimes preserved. These are overlain by coarse-grained anorthositic gabbros. At Satovaara, the uppermost anorthositic gabbros contain pa^{c}thes of granophyre.

A layer of pigeonite gabbro underlies the sulphide deposit, "A", in the Keivitsa intrusion. The gabbro contains up to 3 vol % of euhedral primary (liquidus) graphite (Fig. 19).

Dunite

The dunite body appears on the magnetic map as a ring-shaped positive anomaly, 0.6 by 1.5 km in size. A deep gravity and magnetic low is located in the core of the ring. The nature of the core rock is still unknown. The dunite has only one outcrop. Its contact with the underlying metasomatized hornfelses (?) and feldspathic metapyroxenites of the Keivitsa intrusion has been intersected by two drill holes. The lower part of the dunite, the silicified dunite, hosts the "chondritic PGE deposit".

According to its major and trace element composition, the dunite (Table 3) is a typical peridotitic komatiite.

Table 3. Chemical composition of dunite, Keivitsa (sample TM-84-91.1)

	wt.%
SiO_2	43.96
TiO_2	0.18
Al_2O_3	3.78
FeO	11.49
MnO	0.17
MgO	36.28
CaO	3.99
Na_2O	0.12
K_2O	0.02
P_2O_5	0.00
	ppm
Ba	36
Co	114
Cr	3890
Cu	42
La	<5
Ni	1645
Sc	16
Sr	<5
V	133
Y	<5
Zn	321

U, Rb, Zr, Nb, Mo, Sn, Th < 0.003%, Cs < 0.005%, Ta < 0.010 %

Major elements and Rb, Sr, Y, Zr, Nb, Mo, Sn, Cs, Ba, Ta, Th, U by XRF (Harry Sandström, GSF); Ba, Co, Cr, Cu, La, Ni, Sc, Sr, V, Y, Zn by ICP (Eeva Kallio, GSF).Volatile-free, total Fe as FeO; summed to 100 %.

Occurrence of sulphides and PGE

Offset veins of massive Cu-rich sulphides have been intersected by drilling in the footwall rocks of the Keivitsa intrusion. The veins are barren of PGE. The basal contaminated gabbros and pyroxenites contain massive, disseminated and "buckshot" sulphides across a thickness of 3-4 m, but these rocks have low contents of Ni, Cu and PGE. Geophysical surveys indicate that sulphide concentrations also occur at the base of the Satovaara intrusion.

The peridotites overlying the pyroxenites contain pockets of rich disseminated and massive sulphides; the sulphide phase, however, is very low in Ni, Cu and PGE-Au.

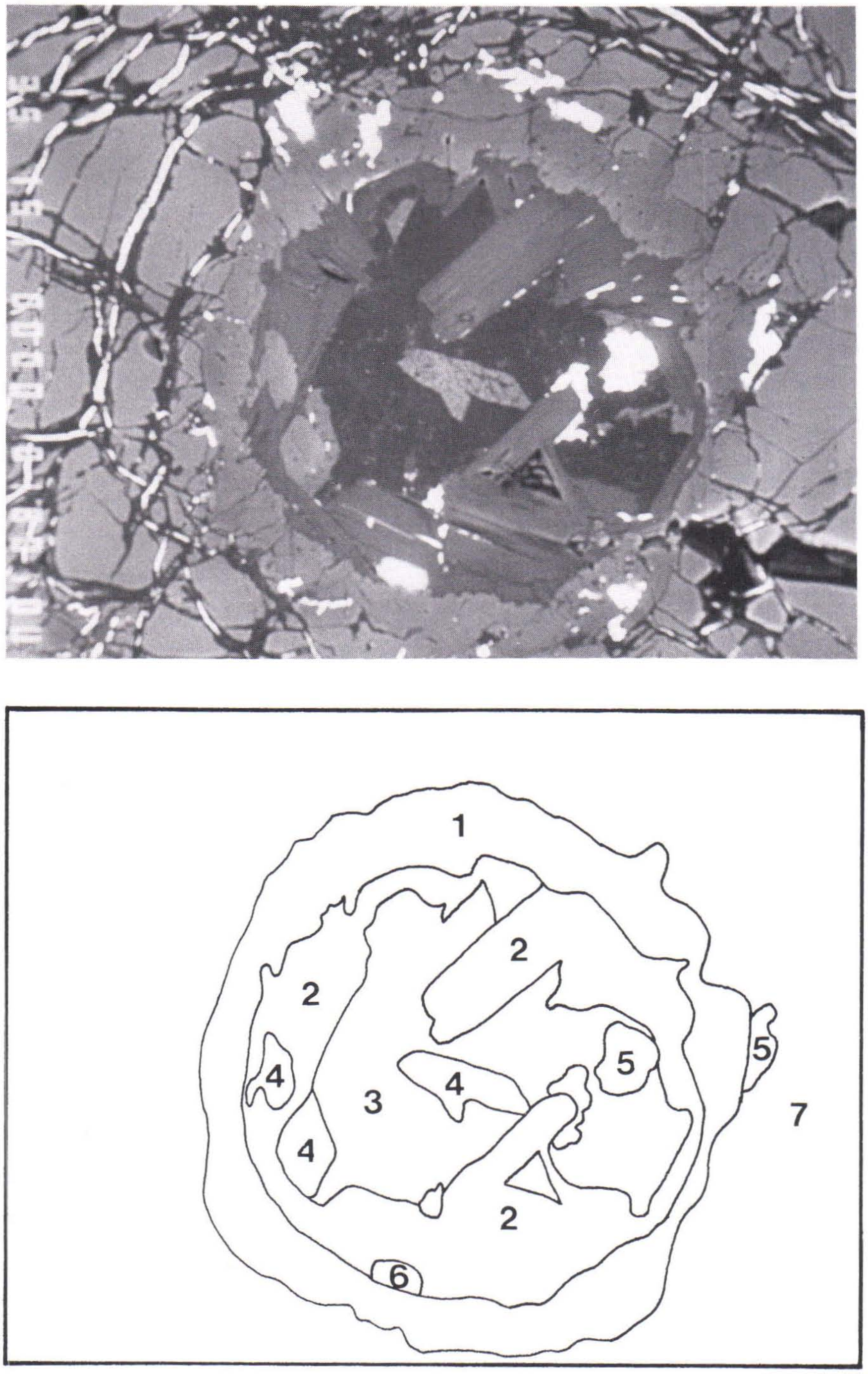


Fig. 20. Back-scattered electron image of a large, well-crystallized granitic melt inclusion in olivine from a peridotite, Satovaara intrusion. Minerals marked with numbers in the sketch; 1 - orthopyroxene; 2 - biotite; 3 - albite; 4 - hornblende; 5 - magnetite; 6 - chlorapatite; 7 - host olivine. The inclusion measures about 0.2 mm. Photo by Bo Johanson.

Beautiful granitic melt inclusions in the olivine of the host peridotites indicate that the cumulus assemblage crystallized (and the sulphide liquid separated) in an environment contaminated with salic material (Fig. 20).

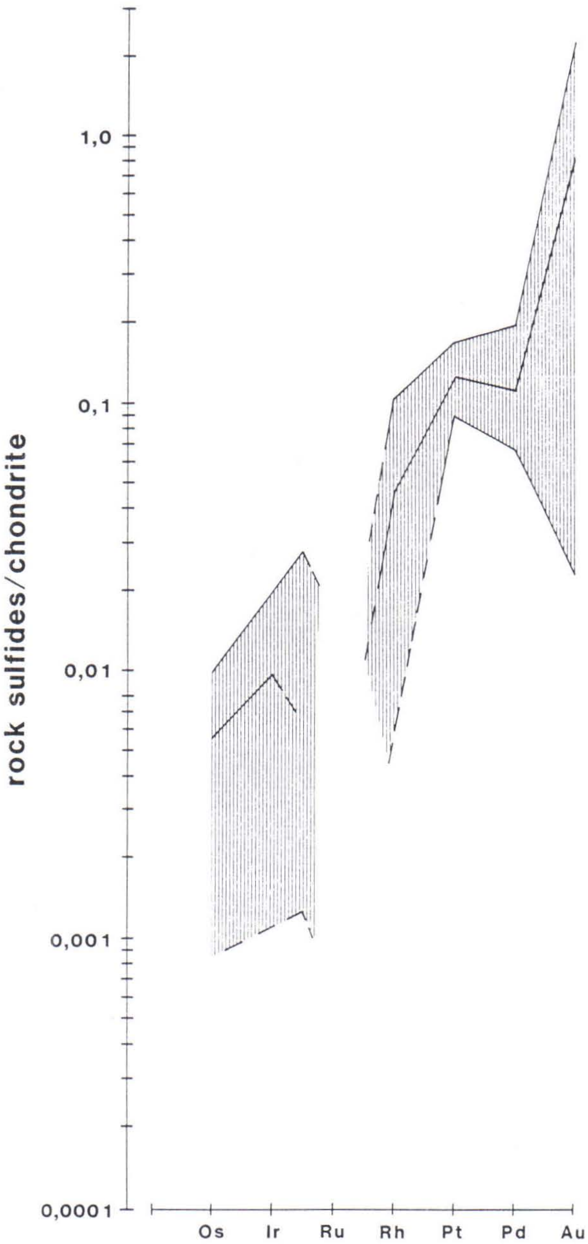


Fig. 21. Chondrite-normalized PGE-Au concentrations of the sulphide phase of the Ni-PGE-poor disseminated and massive sulphides of deposit "A", Keivitsa intrusion.

In the Keivitsa intrusion, the sulphide deposit marked by "A" on the geological map (App. 2) is located between a layer of graphite-bearing gabbro (below) and metaperidotite (above). The deposit consists of massive and breccia ores of the gabbro/peridotite contact zone, and coarse disseminated sulphides in the overlying metaperidotite. The fragments of the breccia ore consist of metasedimentary hornfelses and metaperidotites. The sulphide phase is low in Ni (ca. 1 wt.%) and PGE (0.2–0.37 ppm), and has a low Ni/Co ratio (ca. 5). The chondrite-normalized graph has a positive slope from Os to Au, with a negative Ru-anomaly (Fig. 21). A geochemical feature of these Ni-PGE-poor sulphides

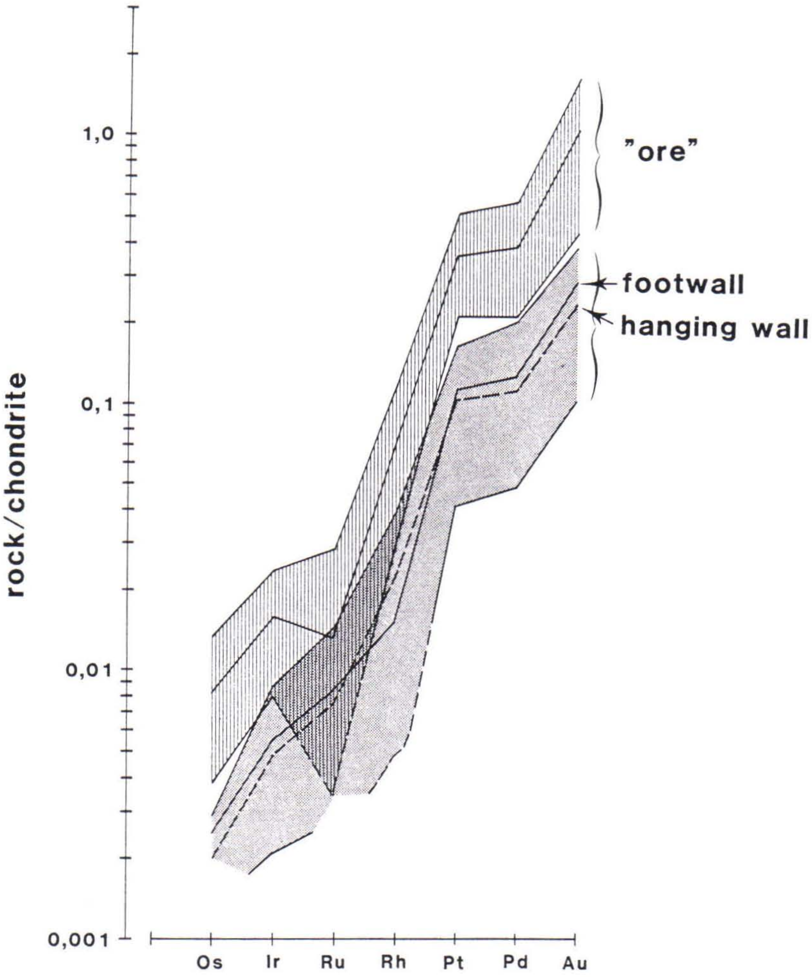


Fig. 22. Chondrite-normalized PGE-Au concentrations of the Ni-PGE-rich disseminated sulphides of deposit "D", Keivitsa intrusion (rock concentrations vs. chondrite). The range of the disseminated footwall sulphides is marked by dark shading.

that distinguishes them from sulphides rich in Ni and PGE-Au (deposit "D") is the presence of Re (40–63 ppb Re in the sulphide phase). This Re enrichment is attributed to contamination. The low Ni and PGE and the low Ni/Co ratio are probably due to barren sulphides incorporated into the magma from melted sediments.

Deposits "B" and "C" (see geological map, App. 2) comprise "barren" sulphides similar to those of the "A" deposit.

Deposit "D" is quite different from those mentioned above. It consists of a layer of disseminated sulphides in wehrlite, with a thickness of 40–50 m. The sulphide phase contains 6–7 wt.% Ni and ca. 20 ppm PGE+Au. The Ni/Co ratio is high, typically in the range 15–25. Re is always below the detection limit of 5 ppb. Veins of massive sulphides occur among the Ni-PGE-rich disseminated sulphides; likewise, the underlying peridotites contain sulphide-rich segregations. All these sulphide-rich parts are poor in Ni and PGE-Au, have a low Ni/Co ratio and an elevated concentration of Re, features typical of the "A" deposit.

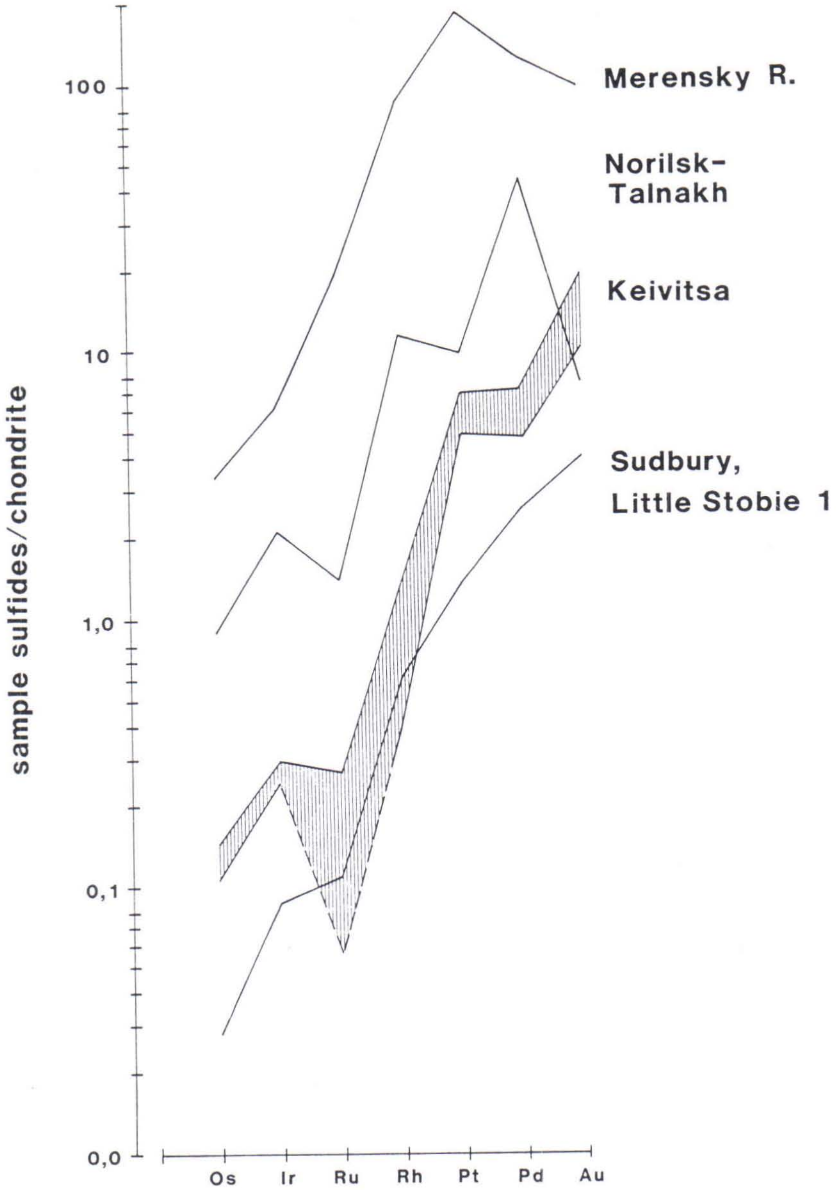


Fig. 23. Chondrite-normalized PGE-Au concentrations of the sulphide phase of the "D" deposit, Keivitsa, compared with the sulphide phase concentrations of Merensky Reef, Norilsk-Talnakh and Little Stobie 1, Sudbury; data on the latter three deposits according to Naldrett (1981)

The chondrite-normalized PGE-Au values for the disseminated ore of the "D" deposit, along with those of the low-grade disseminated hanging wall and footwall rocks, are shown in Fig. 22. In Fig. 23, the chondrite-normalized sulphide phase values of the Keivitsa "D" deposit are compared with those of the Merensky Reef, Norilsk-Talnakh and Little Stobie 1 (Sudbury).

At Satovaara , cumulus chlorapatite (Fig. 24) and primary, high-temperature dashkesanite are associated with Ni-PGE-rich sulphides. Electron microprobe analyses

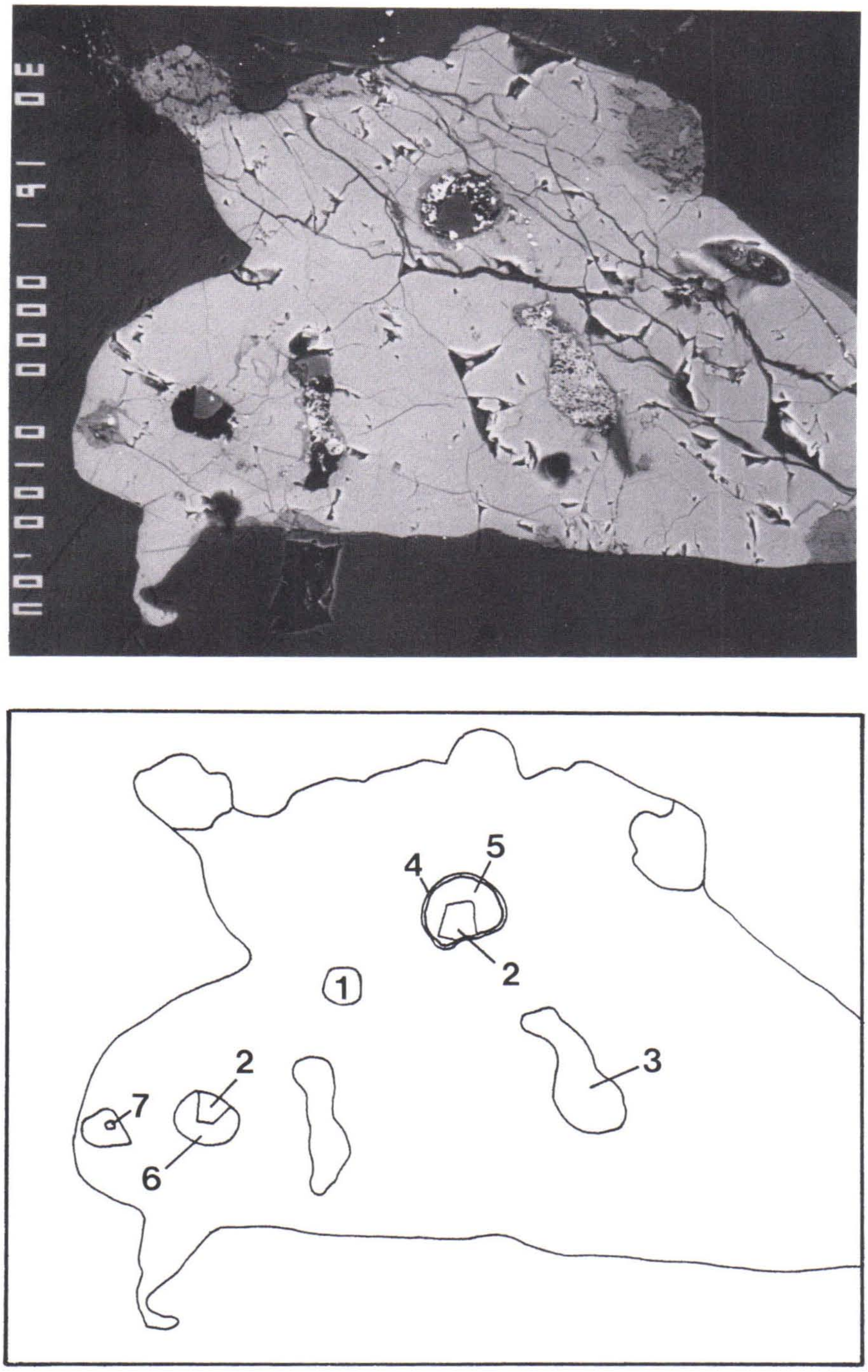


Fig. 24. Secondary-electron image of a crystal of cumulus chlorapatite, peridotite, Satovaara intrusion. The numbers in the sketch: 1 - chlorapatite; 2 - euhedral daughter crystals of phlogopite (poor in Ba and Cl) in melt inclusions; 3 - an inclusion of a Cl-rich amphibole-like mineral (dashkesanite ?); 4 - a narrow rim of fluorapatite, bordering a melt inclusion against the host chlorapatite; 5 - melt inclusion matrix rich in Cl and Ba (Ba-Cl-phlogopite ?) and containing grains of galena and monazite; 6 - melt inclusion matrix mainly composed of Mg and Si (serpentine ?); 7 - monazite in melt inclusion. The length of the chlorapatite crystal is about 2 mm. Photo by Ragnar Törnroos.

Table 4. Compositions of chlorapatite and dashkesanite. Electron microprobe analyses, Ragnar Törnroos (1) and Bo Johanson (2–5)

	1	2	3		4	5
SiO_2	0.08	0.36	0.09	SiO_2	36.6	37.5
FeO	0.02	0.25	0.18	TiO_2	1.05	0.99
MnO	0.03	0.10	0.01	Al_2O_3	14.8	14.1
MgO		0.24	0.03	FeO	18.1	17.2
SrO	1.65			MnO	0.15	0.15
CaO	52.8	54.2	53.5	MgO	8.68	9.32
PbO	0.22			CaO	11.6	11.2
P_2O_5	40.2	40.9	42.1	BaO	0.15	0.16
F	1.66	0.26	0.33	Na_2O	1.81	1.85
Cl	6.18	6.95	7.20	K_2O	1.88	1.62
Br	n.d.			F	0.00	0.17
F,Cl = O	-2.10	-3.50	-3.53	Cl	4.50	4.42
				F,Cl = O	-2.07	-2.16
Total	100.74	99.94	99.94		97.25	96.53

1 – cumulus chlorapatite, mixed rock, Koitelainen
2, 3 – cumulus chlorapatite, peridotite, Satovaara
4, 5 – dashkesanite, peridotite, Satovaara
n.d. – not detected, blank space – not determined.
Note: Another grain of cumulus chlorapatite from mixed rock, Koitelainen, assayed 0.67 wt.% Br.

of cumulus chlorapatite from Koitelainen and Satovaara, and of dashkesanite, are presented in Table 4.

Sperrylite, Pd tellurides and various Pd-bearing Fe tellurides and Ni-Fe tellurides, Pd Bi-tellurides, Pb-Fe tellurides and altaite have been identified from Satovaara. So far, no PGMs have been found in the Keivitsa "D" deposit.

The most unusual PGE deposit of the Keivitsa - Satovaara complex is that associated with the silicified basal part of the dunite body in the lap of the Keivitsa intrusion. The mineralization is hosted by quartz rocks with albite, chromite, magnetite, ilmenite and rutile in varying amounts. The rocks are massive and cavernous (due to dissolved carbonate ?), or banded and hornfels-like. The colour ranges from white and grey to dark grey and black, depending on the abundance of Fe-Ti-Cr oxides.

The silicifield rocks are depleted in Ni (100-600 ppm) as compared with the unsilicified dunite (1700-2000 ppm). Cu is low both in the silicified dunite (generally below 10 ppm) and in the unsilicified dunite (below 1 ppm), suggesting that sulphide liquid played no part in the concentration of PGE. The highest total-PGE grades are 6ppm. No PGMs have been found.

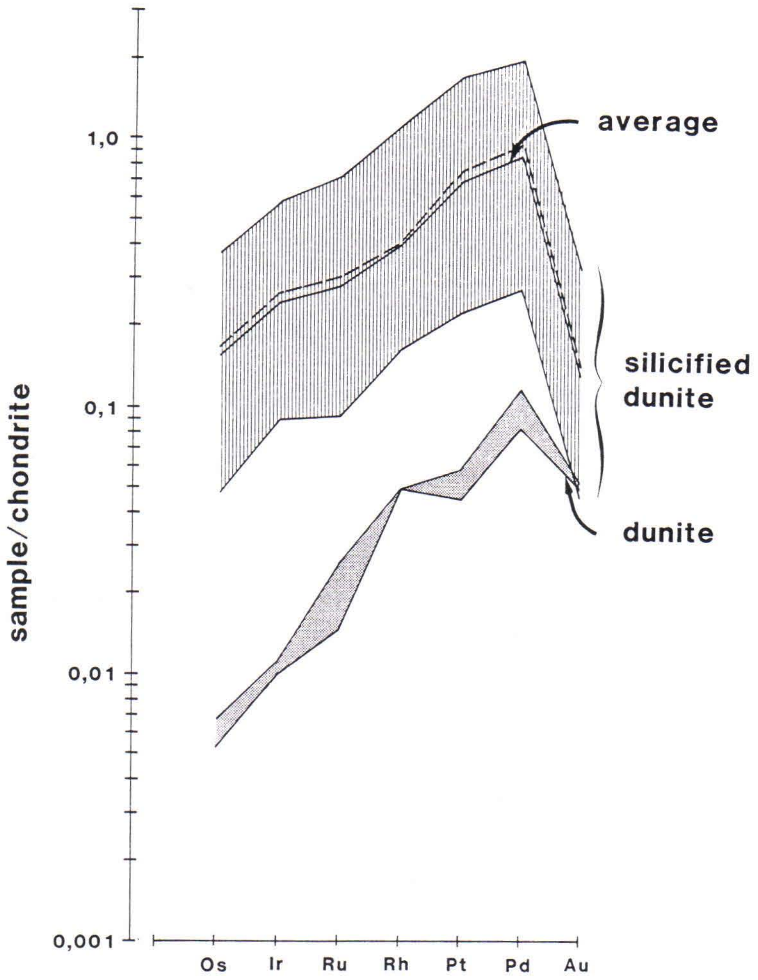


Fig. 25. Chondrite-normalized PGE-Au concentrations of silicified dunite (the "chondritic" PGE mineralization) and unsilicified dunite, Keivitsa.

The deposit has been dubbed the "chondritic PGE deposit", on account of the near-chondritic concentrations of all the PGE (Fig. 25). In the best samples the rock/chondrite ratios range from 0.37 for Os to 2.03 for Pd, the average values being between 0.13 (Os) and 0.97 (Pd). The chondrite-normalized values consistently increase from Os to Pd in all samples. The PGE concentrations of the unsilicified dunite are much lower than those of the mineralized rock; however, the graph for the dunite is similar in form to that for the silicified, PGE-rich dunite. This suggests that the PGE mineralization formed through hydrothermal leaching of the basal dunite, leaving a siliceous residue enriched in PGE. The PGE concentrations thus increased by a factor of about 25. Several questions remain unanswered: What was the source of the hydrothermal fluids ? Why did they affect the basal part of the dunite only ? And where were the leached components (e.g., Mg and Ni) dumped ?

Discussion: the role of halogens in the genesis of PGE deposits

The early sulphide saturation which resulted in the basal sulphide enrichments in the Koitelainen and Keivitsa intrusions was of a transient character, induced by salic contamination and concomitant addition of external sulfur. At Koitelainen, the magma remained undersaturated in sulphur until the magnetite gabbros accumulated. These intrusions do not show any general connection between sulphides and PGE-Au. The sulphides in the lower parts of the intrusions are practically devoid of PGE-Au. PGE are enriched in oxide-rich rocks (chromitites, magnetite-rich pegmatoids, magnetite gabbros), which never contain visible sulphides. Both in Koitelainen and Keivitsa, the most marked concentrations of PGE-Au occur near (or at) the roof.

It was suggested earlier (Mutanen & al., 1987) that halogens, particularly Cl, which were introduced from metasedimentary rocks, controlled the behaviour of PGE. The halogens formed melt-soluble complexes with PGE. Only when these complexes became unstable, were the PGE free to enter the sulphide liquid, if any was present. Even when sulphide liquid was available, the PGM often seem to have shunned the sulphides, as in the Cu-rich part of the magnetite gabbro at Koitelainen. These "independent" grains of PGM are usually enclosed in magnetite and chromite. Such disregard for sulphides by PGE might be more common than previously thought. The association between PGE and sulphides may only be ostensible, owing to the priority given to the sampling and assaying of sulphide-bearing rocks in exploration for PGE (see Alapieti & Lahtinen, 1986, p. 1129).

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STOPS, KOITELAINEN AND KEIVITSA–SATOVAARA EXCURSION

The helicopter excursion covers stops 1 – 17; the cross-country / road excursion stops 18 – 47.

Stop 1.

Northwestern corner of the Koitelainen intrusion. High-aluminous schists, with incipient melting of boron-rich layers (pink tourmaline-bearing neosome segregations). The next outcrop towards the intrusion is granophyre, with relict garnet in the cores of phenocryst-like plagioclase crystals. Amygdaloidal basalt; a similar basalt will be seen later (stop 11) as a xenolith at the base of the mottled anorthosite.

Stop 2.

Northwestern corner of the Archaean Kiviaapa dome. Chilled contact of the Koitelainen intrusion with granitoid rocks of the basement.

Stop 3.

Rookkijärvi, western margin of the Koitelainen intrusion. Sulphide-disseminated feldspathic pyroxenites, with meagre PGE–Au grades. Lower zone peridotite north of the sulphide occurence. To the south, a small monzonite stock associated with sulphide-bearing mafic rocks.

Stop 4.

Mukkajärvi, eastern margin of the Koitelainen intrusion. Mottled anorthosite; ultramafic (komatiitic ?) xenolith at the base of the anorthosite. A trench was excavated here, but it failed to reach solid bedrock. A stringer of chromite sand in till was found on the trench wall.

Stop 5.

Jänessaari, southwestern corner of intrusion. Suboutcrop of Upper Chromitite, excavated. Mottled anorthosite. Contact of mottled anorthosite with the main zone gabbro.

Stop 6.

Satovaara intrusion. Sulphide-disseminated peridotites, locally derived boulders. One boulder with Ni–PGE–Au-rich sulphides, cumulus chlorapatite and intercumulus dashkesanite; two boulders with disseminated sulphides, poor in Ni and PGE–Au. Granitic melt inclusions in olivine.

Stop 7.
Rykimälampi log cabin, Koitelainen. Main zone gabbros. A diabase dyke. Walk to the reversal zone from pigeonite gabbro to contaminated orthopyroxene gabbro. Sulphides in veins and disseminations. PGE–Au grades occur both in association with sulphides and outside them.

Stop 8.
Summit of the Koitelainen fell. Lower main zone gabbros. A view over the Koitelainen intrusion and surrounding areas.

Stop 9.
Lakijänkä, Koitelainen. Camp site. Ultramafic pegmatoid pipes rich in magnetite and ilmenite. The pegmatoids contain 0.1–0.2 ppm Pt. The deepest, small-diameter sections are enriched in magnetite and ilmenite, higher level sections contain blue quartz and granitic pockets, and less Fe-Ti oxides. A fault zone cutting the intrusion is exposed here; in the fault zone, a pegmatoid has been deformed into banded hornblende-ilmenite-magnetite rock. A folded scapolite dyke indicates repeated movements in the fault zone. Large crystals of zircon were found in the pegmatoids in 1973; these rocks yielded the first radiometric age on the layered intrusions of northern Finland.

Stop 10.
A walk over the main zone gabbros. Pigeonite gabbro, with fragments (?) of pyroxenite (0.4 ppm Pt).

Stop 11.
Koitelaisenvosat. Suboutcrop of the Upper Chromitite. Mottled, spotted and banded anorthosites. A xenolith of amygdaloidal basalt in anorthosite. Walk to magnetite gabbro.

Stop 12.
Magnetite gabbro. A xenolith of basalt roughly at about the base of the magnetite gabbro. Lower, Cu-poor magnetite gabbros with PGE-Au; upper, Cu-rich magnetite gabbros with PGE-Au grades similar to those in the lower part.

Stop 13.
Rovapää hill, east of Koitelainen intrusion. High-aluminous schists, with up to 2000 ppm Cr_2O_3. The schists are quartz-plagioclase-muscovite-chlorite rocks with porphyroblasts of andalusite and (or) kyanite, staurolite and chloritoid. Magnetite, ilmenite and hematite are always present. Walk eastwards down the hill.

Stop 14.
Eastern slope of Rovapää. A mafic sill with ultramafic rock at the base. High-aluminous hornfelses below the sill are contorted into chaotic folds, presumably due to the emplacement of the sill. The folds predate thermal metamorphism. Walk to the next stop.

Stop 15.
Rovakumpu. A slabstone quarry. The arkosic quartzite, with fuchsite-rich interlayers, has been used by local people for stoves and fireplaces. In 1982, the company Lapin Kvartsiitti Oy launched a more ambitious effort to exploit the deposit but operation proved uneconomic and was terminated in 1988.

Stop 16.
Kaitaselkä, Bonanza, the northern margin of the Koitelainen intrusion. A periglacial landslide gorge. Fault scarp, and a mound field composed of displaced material. The gorge cuts through granophyre and a big xenolith of metagabbro. Massive chalcopyrite veins in metagabbro. Eluvial gold nuggets occur above the gossany veins. Grussified and hard metagabbro. The granophyre grades downwards into magnetite gabbro underlain by anorthosite.

Stop 17.
Riskaskama hill. Statuesque tors of post-tectonic granite, 1.77 b.y. old.

Stop 18.
East of Vajukoski hydroelectric-power plant, west of Keivitsa intrusion. Sheared komatiite.

Stop 19.
Iso Hanhilehto. Albitized anorthosite gabbro of the western margin of the Keivitsa intrusion.

Stop 20.
Dunite in the middle of the Keivitsa intrusion. The outcrop, which belongs to the western part of the ring-shaped dunite body, lies above the ultramafic cumulates of the Keivitsa intrusion. In the eastern part of the dunite, the "chondritic" PGE mineralization in silicified dunite has been intersected by drilling.

Stop 21.
Keivitsa hill. Hornfelses of sulphide-bearing sedimentary and volcanic rocks. Gravity data indicate that the hornfelses form a thin slab underlain by peridotites. A view over the Keivitsa intrusion.

Stop 22.
Keivitsa hill, northern slope . Fine-grained chilled gabbros, grading downwards into uralite gabbros.

Stop 23.
Between Keivitsa and Keivitsansarvi. Deposit "A" (not exposed). Massive and breccia ores and disseminated sulphides in peridotites. A graphite-bearing pigeonite-augite gabbro, about 20–30 m thick, underlies the sulphide deposit. The graphite is a primary liquidus mineral. Feldspathic peridotites below the gabbro.

Stop 24.
Keivitsansarvi ridge. Large outcrops of pitted peridotite. The protruding knobs are wehrlite, the weathered pits phlogopite-bearing lherzolite.

Stop 25.
Keivitsansarvi, deposit "D". The ore zone, about 50 m thick, consists of disseminated sulphides in wehrlite. The sulphide phase contains 6–7% Ni, 8–9% Cu and ca. 20 ppm PGE+Au, the Pt/Pd ratio is 1.7. The ore zone is visible in a trench. The rock is quite fresh beneath a till layer 0.5-2.5 m thick. Fractures contain Fe hydroxides, malachite and rare azurite. An older trench, excavated by Outokumpu Oy, in the 1960s, missed the ore zone by few metres. Sulphides occur in peridotite, but they are poor in Ni and PGE-Au.

Stop 26.
Dark hornfelses immediately below the Keivitsa intrusion.

Stop 27.
Northern margin of the Keivitsa intrusion. Feldspathic pyroxenite (metapyroxenite) with spots of disseminated sulphides, which typically wet euhedral cumulus orthopyroxene.

Stop 28.
Metaperidotite, strongly altered. Vugs of euhedral quartz and siderite. Walk to stop 29: a granophyre dyke cutting greenstones (metagabbro, chlorite-amphibole schists). Stops 29 and 30 are between the Keivitsa and Koitelainen intrusions.

Stop 29.
Vein quartz (a local boulder) and limestone; calcareous banded hornfelses and komatiitic peridotites.

Stop 30.
Pikku Vaiskonselkä. Spotted komatiite. This rock occurs rather regularly immediately above the Koitelainen intrusion on the southern, western and northern border. The spots, originally augite but now mostly altered to amphibole, enclose clusters of olivine crystals. The spots formed through the thermal effect of the Koitelainen intrusion.

Stop 31.
Iso Vaiskonselkä ridge. Granophyre of the southern part of the Koitelainen intrusion.

Stop 32.
Iso Vaiskonselkä. Anorthositic gabbro between granophyre and underlying magnetite gabbros. To the north, a vein of granophyre projecting downward from granophyre into underlying magnetite gabbros. The magnetite gabbros here are strongly sheared and altered. Vein quartz and clots of epidote are common.

Stop 33.
Iso Vaiskonselkä. Silicated magnetite gabbro; rhythmic layering. A hole drilled beside the road first intersected a thick xenolith of melanocratic gabbros and feldspathic hornblendites (a komatiitic sill ?; not exposed) before finally intersecting the UC layer.

Stop 34.
Kuivakoskenmaa, Roadside outcrop of main zone gabbro. Both fresh and uralitized gabbros occur.

Stop 35.
Kivelä area. Lower zone rocks of the Koitelainen intrusion. Chilled hybrid rocks underlain by a syeno-monzonite diapir. Contact of the chilled rock and syeno-monzonite. Hornfels-xenolith associated with the syeno-monzonite. Another syeno-monzonite diapir about 200 m to the north, with typical birch vegetation.

Stop 36.
Kivelä area. "Spinifex" syeno-monzonite: Large branched crystals of plagioclase and hornblende (former pyroxene) in syeno-monzonite. The syeno-monzonite is part of a big diapir which penetrates the basal ultramafic cumulates of the intrusion.

Stop 37.
Kivelä. Chilled hybrid rocks overlying the diapir seen at the previous stop. Sulphides occur as roundish droplets and dissemination. The chemical composition of the rock roughly corresponds to that of the syeno-monzonite.

Stop 38.
Lower part of the lower zone of the Koitelainen intrusion. Dunite (olivine-chromite cumulate) with poikilitic, sometimes cumulus-like, crystals of orthopyroxene, intercumulus augite and plagioclase. Olivine crystals contain inclusion of contaminant and contaminated melt.

Stop 39.
Tojottamaselkä. Archaean basement granitoids, the oldest rocks in Finland (3.1 b.y.).

Stop 40.
Sadinoja. Rhyolite breccia. With the appearance of fragments of Archaean granitoids and Lapponian volcanic rocks, the volcanic breccia grades into a mixed volcanic breccia and further into volcanic diamictites (conglomerates).

Stop 41.
Sadinoja. Komatiite gabbro; hornfelses of volcanic conglomerate, which contains clasts of Archaean granitoids.

Stop 42.

East of Liesin pirtti (cabin); the western contact of the Koitelainen intrusion. Spotted komatiite, granophyre, upper zone gabbros (UC intersected by a drill hole) and biotite-plagioclase gneisses of the floor of the Koitelainen intrusion.

Stop 43.

River Ylä-Liesijoki . High-aluminous schists and intercalated arkosic quartzites.

Stop 44.

Liesin pirtti. A heap transported from Jänessaari trench (Stop 5). Boulders of mottled anorthosite and uralite gabbro, some hard cobbles of chromitite. Most of the ore is grussified into chromite-biotite sand.

Stop 45.

Peurapalo, roadside outcrop. Peridotite, possibly similar to the peridotites that occur above and beneath the Keivitsa intrusion.

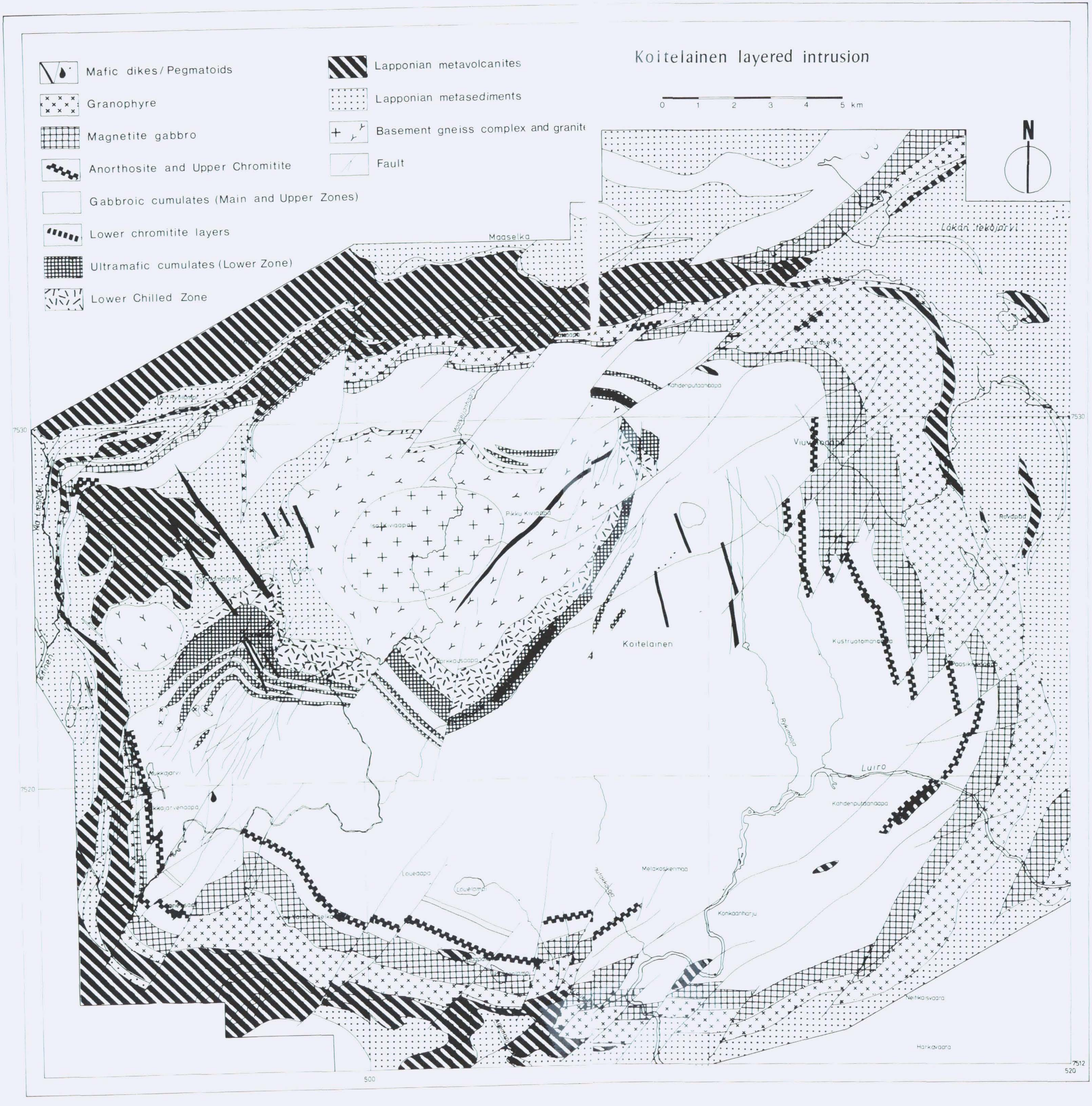
Stop 46.

River Kitinen , river bank outcrop, with "giant´s cauldrons". Folded stratified pyroclastic basaltic komatiite. Boundins of massive tholeiitic greenstone (a flow or a sill).

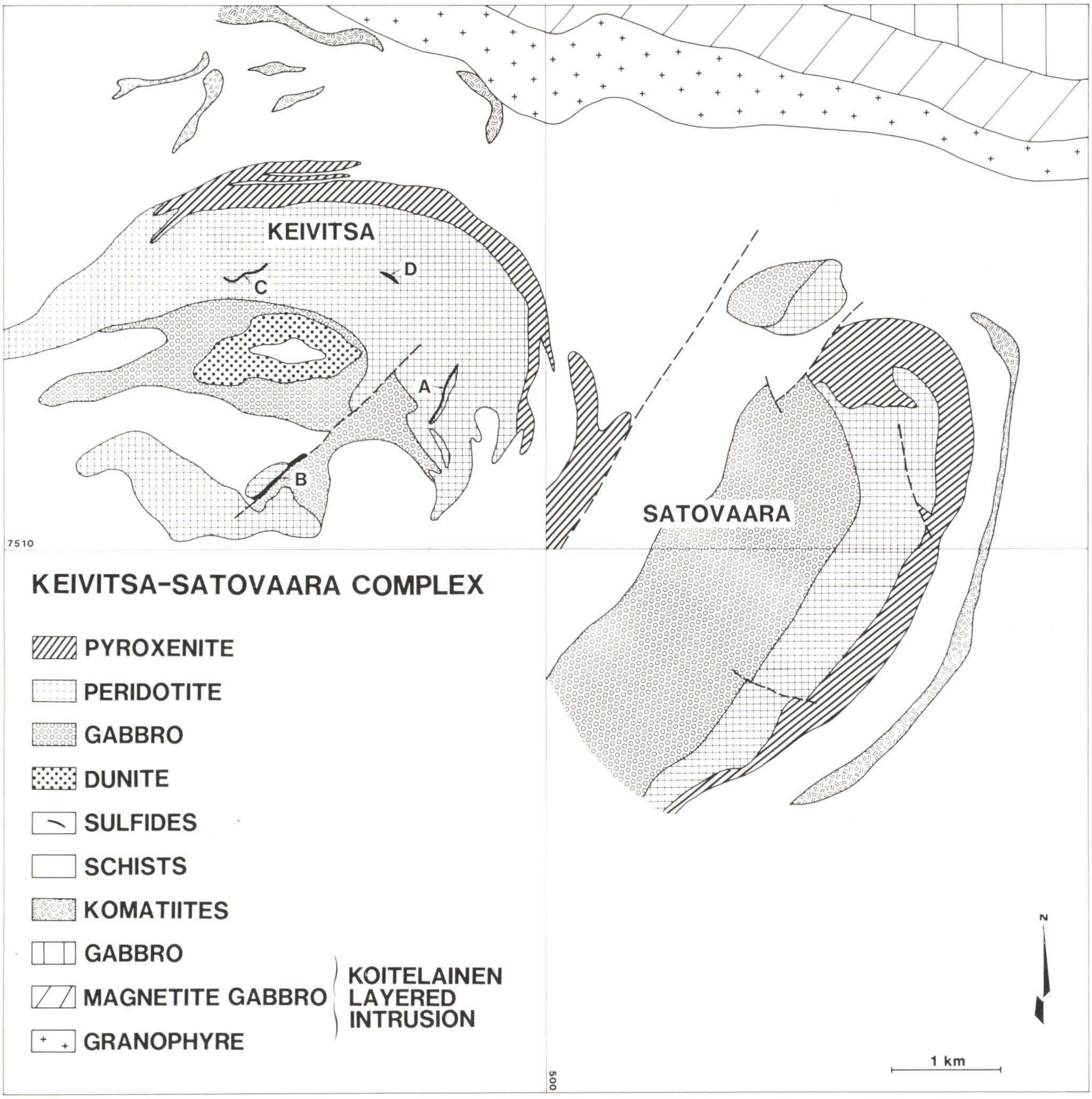
Stop 47.

Porttipahta hydroelecric-power plant. Archaean basement gneisses.

Appendix 1


Koitelainen layered intrusion
Mafic dikes / Pegmatoids
Granophyre
Magnetite gabbro
Anorthosite and Upper Chromitite
Gabbroic cumulates (Main and Upper Zones)
Lower chromitite layers
Ultramafic cumulates (Lower Zone)
Lower Chilled Zone
Lapponian metavolcanites
Lapponian metasediments
Basement gneiss complex and granite
Fault
0 1 2 3 4 5 km
N
Maaselkä
Lokan tekojärvi
Kaitaselkä
Kahdenputaanaapa
Iso Ryhtilampi
Viuvaoaapa
Ylä-Luestijoki
Isokiviaapa
Pikku Kiviaapa
Kivimaara
Kivijärvi
Tojandmalampi
Revapaa
Koitelainen
Kustruotomanaapa
Paasikivenaapa
Porkkausaapa
Arttinen
Pulijärvi
Mukkajärvi
Ukkajärvenaapa
Rykimaoja
Luiro
Kahdenputaanaapa
Loueaapa
Louelampi
Melakoskenmaa
Konkaanharju
Vaiskonselkä
Neitikaisvaara
Harkavaara
7530
7520
7512
500
520

APPENDIX 2



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