

Geologian tutkimuskeskus  
Opas 51a

Geological Survey of Finland  
Guide 51a

# **FIELD TRIP GUIDEBOOK**

EARLY PALAEOPROTEROZOIC (2.5-2.4)  
TORNIO – NÄRÄNKÄVAARA LAYERED  
INTRUSION BELT AND RELATED CHROME  
AND PLATINUM-GROUP ELEMENT  
MINERALIZATION, NORTHERN FINLAND

Edited by T.T. Alapieti and A.J. Kärki

*PREPARED FOR*  
*THE 10th PLATINUM SYMPOSIUM*  
*IN OULU FINLAND 2005*

GEOLOGIAN TUTKIMUSKESKUS  
GEOLOGICAL SURVEY OF FINLAND  
ESPOO 2005



## CONTENTS:

### Chapter 1

Early Palaeoproterozoic (2.5-2.4 Ga) Tornio – Näränkäväära Layered Intrusion Belt and Related Chrome and Platinum-group Element Mineralization, Northern Finland

*Tuomo T. Alapieti*

Page 5

### Chapter 2

The Kemi Intrusion and Associated Chromitite Deposit

*Timo A. Huhtelin, Tuomo T. Alapieti*

Page 13

### Chapter 3

The Sompujärvi, Ala-Penikka and Paasivaara PGE Reefs in the Penikat Layered Intrusion, Northern Finland

*Tapio Halkoaho, Tuomo Alapieti and Timo Huhtelin*

Page 33

### Chapter 4

Portimo Layered Igneous Complex

*Markku Iljina*

Page 77

### Chapter 5

Koillismaa Layered Complex and Related Copper-nickel and PGE Mineralizations

*Tuomo T. Alapieti*

Page 101



## Chapter 1

# EARLY PALAEOPROTEROZOIC (2.5-2.4 GA) TORNIO – NÄRÄNKÄVAARA LAYERED INTRUSION BELT AND RELATED CHROME AND PLATINUM-GROUP ELEMENT MINERALIZATION, NORTHERN FINLAND

Tuomo T. Alapieti

Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland

## INTRODUCTION

Early Palaeoproterozoic layered intrusions, 2.5-2.4 Ga in age, are widespread over a vast area of the northeastern Fennoscandian Shield (also known as the Baltic Shield) in Finland, Russia and Sweden (Fig. 1); an area amounting to about 600 × 900 km<sup>2</sup> (Alapieti and Lahtinen 2002). Many of these intrusions are known to have anomalous zones enriched in platinum-group elements (PGE). In addition, a younger group of intrusions, about 2.05 Ga in age, are also encountered in the same area, one of which, the Keivitsa (or Keivitsa) Intrusion, is known to contain a large, low-grade Cu-Ni-PGE-Au deposit (Mutanen, 1997).

The bedrock of the northeastern part of the Fennoscandian Shield is mainly composed of late Archaean tonalitic gneisses (2.8-2.6 Ga) and late Archaean and early Palaeoproterozoic greenstone belts. The Proterozoic layered intrusions are usually emplaced through the Archaean basement and the lowermost Proterozoic supracrustal rocks. They were preceded by bimodal volcanism soon after cratonization of the late Archaean

crust, in which komatiites, basalts and siliceous high-magnesium basalts represent the mafic members and rhyolites the felsic ones. These intrusions are now located within the basement itself and/or at the contact between the basement and the unconformable overlying Proterozoic supracrustal sequence of felsic or mafic volcanics, subvolcanic sills, or in places polymictic conglomerates, which all are younger than the intrusions. In addition, Palaeoproterozoic acid intrusive rocks, which are not spatially associated with layered intrusions, although commonly occurring in their vicinity, are widespread in northeastern Fennoscandia. These acid intrusions include the Kynsijärvi quartz alkali-feldspar syenite (2440 Ma) in the Koillismaa area (Landén and Mänttari, 2002), alkaline granite-syenite complexes (~2455 Ma) on the Kola Peninsula (Balashov, 1996), the Nuorunen granite (2450 Ma) in Russian Karelia (Buiko *et al.*, 1995), and a granite porphyry dyke (2435 Ma) east of the Kuhmo Greenstone Belt (Luukkonen, 1988).

The Palaeoproterozoic intrusions in Fin-

<sup>1</sup> T. Alapieti's text in this guide book is partly based on the paper: Alapieti and Lahtinen: "Platinum-group element mineralization in layered intrusions of northern Finland and the Kola Peninsula, Russia". Full paper originally published in CIM Special Volume 54 (2002) 'The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements.' Quoted with permission from the Canadian Institute of Mining, Metallurgy and Petroleum.

land began to interest prospecting organisations in the 1950s, leading in the first instance to the discovery of the large chromitite deposit in the Kemi Intrusion found by the Geological Survey of Finland in 1959 (Alapieti *et al.*, 1989a), which is still currently being mined. Soon after this discovery, Outokumpu Oy also began chrome exploration in the areas of the Penikat and certain other intrusions. The results did not prove encouraging, however, and efforts were terminated quite soon. Thereafter, the main exploration effort in the 1960's and 1970's was focused on the Ni-Cu ores, and as a result, large, low-grade PGE-bearing sulphide occurrences were found within the marginal series of the Koillismaa Complex (Alapieti and Piirainen, 1984, Lahtinen, 1985), as well as many types of PGE-bearing massive and disseminated base-metal sulphide deposits within the Portimo Complex (Alapieti *et al.*, 1989b). However, these discoveries have not led to any mining activity to date. In addition, Rautaruukki Oy became interested in the vanadium-bearing magnetite gabbros of the Koillismaa Layered Series, and vanadium mining commenced at Mustavaara in 1976.

Stimulated by PGE discoveries in the Stillwater Complex, Outokumpu Oy started a new exploration programme in 1981 aimed at discovering PGE deposits (Alapieti and Lahtinen, 1986). Lapin Malmi, established in 1982 as a joint venture between Outokumpu Oy and Rautaruukki Oy then continued PGE exploration. At the same time, ore geological investigations related to this Lapin Malmi's exploration program also began at the Univer-

sity of Oulu in cooperation. These investigations led almost immediately to the discovery of three PGE-mineralised zones in the Penikat Intrusion, which were found to be continuous for almost the entire 23 km length of the intrusion, and also to the discovery of the RK Reef and PGE-bearing offset deposits in the Portimo Complex. Thus all the currently known PGE deposits in the Penikat and Portimo areas were discovered and had been studied in a preliminary manner before the end of the 1980's. Arctic Platinum Partnership (APP), a company established in 2000 by Outokumpu Mining Oy and Gold Fields Limited and later on Gold Fields Arctic Platinum Oy (GAAP) have continued these exploration activities and examined the possibility of producing palladium and platinum by mining in the Penikat and Portimo areas.

The Geological Survey of Finland commenced explorations on mafic intrusions in Finnish Lapland in 1969. After a brief interruption, the work continued in 1973 leading to the discovery of chromitite layers in the Koitelainen and Akanvaara Intrusions, the uppermost ones of these being PGE-bearing, and of the low-grade Cu-Ni-PGE-Au deposit in the Keivitsa Intrusion (Mutanen, 1997). Exploration in the central part of the Kola Peninsula has a long history, but the focus on PGE intensified in the 1990's. Erratic zones enriched in PGE were discovered within the marginal and layered series of the Monchegorsk and Fedorova Tundra - Pana Tundra Intrusions leading to the current feasibility study (Dedeev *et al.*, 2002; Mitrofanov *et al.*, 1998).

## EARLY PALAEOPROTEROZOIC LAYERED INTRUSIONS IN THE FENNOSCANDIAN SHIELD

Approximately two dozen early Palaeoproterozoic layered intrusions and intrusion fragments are found scattered in a zone across the Fennoscandian Shield between latitudes 65.5° and 69.5°, i.e. on both sides of the Arctic Circle, in Sweden, Finland and Russia (Fig. 1). The southernmost group of intrusions forms a discontinuous belt from west to east named the **Tornio-Näränkävåara Belt**, beginning

with the Tornio Intrusion, the western part of which is known in Sweden as the Kukkola Intrusion, the Kemi and Penikat Intrusions and the scattered remnants of the Portimo and Koillismaa Complexes. Another belt trends in a southeasterly direction through Finnish Lapland into Russia, and includes the Tsohkoaiivi, Koitelainen and Akanvaara Intrusions in Lapland and the Oulanka Complex (also



Fig 1. Generalized geological map of the northeastern part of the Fennoscandian Shield showing the locations of the most important Palaeoproterozoic layered intrusions. Modified from Alapieti et al. (1990).

transliterated Olanga) on the Russian side of the border. In addition, Fennoscandia's largest layered intrusion, the Burakovo (or Burakovsky) Intrusion in Russian Karelia, may be regarded as a continuation of this belt. The layered intrusions on the Kola Peninsula include Mt. Generalskaya (or Luostari, according to its former Finnish name), Karikjavr in the northwestern part of the Kola Peninsula, the Monchegorsk and Monche Tundra Intrusions, the Imandra Lopolith, and the Fedorova Tundra, Lastyavr and Pana Tundra (also known as Pansky Tundra) Intrusions in the central part of the Kola Peninsula (Fig. 1). In addition, it should be mentioned the 2058±4 Ma Keivitsa Intrusion in Central Finnish Lapland (Huhma *et al.*, 1996, Mutanen, 1997, Mutanen and Huhma, 2001), since it hosts the aforementioned remarkable low-grade Cu-Ni-PGE-Au deposit. Roughly contemporaneous with the Keivitsa intrusion is the gabbro-anorthosite complex of Otanmäki (2060 Ma, Talvitie and Paarma, 1980) some 300 km south of Keivitsa and about 100 km southeast of Oulu. This complex was known for its vanadium-titanium-iron ores, which were mined until 1986.

Numerous age determinations have been carried out on the Fennoscandian Palaeoproterozoic layered intrusions using the U-Pb method for zircon and baddeleyite and the Pb-Pb whole rock and Sm-Nd methods. These have provided a fairly coherent set of ages, the mean being about 2440 Ma. The age determinations have yielded a U-Pb age of 2440 Ma (Kouvo, 1977, Alapieti and Laitinen, 1986) and a Sm-Nd age of 2410±64 Ma (Huhma *et al.*, 1990) for the Penikat Intrusion. The initial  $\epsilon_{Nd}(2440)$  for this intrusion was determined to be  $-1.6 \pm 0.6$  (Huhma *et al.*, 1990). The Portimo Complex proved to be too seriously altered for U-Pb dating, and no acceptable determination is available. The  $\epsilon_{Nd}(T)$  values show a relatively wide range, between  $-0.3 \pm 0.6$  and  $-3.9 \pm 0.5$  (Iljina, 1994). The Koillismaa Complex has provided a set of U-Pb ages with an average of 2436±5 Ma (Alapieti, 1982), while the Koitelainen and Akanvaara Intrusions have yielded U-Pb ages of 2439±3 Ma and 2436±6 Ma, respectively (Mutanen and Huhma, 2002). The U-Pb ages for the gabbro-norite of the Fedorova - Pana

Tundra Complex are 2491±1.5 Ma (Mitrofanov and Bayanova, 1999) and 2501±1.4 Ma (Amelin *et al.*, 1995), and the  $\epsilon_{Nd}(2487 \pm 51)$  value is  $-2.1 \pm 0.5$  (Balashov *et al.*, 1996). The emplacement of the above Palaeoproterozoic intrusions marks a large plume event in the geological history of the northeastern Fennoscandian Shield, suggesting that the plume remained active for about 100 Ma, from 2505 Ma to 2396 Ma (Mitrofanov and Bayanova, 1999). The long-term plume event could be in a complex relationship with the initial breakdown of the Late Archaean supercontinent.

The Fennoscandian Palaeoproterozoic layered intrusions have undergone a complex history of post-emplacement disruptions associated with the deposition of Jatulian (2200-2100 Ma) and Kalevian (2000-1900 Ma) sedimentary formations and with deformation and metamorphic events associated with the Svecofennian Orogeny (1900-1800 Ma). In the first stage after consolidation, when the layering was mostly quite flat, many of the intrusions became affected by brittle vertical faults, which commonly broke up the intrusions into several blocks and moved them on different levels. Land uplift and erosion, which even exposed the overlying granophyres and the uppermost cumulates to weathering in some cases, followed this faulting phase, and thus these also have frequently been obliterated. The younger sedimentary and volcanic rocks, the lowermost members of which were generally represented by polymictic conglomerates, were then deposited on this erosional surface, so that they nowadays form the discordant hanging walls of the many intrusions. The main tilting phase took place considerably later, the blocks reaching their final orientation during the Svecokarelian Orogeny. This tilting has meant that representative stratigraphic sections for the intrusions are in many cases exposed at the present ground surface.

The tectonic events affected the intrusions in the eastern parts to a lesser degree, whereas those in the western parts were generally more heavily metamorphosed. Similarly the primary magmatic minerals were altered in variable ways in the west, while in the easternmost intrusions they generally re-



mained almost unaltered. Cumulus textures are generally fairly well preserved as pseudomorphs even in the completely altered intrusions, however, enabling determination of the cumulus stratigraphy.

Several compositionally distinctive dyke swarms of age ~2440 Ma (Vuollo, 1994), which are characterized by relatively high MgO and Cr contents at intermediate SiO<sub>2</sub> contents, low HFSE and TiO<sub>2</sub> (mostly below 0.5 wt.% TiO<sub>2</sub>), and relatively high Pd (~20-40 ppb) (Alapieti *et al.* 1989), provide the most likely parental magma compositions for certain Fennoscandian layered intrusions (Saini-Eidukat *et al.*, 1997, Vogel *et al.*, 1998). Another characteristic feature of these intrusions is that they typically have  $\epsilon_{Nd}$  values between 0 and -4, which are similar to those of the Stillwater Complex (Lambert *et al.*, 1989), but slightly less negative than those of the Bushveld Complex (Sharpe, 1986).

The emplacement of the 2.5-2.4 Ga layered intrusions in Fennoscandia was part of the worldwide igneous activity at the beginning of Proterozoic, as suggested by the occurrence of large layered intrusions and mafic

dyke swarms of similar age in other cratons. These examples include the Jimberlana Intrusion (2420±30 Ma) in the Yilgarn Block, Western Australia (McClay and Campbell, 1976) and the East Bull Lake Suite (2491-2441 Ma) in Ontario (Peck *et al.*, 1993). The Great Dyke in Zimbabwe is somewhat older, viz. 2579±7 Ma (Mukasa *et al.*, 1998; Oberthür 2002). Dyke swarms emplaced at approximately the same time include, in addition to the Fennoscandian dykes, the Scourie mafic dykes (2418 Ma) in Scotland (Heaman and Tarney, 1989), the Hearst-Matachewan dyke suite (2452 Ma) in the Superior Province (Heaman, 1988), the Mysore dykes in southern India (Ikramuddin and Stueber, 1976), the Widgiemootha dyke suite in the Yilgarn Block (Glickson 1996) and the Vestfold Hills Complex (2424±72 Ma) in Antarctica (Collerson and Sheraton, 1986). An interesting explanation for this worldwide igneous activity at the very beginning of the Proterozoic was provided by Glickson (1996), who correlated mantle-melting episodes with contemporaneous mega-impact events.

## REFERENCES

- ALAPIETI, T.T., 1982. The Koillismaa layered igneous complex, Finland - its structure, mineralogy and geochemistry, with emphasis on the distribution of chromium. Geological Survey of Finland, Bulletin, 319, p.1-116.
- ALAPIETI, T.T., FILEN B.A., LAHTINEN, J.J., LAVROV, M.M., SMOLKIN, V.F. and VOITSEKHOVSKY, S.N., 1990. Early Proterozoic layered intrusions in the northeastern part of the Fennoscandian Shield. Mineralogy and Petrology, 42, p.1-22.
- ALAPIETI, T.T., KUJANPÄÄ, J., LAHTINEN, J.J. and PAPUNEN, H., 1989a. The Kemi Stratiform Chromitite Deposit, Northern Finland. Economic Geology, 84, 1057-1077.
- ALAPIETI, T.T., LAHTINEN, J.J., HÄNNINEN, E., PIIRAINEN, T.A. and SIVONEN, S.J., 1989b. Platinum-group mineralization in the marginal series of the early Proterozoic Suhanko-Konttijärvi layered intrusion, northern Finland. In Magmatic sulphides - the Zimbabwe volume. Edited by M.D. Prendergast and M.J. Jones. The Institution of Mining and Metallurgy, London, p.177-187.
- ALAPIETI, T.T. and LAHTINEN, J.J., 2002. Platinum-Group Element Mineralization in Layered Intrusions of Northern Finland and the Kola Peninsula, Russia. In The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements. Edited by L.J. Cabri. The Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume, 54, p.507-546.
- ALAPIETI, T.T. and LAHTINEN, J.J., 1986. Stratigraphy, petrology, and platinum-group element mineralization of the early Proterozoic Penikat layered intrusion, northern Finland. Economic Geology, 81, p.1126-1136.
- ALAPIETI, T.T. and PIIRAINEN, T.A., 1984. Cu-Ni-PGE mineralization in the marginal series of the early Proterozoic Koillismaa layered igne-

ous complex, northeast Finland. In Sulphide deposits in mafic and ultramafic rocks. Edited by D.L. Buchanan and M.J. Jones. The Institution of Mining and Metallurgy, London, p.123-131.

AMELIN, YU.V., HEAMAN, L.M. and SEMENOV, V.S., 1995. U-Pb geochronology of layered mafic intrusions in the eastern Baltic Shield: implication for the timing and duration of Paleoproterozoic continental rifting. *Precambrian Research*, 75, p.31-46.

BALASHOV, YU, VETRIN, V.R. and ZOZULUA, D.R., 1996. Age correlation of overprinted processes in peralkaline granites of Kola Peninsula and volcanic episodes in Pechenga-Varzuga paleorift. In *Fennoscandian Geological Correlation*. Edited by Yu.B. Bogdanov, V.V. Ivanikov and N.B. Philippov. Fennoscandian Geological Correlation. 1st International Conference, 8-11 September 1996, St.Petersburg. Abstract Volume. p.112.

BUIKO, A., LEVCHENKOV, O., TURCHENKO, S. and DRUBETSKOI, E., 1995. Geology and isotopic dating of the early Proterozoic Sumian-Sariolian Complex in northern Karelia (Paanajärvi-Tsipringa structure). *Stratigraphy and Geological Correlation*, Vol. 3 (4), p.16-30 (in Russian).

COLLERSON, K.D. and SHERATON, J.W., 1986. Age and geochemical characteristics of a mafic dyke swarm in the Archaean Vestfold Block, Antarctica: Interferences about Proterozoic dyke emplacement in Gondwana. *Journal of Petrology*, 27, p.853-886.

DEDEEV, A.V., KHASCHKOVSKAYA, T.N. and GALGIN, A.S., 2002. The PGE Mineralization of the Monchegorsk Layered Intrusion of the Kola Peninsula. In *The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements*. Edited by L.J. Cabri. The Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume, 54, p.569-577.

GLICKSON, A.Y., 1996. Mega-impacts and mantle-melting episodes: test for possible correlations. *AGSO Journal of Australian Geology and Geophysics*, 16, p.587-607.

HEAMAN, L.M., 1988. A precise U-Pb zircon age for a Hearst Dyke, Geological Association of Canada, Mineralogical Association of Canada,

Canadian Society of Petroleum Geologists, 1988 Joint Annual Meeting; Program with abstract, 13, p. A53.

HEAMAN, L.M. and TARNEY, J., 1989. U-Pb baddeleyite as gas for the Scourie dyke swarm, Scotland: evidence for two distinct intrusion events. *Nature* 340, p.705-708.

HUHMA, H., CLIFF, R.A., PERTTUNEN, V. and SAKKO, M., 1990. Sm-Nd and Pb isotopic study of mafic rocks associated with early Proterozoic continental rifting: the Peräpohja schist belt in northern Finland. *Contributions to Mineralogy and Petrology*, 104, p.369-379.

HUHMA, H., MUTANEN, T., HANSKI, E. and WALKER, R.J., 1996. Sm-Nd, U-Pb and Re-Os isotopic study of the Keivitsa Cu-Ni-bearing intrusion, Northern Finland. In *The 22nd Nordic Geological Winter Meeting, Turku, January 8-11, 1996*. Abstracts, p.72.

IKRAMUDDIN, M and STUEBER, A.M., 1976. Rb-Sr ages of Precambrian dolerite and alkaline dykes of Southeast Mysore State, India. *Lithos*, 9, p.235-241.

ILJINA, M., 1994. The Portimo Layered Igneous Complex, with emphasis on diverse sulphide and platinum-group element deposits. *Acta Universitatis Ouluensis. Series A, Scientiae Rerum Naturalium* 258, p.1-158.

KOUVO, O., 1977. The use of mafic pegmatoids in geochronometry. In *European Colloquium Geochronology, Cosmochronology, Isotope Geology*, 5th Pisa, Italy, 5-10 September, 1977, Abstracts, unpaginated.

LAHTINEN, J., 1985. PGE-bearing copper-nickel occurrences in the marginal series of the early Proterozoic Koillismaa Layered Intrusion, northern Finland. In *Nickel-Copper Deposits of the Baltic Shield and Scandinavian Caledonides*. Edited by H. Papunen and G.I. Gorbunov. Geological Survey of Finland, Bulletin, 333, p.161-178.

LAMBERT, D.D., MORGAN, R.J., WALKER, S.B., SHIREY, R.W., CARLSON, M.L., ZIENTEK, M.L. and KOSKI, M.S., 1989. Rhenium-osmium and samarium-neodymium isotopic systematics of the Stillwater Complex. *Science* 244, p.1169-1174.

- LANDÉN, L.S. and MÄNTTÄRI, I., 2002. The Kynsijärvi quartz alkali feldspar syenite, Koillismaa, eastern Finland – silicic magmatism associated with 2.44 Ga continental rifting. Submitted to Precambrian Research.
- LUUKKONEN, E., 1988. The structure and stratigraphy of the northern part of the late Archaean Kuhmo greenstone belt, eastern Finland. In Archaean geology of the Fennoscandian Shield, Finnish-Soviet Symposium in Finland July 28 - August 7, 1986. Edited by E. Mattila. Geological Survey of Finland, Special Paper 4, p.71-96.
- MCCLAY K.R. and CAMPBELL, I.H., 1976. The structure and shape of the Jemberlana Intrusion, Western Australia, as indicated by an investigation of the Bronzite Complex. Geological Magazine, 113, p.129-139.
- MITROFANOV, F, BALABONIN, N, KORCHAGIN, A, BAYANOVA, T., LATYPOV, R., GONCHAROV, Y., OSOKIN, A. and GRITSAI, A., 1998. PGE mineralization of the Fedorovo-Pansky Intrusion (Kola Peninsula, Russia). In International Platinum. Edited by N. Laverov and V. Distler. Theophrastus Publications, St-Petersburg-Athens, p.62-72.
- MITROFANOV, F.P. and BAYANOVA T.B., 1999. Duration and timing of ore-bearing Paleoproterozoic intrusions of Kola province. In Mineral Deposits: Processes to Processing. Edited by C.J. Stanley et al., A.A. Balkema/Rotterdam/Brookfield, p.1275-1278.
- MUKASA, S.B., WILSON, A.H. and CARLSON, R.W. 1998. A multielement geochronologic study of the Great Dyke, Zimbabwe: significance of the robust and reset ages. Earth and Planetary Science letters 164, p.353-369.
- MUTANEN, T., 1997. Geology and petrology of the Akanvaara and Koitelainen mafic layered intrusions and Keivitsa-Satovaara layered complex, northern Finland, Geological Survey Finland, Bulletin, 395, p.1-233.
- MUTANEN, T. and HUHMA, H., 2001. U-Pb geochronology of the Koitelainen, Akanvaara and Keivitsa mafic layered intrusions. In: Radiometric age determinations from Finnish Lapland and their bearing on the timing of Precambrian volcano-sedimentary sequences. Edited by M.Vaasjoki. Geological Survey of Finland. Special Paper 33, 229-246.
- OBERTH R, T., 2002. Platinum-group element mineralization of the Great Dyke, Zimbabwe. In The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements. Edited by L.J. Cabri. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, p. 483-506.
- PECK, D.C., JAMES, R.S. and CHUBB, P.T., 1993. Geological environments for PGE-Cu-Ni mineralization in the East Bull Lake Gabbro-Anorthosite Intrusion, Ontario. Journal of Exploration Mining Geology, 2, p.85-104.
- SAINI-EIDUKAT, B., ALAPIETI, T.T., THALHAMMER, O.A.R. and ILJINA, M.J., 1997. Siliceous high-magnesium parental magma compositions of the PGE-rich early Paleoproterozoic layered intrusion belt of northern Finland. In Proceedings of the 30th International Geological Congress, Beijing. Edited by Pei Rongfu Vol. 9, p.177-197.
- SHARPE, M., 1986. Bushveld complex - excursion guide book: Geocongress '86, p.1-142.
- TALVITIE, J. and PAARMA, H., 1980. Precambrian basic magmatism and the Ti-Fe ore formation in Central and Northern Finland. In Metallogeny of the Baltic Shield. Edited by J. Siivola. Geological Survey of Finland, Bulletin, 307 p.98-107.
- VOGEL, D.C., VUOLLO, J.I., ALAPIETI, T.T. and JAMES, R.S., 1998. Tectonic, stratigraphic, and geochemical comparisons between ca. 2500-2440 Ma mafic events in the Canadian and Fennoscandian Shields. Precambrian Research, 92, p.89-116.
- VUOLLO, J.I., 1994. Palaeoproterozoic basic igneous events in Eastern Fennoscandian Shield between 2.45 Ga and 1.97 Ga, studied by means of mafic dyke swarms and ophiolites in Finland. Acta Universitatis Ouluensis. Series A, Scientiae Rerum Naturalium 250.



## Chapter 2

# THE KEMI INTRUSION AND ASSOCIATED CHROMITITE DEPOSIT

Tuomo T. Alapieti

Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland

Timo A. Huhtelin

Outokumpu Chrome Oy Kemi Mine, P.O. Box 172, FIN-94101 Kemi, Finland

### INTRODUCTION

The Kemi Layered Intrusion (Fig. 1) may be considered the most significant of the early Palaeoproterozoic (2.5-2.4 Ga) Fennoscandian layered intrusions, since the only functioning mine is located in its area, namely the Kemi chrome mine (Alapieti *et al.*, 1989a). The chromitite deposit is hosted by a layered intrusion extending some 15 km northeast of Kemi, a town on the coast of the Gulf of Bothnia. U-Pb zircon data yield an age of 2.44 Ga for the Kemi Intrusion (Patchett *et al.*, 1981), and Pb-Pb data for whole rocks define an age of  $2.44 \pm 0.16$  Ga (Manhes *et al.*, 1980).

In essence the Kemi Intrusion was already known in the 1940s (Härme, 1949, Mikkola, 1949), but because of its poor outcropping, the chromite-bearing basal part, particularly the chromite deposit, remained hidden until the 1950s, when, owing to the relatively thin soil cover, a fresh-water channel was excavated through the solid rock. The first chromite-bearing blocks were discovered in this excavated channel in 1959 by Matti Matilainen, a local diver who was interested in ore prospecting, and he sent them to the Geo-

logical Survey of Finland for examination. Based on these blocks, the Geological Survey began the exploration which led to the discovery of a chromitite-bearing layer. From 1960 onwards the exploration was conducted by Outokumpu Oy under contract from the government of Finland.

The exploration carried out by Outokumpu Oy lasted until the late summer of 1964, and included geophysical, mainly gravimetric surveys, diamond drilling, concentration tests on the drill cores and on 10,000 metric tons of ore extracted for mining, and metallurgical tests. By the end of the exploration period, 30 million metric tons of chromite ore had been located, and in autumn 1964 Outokumpu Oy decided to begin mining the chrome ore. Construction of the mine began in spring 1965. In 1966 through 1968 the ore was extracted only in summer and was treated in a pilot concentration plant, but since then it has been mined throughout the year using open pit mining. The main open pit has now reached a depth of 180 meters and annual production during recent years has amounted

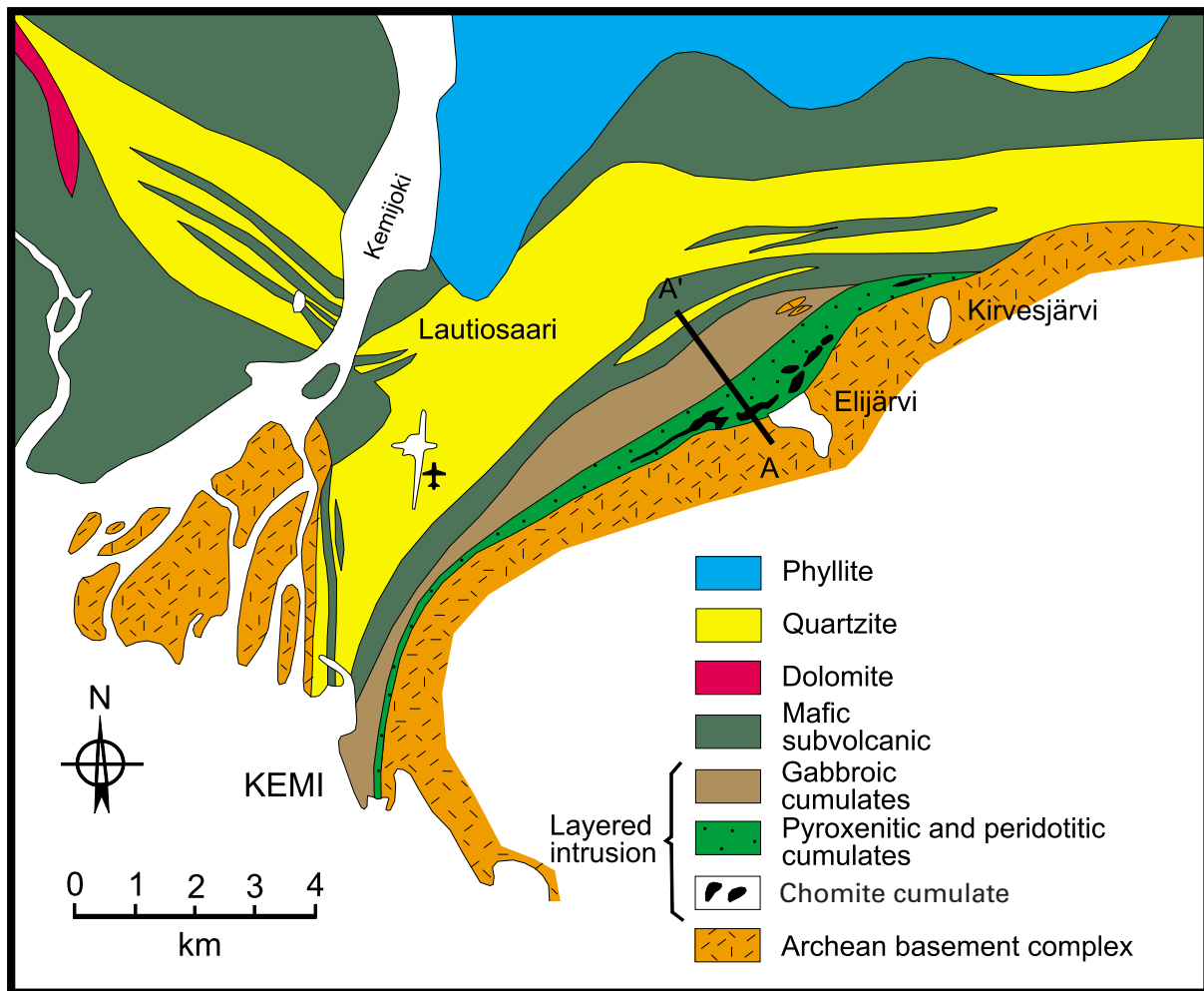


Fig. 1. Generalized geologic map of the Kemi Intrusion, showing the location of drilling profile A-A' (see Fig. 2), after Alapieti *et al.* 1989.

to around 1.2 million tons of ore and about 3.5 million tons of barren rock. Construction of the underground mine began in 1999. The opening ceremony of the underground mine was held in September 2003. Change-over to underground mining is taking place and open pit mining will be fully replaced by underground mining by 2006.

The associated industrial facilities, including the ferro-chrome plant and stainless steel works at Tornio, were completed in 1976. The ore was originally concentrated by wet grinding followed by drying and high intensity magnetic separation with a Salzgitter separator, but Jones heavy magnetic wet separators were added between the grinding and

dry magnetic separation stages in 1972 and the Salzgitter separators were replaced with Reichert cones in 1979. The heavy magnetic separators were removed in 1982, and since 1984 heavy media separation has been applied between crushing and grinding.

At present, the chrome ore feed is concentrated into upgraded lumpy ore and fine concentrate. In the first stage of the process, at the crushing plant, the ore is crushed and screened to a diameter of 12 - 100 millimeters. After crushing, ore lumps are processed by means of heavy media separation. In this process upgraded lumpy ore is separated from the ore. Further processing takes place in the concentrating plant where the ore is



first ground in the rod mill and in the ball mill. The fine concentrate is produced by gravity separation using spirals and Reichert

cone separators. In addition high gradient magnetic separation is used in the latter stage of the process.

## SHAPE AND LAYERING OF THE INTRUSION

The present surface section of the Kemi Intrusion is lenticular in shape, being some 15 km long and 0.2 to 2 km wide (Fig. 1, 2 and 3). It represents a cross-section of an originally funnel-shaped intrusion which was tilted by tectonic movements during the Svecofennian orogeny to form a body dipping about 70° northwestward and, according to geophysical interpretations, extending down for at least 2 km. The geologic map also shows that the individual cumulate layers are thickest in the middle part of the intrusion and become thinner toward the ends. This feature is well established from the variation in thickness of the ultramafic cumulates (Fig. 1). Underground inclined tunneling has recently proved that the magmatic conduit which fed the magma chamber was located just below the thickening, as suggested earlier

by Alapieti et al. (1989a). This feeder dike, which is also visible on the southeastern wall of the open pit (Fig. 4) is about 20 m thick. It is composed of a fine-grained, uralitized rock types close to the contacts which grade more coarse grained ones inward, and the middle part of the dyke is composed of a few meter thick, almost vertical chromitite. The foot-wall rock of the intrusion consists of late Archean granitoids, and the hanging-wall rocks are either younger mafic volcanics or subvolcanic sills 2,150 Ma in age (Sakko, 1971), or a polymict conglomerate of unknown age but younger than the intrusion. This indicates that the present upper contact is erosional, implying that the original roof rocks and the uppermost cumulates of the layered series, together with the possible granophyre layer, may have been obliterated by erosion. The

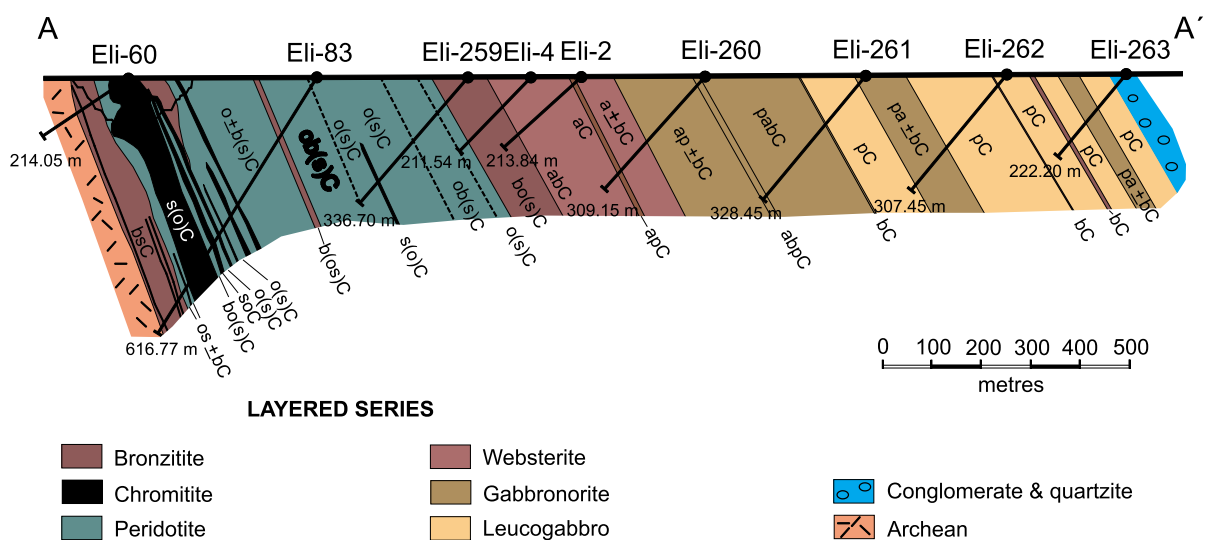


Fig. 2. Cross-section of the Kemi Intrusion based on drilling profile A-A', marked in Figure 1. For abbreviations, see Table 1.

feeder dikes of the subvolcanic sills, referred to as albite diabase, intersect the Kemi Intrusion.

The area of the Kemi Intrusion underwent lower amphibolite facies metamorphism during the Svecokarelidic orogeny. The original magmatic silicates have been completely altered to secondary minerals in the lower and upper parts of the intrusion, whereas those in the middle have been preserved and are fresh

in appearance. Many chromites have nevertheless preserved their original composition in their cores, even though the silicates of the same rock have been completely altered. The unaltered cores of the chromites are quite easy to find by careful examination under an electron or light microscope. The altered rocks have preserved their cumulate textures fairly well, however, and despite alteration, many of the primary minerals can still be

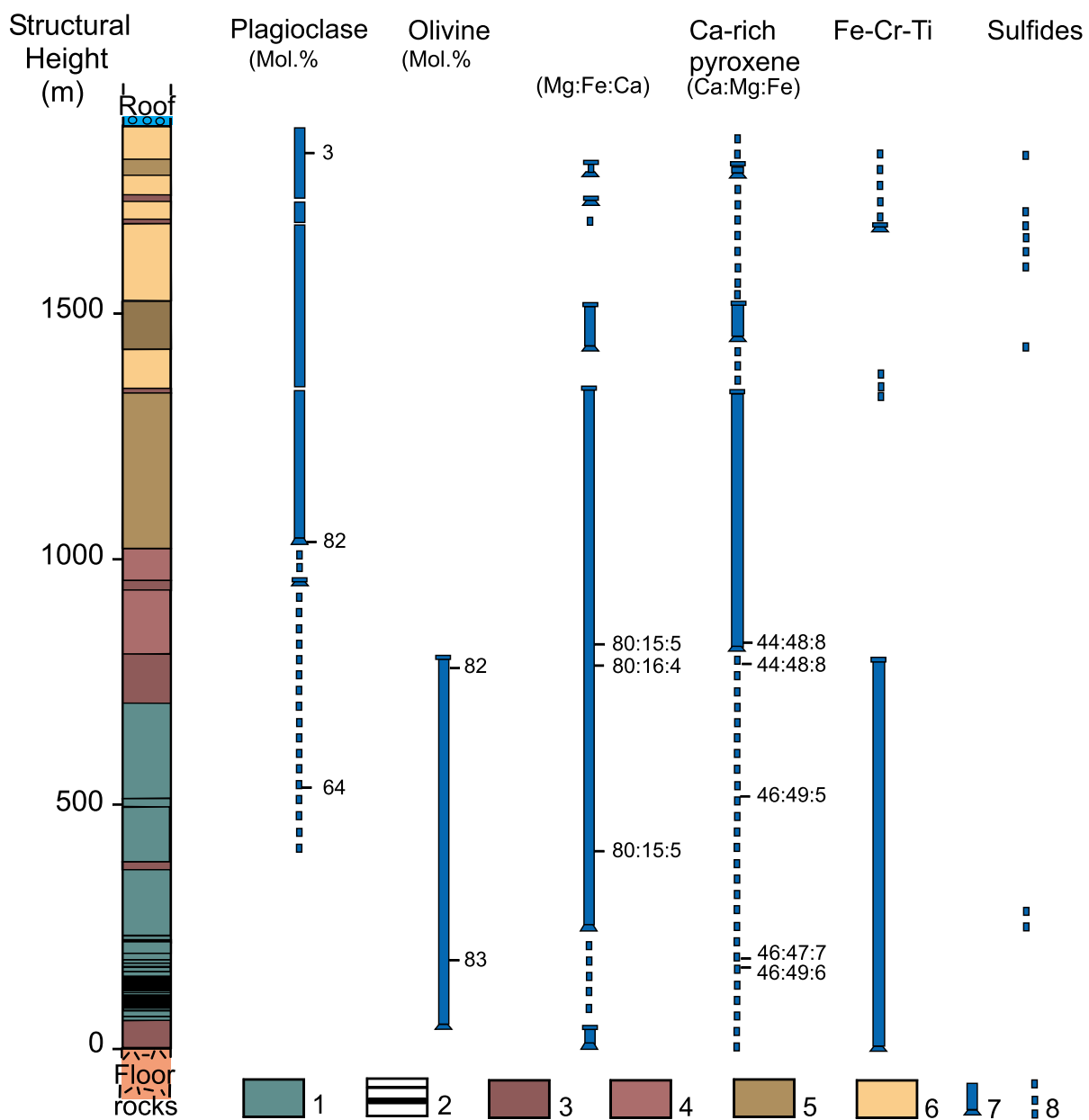






Fig. 4. 'Feeder channel' on the southeastern wall of the Kemi open pit.

recognized by means of pseudomorphs, thus enabling the cumulate sequences to be determined.

The complex basal contact series typically indicating reserved fractionation and being characteristic of the many other layered intrusions in northern Finland has not been observed in the Kemi Intrusion. Either no such series formed at all or else it was obliterated by erosion during the magmatic stage. Instead, a fine-grained, ultramafic marginal rock about 10 cm thick which has preserved its original texture occurs in borehole Eli-60 in contact with the basement granitoid. The silicate minerals in this ultramafic rock are completely recrystallized, whereas the chromite, which accounts for about 15 vol. percent of the whole rock, has been preserved and occurs as euhedral phenocrysts about

0.5 mm in diameter. This rock is overlain by a markedly altered sequence 50 to 100 m thick, the lower part of which is composed of a bronzite-chromite cumulate and the upper part of an olivine-chromite  $\pm$  bronzite cumulate, with chromitite interlayers from 0.5 to 1.5 m thick. The bronzitic cumulates are often characterized by gneissic xenoliths from the underlying basement complex.

The sequence described above is followed by the main chromitite layer, which in borehole Eli-83 (Fig. 2) is composed of two parts with a more silicate-rich rock between them. The total thickness of the main chromitite layer is almost 60 m in this borehole. Its cumulus minerals are chromite and olivine, and the intercumulus minerals comprise poikilitic bronzite and to a lesser extent augite. The abundance of cumulus olivine in relation to

chromite is relatively low in the upper part. Bronzite occurs temporarily as the cumulus phase in the more silicate-rich interlayer, which is typified by annular textures constituting accumulations of small chromite grains around the larger cumulus silicate minerals. The main chromitite layer is overlain by about 550 m of peridotitic cumulates with olivine, chromite and occasional bronzite as the cumulus minerals. This thick cumulate sequence contains about 15 chromite-rich interlayers varying in thickness from 5 cm to 2.5 m, the uppermost being about 370 m above the main chromitite layer. A 5 to 10 m thick pyroxenitic interlayer occurs around the core of the peridotitic sequence, and about 10 m below this a sodium-rich rock type is encountered which could also be a xenolith from the basement complex. This interpretation is suggested by the fine-grained chilled margins in

the surrounding ultramafic rock.

Bronzite becomes the dominant cumulus mineral about 700 m above the basal contact of the intrusion, with olivine and chromite as the other cumulus phases. Then, about 100 m higher up, augite becomes the dominant cumulus mineral alongside bronzite, but olivine and chromite disappear. Even bronzite is so low in abundance in places that the rock could be referred to as a diallagite.

At about 1,000 m above the basement, plagioclase becomes the cumulus phase alongside augite and bronzite. These rather monotonous plagioclase cumulates continue for about 800 m upward to the contact with the hanging wall. In the upper part of the sequence augite occurs as the intercumulus phase, however, and there is little or no Ca-poor pyroxene. In conventional terms, these rocks are therefore leucogabbros or anorthosites (Table 1)

**Table 1. Rock-type nomenclature used**

<b>Conventional rock name</b>	<b>Cumulus mineral assemblage</b>	<b>Cumulate abbreviation</b>
Peridotite	Olivine $\pm$ bronzite $\pm$ chrome spinel	$o \pm b \pm sC$
Chromitite	Chrome spinel ( $\pm$ minor olivine)	$s(o)C$
Bronzitite and olivine bronzitite	Bronzite-olivine ( $\pm$ minor chrome spinel)	$bo(s)C$
Websterite and diallagite	Augite $\pm$ bronzite	$a \pm bC$
Gabbronorite and gabbro	Plagioclase-augite $\pm$ bronzite	$pa \pm bC$
Leucogabbro and anorthosite	Plagioclase	$pC$

## MINERALS AND MINERAL CHEMISTRY

**Olivine:** Olivine is a typical cumulus mineral of peridotitic and pyroxenitic rocks, the augite cumulates excluded (Fig. 3). It has been completely altered in the lowermost cumulates, however. The olivines analyzed were of constant composition, Fo<sub>82</sub>-Fo<sub>83</sub>.

**Ca-poor pyroxene:** Ca-poor pyroxene is present as a cumulus phase practically throughout the intrusion, although it occurs typically in the form of largish oikocrysts in the chromite-rich layers. It, too, is fairly constant in composition, the  $100 * \text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Mn})$  ratio being about 83 and the Cr<sub>2</sub>O<sub>3</sub> content quite high. The orthopyroxenes analyzed represent cumulus minerals in olivine-bronzite-(chromite), bronzite-olivine, and bronzite-augite cumulates, their Cr<sub>2</sub>O<sub>3</sub> content varying from 0.41 to 0.60 wt. percent with a mean value of 0.51 wt. percent.

**Ca-rich pyroxene:** Augite exists as an intercumulus mineral in the lower half of the intrusion but becomes a cumulus mineral in the clinopyroxenites. It continues upward as a cumulus phase, reverting to an intercumulus mineral in the leucogabbros and anorthosites of the upper part. Like the bronzite, it has a surprisingly high chromium content. The lowermost, poikilitic augite, which is located about 30 m above the main chromitite, contains around one wt. percent Cr<sub>2</sub>O<sub>3</sub>. The highest content, 1.18 wt. percent, was found in the poikilitic augite in the uppermost chromitite layer, 370 m above the main chromitite. The uppermost intercumulus augite occurring in the bronzite-olivine-(chromite) cumulate about 650 m above the main chromitite,

contains 1.1 wt. percent Cr<sub>2</sub>O<sub>3</sub> and the lowermost cumulus augite in the bronzite-augite cumulate 0.83 wt. percent.

**Plagioclase:** Plagioclase, with an anorthite content of about An<sub>65</sub>, occurs as an intercumulus phase above the pyroxenitic interlayer in the peridotitic cumulates. It appears as a cumulus mineral around the middle part of the intrusion, where it increases sharply in abundance and its anorthite content rises to An<sub>82</sub>. From this point it continues as a cumulus phase up to the upper contact of the intrusion. Microanalyses show that the plagioclase is albitic in composition close to the roof of the intrusion, with some evidence of saussuritization.

**Cr-Fe-Ti oxides:** Chromite is by far the most prominent Cr-Fe-Ti oxide in the Kemi Intrusion, occurring as a cumulus mineral throughout the lower part, up to the level at which augite appears as the cumulus phase, 800 m above the base.

Especially in the silicate-rich rocks, the chromite grains are frequently altered at the rims, usually with a sharp drop in aluminium from the core of the grain outward, this being replaced by ferric iron. On the other hand, the chromium content declines only slightly in an outward direction (Table 2), the difference in Cr<sub>2</sub>O<sub>3</sub> content between the core and the outer rim being only 3.5 wt. percent, whereas the Al content decreases about 16 wt. percent at the same time. Magnesium, like aluminium, also declines abruptly, whereas the nickel content increases distinctly toward the rim, as

**Table 2. Analyses of selected chromites from the Kemi Intrusion**

Sample	1	2	3	4	5	6	7	8
<b>Weight percent</b>								
TiO <sub>2</sub>	0,39	0,96	0,4	0,41	0,61	0,57	0,42	0,62
Al <sub>2</sub> O <sub>3</sub>	14,17	9,63	15,43	14,51	16,98	2,3	0,84	16,79
Cr <sub>2</sub> O <sub>3</sub>	51,32	42,18	49,03	48,63	42,94	39,65	39,43	45,1
Fe <sub>2</sub> O <sub>3</sub>	3,90	10,81	5,29	5,69	5,89	23,7	26,49	7,82
V <sub>2</sub> O <sub>3</sub>	0,22	0,21	0,11	0,15	0,13	0,13	0,14	0,2
FeO	15,52	29,57	18,09	19,06	28,6	29,73	30,36	17,16
MnO	0,31	0,67	0,3	0,32	0,26	0,28	0,26	0,32
MgO	11,71	0,14	10,54	9,67	4,06	1,18	0,78	11,45
ZnO	0,00	3,40	0,08	0,06	0,05	<0,05	0,07	<0,05
NiO	0,17	<0,05	0,11	0,1	0,05	0,17	0,18	0,09
Sum	97,70	97,57	99,34	98,6	99,57	97,71	98,97	99,58
<b>Number of ions on the basis of 32 oxygen atoms</b>								
Al	4,38	3,333	4,719	4,512	5,385	0,82	0,299	5,067
Cr	10,645	9,794	10,059	10,144	9,135	9,477	9,419	9,128
Fe <sup>3+</sup>	0,77	2,389	1,025	1,13	1,193	5,392	6,023	1,506
Ti	0,077	0,212	0,078	0,081	0,123	0,13	0,095	0,119
V	0,046	0,049	0,028	0,032	0,028	0,032	0,034	0,043
Mg	4,577	0,061	4,076	0,803	1,628	0,532	0,351	4,37
Ni	0,035		0,023	0,021	0,011	0,041	0,044	0,018
Fe <sup>2+</sup>	3,404	7,262	3,926	4,205	6,425	7,516	7,671	3,673
Zn	0	0,737	0,015	0,012	0,01		0,016	
Mn	0,068	0,167	0,066	0,072	0,059	0,041	0,067	0,07
<b>Mole percent</b>								
(Fe,Mg)Cr <sub>2</sub> O <sub>4</sub>	67,4	63,1	63,6	64,3	58,1	60,4	59,8	58,1
(Fe,Mg)Al <sub>2</sub> O <sub>4</sub>	27,7	21,5	29,9	28,6	34,3	5,2	1,9	32,3
Fe <sub>3</sub> O <sub>4</sub>	4,9	15,4	6,5	7,1	7,6	34,4	38,3	9,6
Cr/Fe	2,37	0,94	1,88	1,77	1,11	0,68	0,64	1,64

1 'Feeder channel'

2 Fine-grained ultramafic marginal rock, borehole Eli-60 128,00 m

3 Average composition of chromites in the lower part of the main chromitites (6 samples)

4 Average composition of chromites in the upper part of the main chromitites (5 samples)

5 Homogeneous core of a rimmed chromite in silicate-rich rocks just below the main chromitite layer

6 Inner rim of the rimmed chromite mentioned above

7 Outer rim of the rimmed chromite mentioned above

8 Uppermost chromitite-rich layer (0.5 m thick) located 370 m above the main chromitite layer

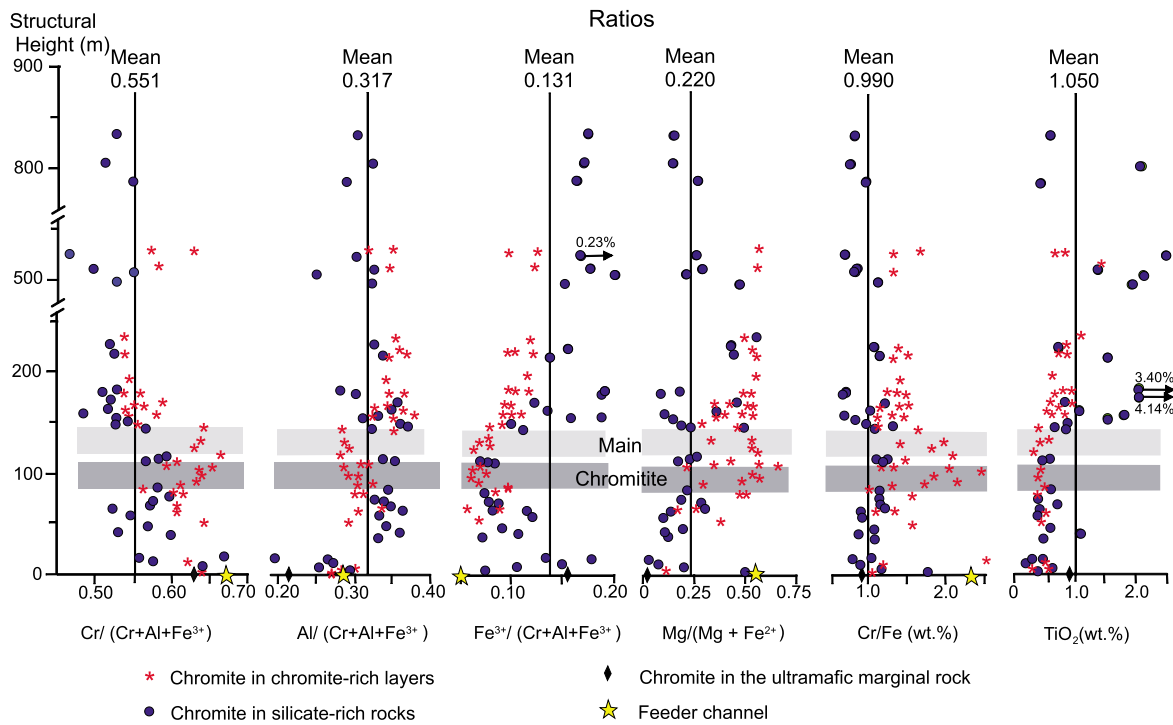


Fig. 5. Selected cation and Cr/Fe ratios and TiO<sub>2</sub> content for chromites in the Kemi Intrusion, after Alapieti *et al.* 1989a.

the altering chromite probably absorbs nickel from the surrounding mafic silicates, thereby increasing the mole fraction of trevorite. In addition, the chromite grains have also altered to ferrichromite in places, and then the chromium content can be higher than 65 wt. %, while aluminium and magnesium are distinctly lower than in the main chromitite.

The highest Cr-content in the Kemi chromitites was encountered in the probable feeder channel (Table 2). Similarly the Cr/Fe ratio is there distinctly higher than in the main chromitite (Fig. 5).

The chromite in the fine-grained ultramafic rock at the basal contact of the intrusion has an anomalously high zinc content, containing an average of 3.4 wt. percent ZnO, whereas a sample taken 0.5 m above the boundary of this rock type showed the ZnO content to have dropped to only 0.11 wt. percent, a

value characteristic of the other chromites of the Kemi Intrusion. The fine-grained contact rock also contains galena, as found in the granitoid below the Penikat intrusion and in the pyrrhotite-dominated mineralization in the marginal series of the Suhanko intrusion in the Portimo area, where it is associated with sphalerite and has been shown by isotope determinations to be derived from the rocks of the Archean basement (Alapieti *et al.*, 1989b). Thus the chromite enriched in the gahnite molecule may be the product of a reaction between sphalerite and chromite, and the sphalerite itself may be a result of contamination from the basement complex.

The Cr content of the chromites in the chromite-rich layers below the main chromitite layer and in the main chromitite layer itself is fairly constant, whereas a declining trend sets in above this (Fig. 5). The highest values are encountered in the main chromitite, however.



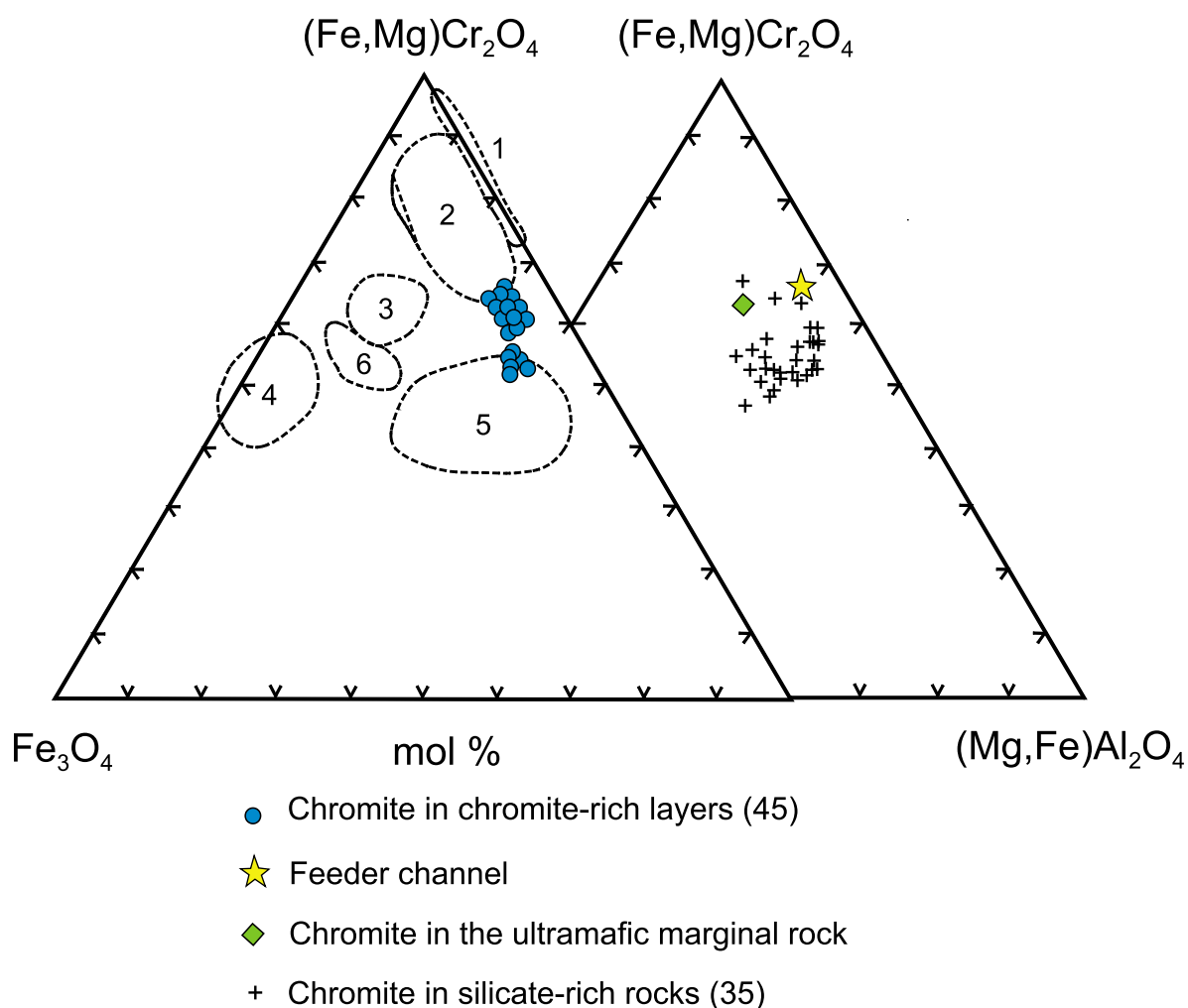


Fig. 6. Chromite-spinel-magnetite ternary diagram, showing the composition of the minerals of the spinel group in the Kemi Intrusion (numbers of samples in parenthesis). The provinces of the chromite deposits after Weiser (1967) and Ghisler (1976) are also shown. 1. Southern Europe and Asia. 2. Bushveld and Great Dyke complexes. 3. Chromites in Bushveld anorthosites. 4. Western Norway. 5. Fiskenaasset chromites. 6. Kemi chromites after Weiser (1967).

The Al, Fe<sup>3+</sup>, and Ti concentrations behave in the opposite manner, and the vanadium content (not shown in Fig. 5) also increases from the main chromitite upward. The Mn content remains more or less stable (MnO = 0.3-0.6 wt. %), except in one Cr-rich layer below the main chromitite, where it exceeds two wt. percent.

Comparison of the chromite compositions of the chromite-rich layers with those of the chromite-poor silicate rocks (Fig. 5) shows the former to have higher Cr/(Cr + Al + Fe<sup>3+</sup>),

Mg/(Mg + Fe<sup>2+</sup>) and Cr/Fe ratios and lower Al/(Cr + Al + Fe<sup>3+</sup>) and Fe<sup>3+</sup>/(Cr + Al + Fe<sup>3+</sup>) ratios than the chromites in the stratigraphically associated chromite-poor silicate rocks. These findings are in agreement with the observations of Cameron (1977) on the Bushveld Complex, with the exception of the Al/(Cr + Al + Fe<sup>3+</sup>) ratio, which is distinctly higher in the Bushveld chromitites than in the silicate-rich rocks. The Ti concentrations in the chromites of the chromite-poor silicate rocks (Fig. 5) increase upward considerably more than do the corresponding concentra-

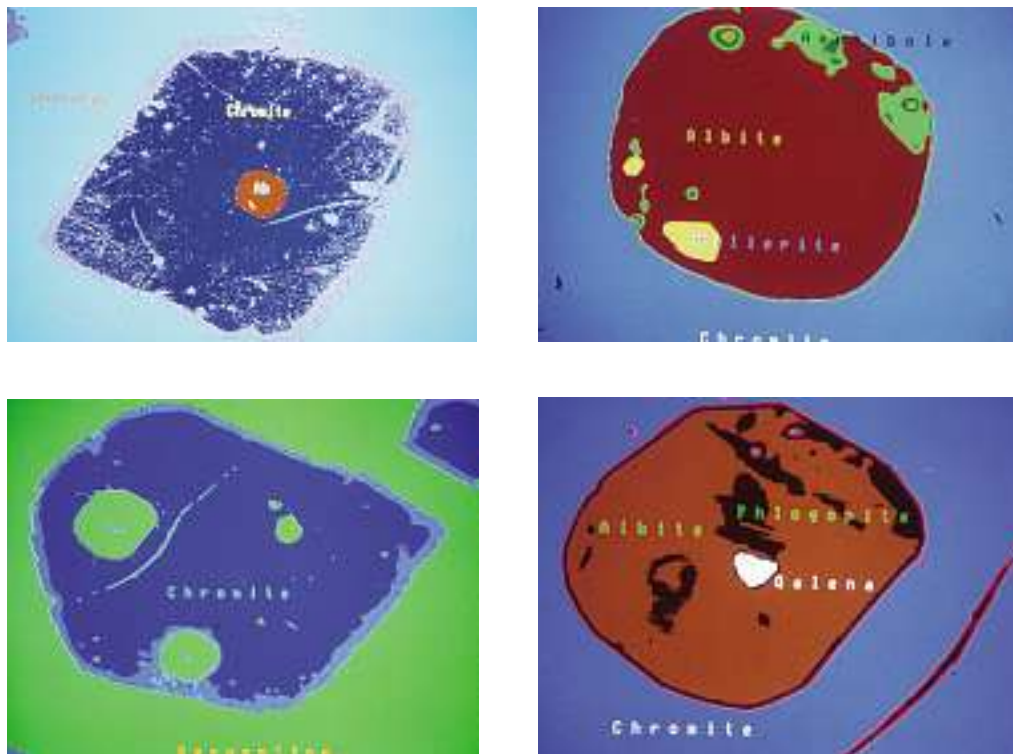


Fig. 7. Backscattered electron image showing silicate inclusions in chromite grains in the Kemi chromitite layers after Alapieti *et al.* 1989a.

tions in the chromite-rich layers, to the extent that some samples above the main chromitite layer have  $\text{TiO}_2$  concentrations of up to 3 to 4 wt. percent.

The first intercumulus ilmenite makes its appearance in the upper part of the bronzite-olivine cumulate, about 770 m above the base of the intrusion, and ilmenite becomes a cumulus phase in the anorthosite of the upper part, at about the same level at which apatite emerges as a cumulus mineral. No cumulus magnetite is found at any level.

The chromite grains are in many places characterized by spherical silicate inclusions 5 to 100  $\mu\text{m}$  in diameter, so that those in some of the lowermost chromite-rich layers commonly resemble Emmenthal cheese. The most common inclusions, and usually also the largest ones, are composed of mafic

silicates similar to those in the surroundings of the chromite grains, whereas many other inclusions are completely different in composition (Fig. 7). The most common among these latter are the albite-bearing inclusions.

Chromites in one 1.8 m thick chromitite layer about 60 m above the basal contact of the intrusion contained an exceptionally large number of silicate-rich inclusions characterized by a variety of minerals. One of these contained potassium-bearing pargasitic amphibole, hornblende, albite and millerite (Fig. 7.), while another chromite grain in the same sample was composed of three silicate inclusions (Fig. 7). The largest of these inclusions contained albite, phlogopite and galena. The occurrence of the last-mentioned mineral in this connection is interesting, because it has also been found in fine-grained border rock, as mentioned above.

Silicate-rich inclusions resembling those presented above have also been described by McDonald (1965) in the Bushveld chromitites, by Jackson (1961, 1966) in the Stillwater chromitites, and by Irvine (1975) in the Muskox chromitites. An albite-bearing inclusion has also been found by Alapieti (1982) in an olivine-bronzite-chromite cumulate in the Näränkäväära intrusion, north-eastern Finland, which belongs to the same age group as the Kemi Intrusion.

**Sulfides:** Although no more than a weak dissemination, the sulfide assemblage pyrrhotite-pentlandite-chalcopyrite is most abundant in the silicate-rich rock in the middle part of the main chromitite and on both sides of a 2.5 m thick chromite-rich layer situated above the main chromitite. Some chalcopyrite also

occurs in the lower part of the augite-bronzite cumulate and in the anorthosite of the upper part of the intrusion. In the anorthosite it is accompanied by pyrite.

**Phlogopite:** Abundant phlogopite is present as an intercumulus mineral in the upper part of the peridotitic cumulates, its mode fraction being as high as 10 vol. percent in some samples.

**Platinum-group minerals:** Platinum-group minerals are quite common in chromitites. They are mostly represented by Os, Ir and Ru minerals, especially laurite. On the other hand, in the sulphide-bearing silicate rich rock in the middle of the main chromitite, which is palladium-rich (Fig. 9), the Pd-Pt minerals are dominating.

## GEOCHEMISTRY OF THE KEMI INTRUSION

Variations in the CIPW norms within the intrusion are given in Fig. 8. Note that the relatively high plagioclase abundances assigned to the ultramafic rocks are due to the Al of chromite and the Ca of augite. The diagram illustrates well the high incidence of chromite-rich layers in the intrusion. The emergence of plagioclase as a cumulus phase, a feature which divides the whole intrusion into an upper and a lower part, is also conspicuous.

Of the individual oxides (Table 3), mention should be made of the steep increase in the  $\text{Al}_2\text{O}_3$  content above the contact between the pyroxenitic and gabbroic cumulates. MgO concentrations remain relatively constant up to the upper part of the peridotitic cumulates, above which they decline steadily toward the

roof of the intrusion. A sharp rise in CaO content is seen where augite becomes a cumulus mineral of the clinopyroxenites, after which it decreases gradually toward the roof of the intrusion.  $\text{Na}_2\text{O}$  concentrations increase steadily throughout the intrusion.  $\text{K}_2\text{O}$  is highest in the anorthosites of the upper part, although it increases to over 3 wt. percent in one chromite-rich layer, mentioned earlier, immediately below the main chromitite and below another chromite-rich layer 5 cm thick located above the main chromitite. The latter chromite-rich layer also has high La and Ce concentrations of 130 and 300 ppm, respectively, suggesting the presence of loweringite, although this mineral has not been encountered so far in the Kemi Intrusion (cf. Alapieti, 1982; Tarkian and Mutanen, 1987). The highest Pd, Pt,



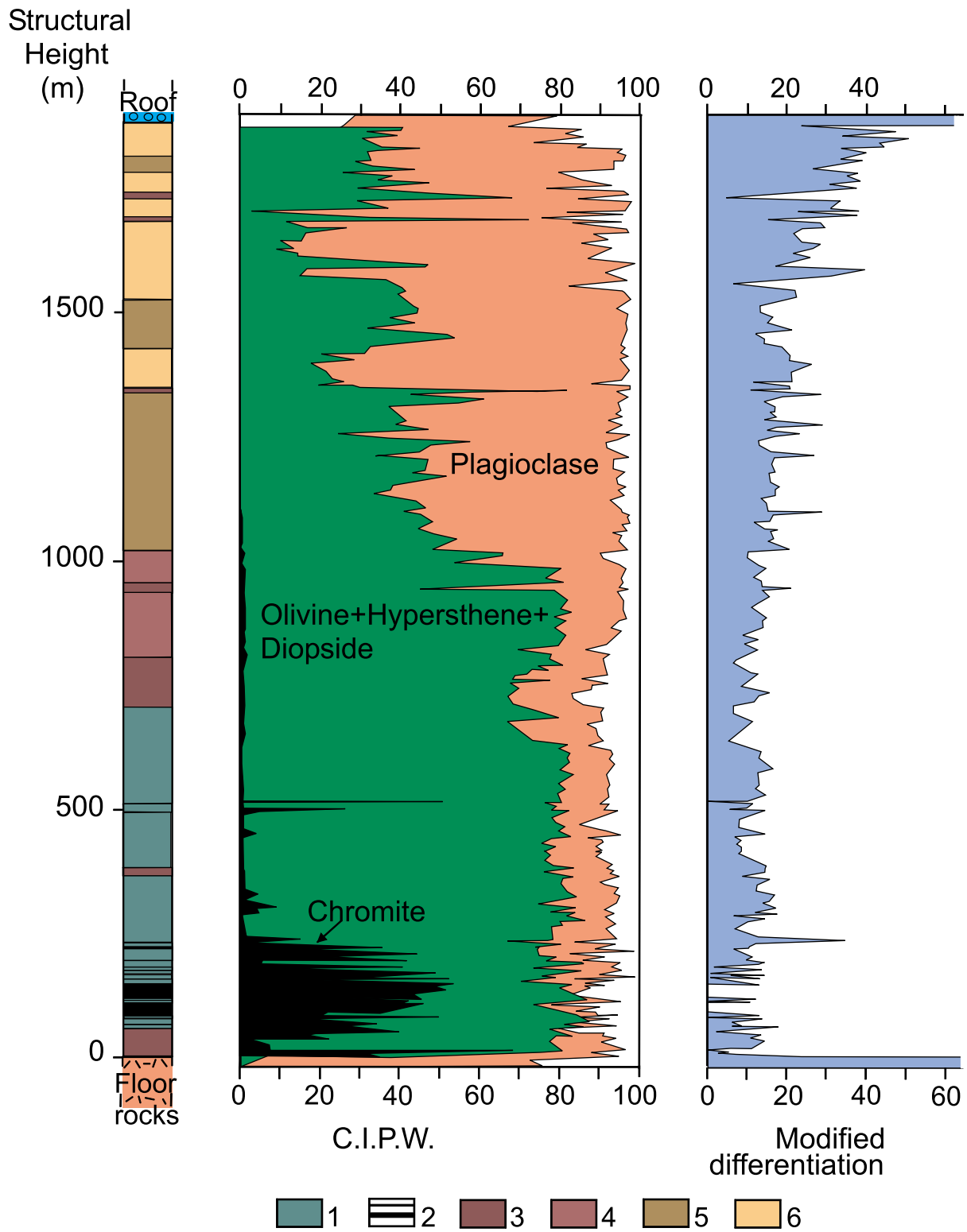


Fig. 8. Variations in the CIPW norm and modified differentiation index (von Gruenewaldt, 1973) in the Kemi Intrusion. The chemical analyses were recalculated in volatile-free form before computing the norms and the differentiation index.

**Table 3. Representative analyses of rock types in the Kemi Intrusion (recalculated volatile-free)**

Sample	1	2	3	4	5	6
SiO <sub>2</sub>	52,17	28,44	10,30	6,56	48,21	47,30
TiO <sub>2</sub>	0,49	0,64	0,36	0,43	0,14	0,18
Al <sub>2</sub> O <sub>3</sub>	10,80	15,81	12,09	12,98	27,10	12,00
Fe <sub>2</sub> O <sub>3</sub>		4,16	3,72	4,59	0,95	
Cr <sub>2</sub> O <sub>3</sub>	0,64	11,22	41,91	41,62	0,01	2,56
FeO	10.39*	14,96	13,42	16,52	3,09	7.80*
MnO	0,15	0,27	0,27	0,25	0,05	0,15
MgO	17,06	19,73	17,25	16,67	5,92	19,50
CaO	3,33	4,24	0,62	0,37	10,41	9,08
Na <sub>2</sub> O	0,00	0,23	0,06	0,00	3,83	1,11
K <sub>2</sub> O	4,89	0,25	0,00	0,00	0,27	0,27
P <sub>2</sub> O <sub>5</sub>	0,08	0,04	0,00	0,00	0,01	0,02
S	0,01	0,01	0,00	0,00	0,01	0,04

1 'Feeder channel'

2 Fine-grained ultramafic rock at the contact of the Kemi Intrusion (includes Zn = 0.70 and Pb 0.25 wt. %)

3 Chromite mesocumulate (heteradcumulate), with poikilitic postcumulus augite as the intercumulus material, lower part of the main chromitite

4 Chromite mesocumulate (heteradcumulate), with poikilitic postcumulus bronzite as the intercumulus material, upper part of the main chromitite

5 Plagioclase mesocumulate, with augite and quartz as intercumulus crystals (anorthosite) about 300 m below the roof of the intrusion

6 Average composition of the borehole profile A-A' in Fig. 1, based on 375 samples; weighted mean, weighted by the thickness and density of the layer represented by each sample

\* total iron as FeO

and Rh concentrations recorded in the Kemi Intrusion, 50, 180, and 120 ppb, respectively, are from immediately above this Cr-rich layer (Fig. 9). The chromium content is unusually high throughout the intrusion. The chromite-rich layers generally contain more than 20 wt. percent Cr, and the Cr content of the peridotitic and pyroxenitic cumulates is relatively constant, varying between 0.2 and 0.6 wt. percent. Only in the lower part of the gabbroic cumulates does the Cr content fall below 0.1 wt. percent, and values below 600 ppm are encountered only in the plagioclase cumulates of the upper part of the intrusion.

The Cr content rises above the 600-ppm level again close to the roof. The nickel content is quite constant, about 0.1 wt. percent in the lower part of the intrusion. The decline in Ni begins in the upper part of the peridotitic cumulates and continues almost linearly toward the roof of the intrusion. Zn is highest in the chromite-rich layers and diminishes gradually toward the uppermost anorthosites, where it begins to increase again. Sr behaves in much the same way as Na<sub>2</sub>O, i.e., it increases gradually from the lower parts of the intrusion upward.

## THE CHROMITE ORES

The chromite-rich layer which parallels the basal contact zone of the Kemi Intrusion is known over the whole length of the complex, beginning from the town of Kemi and extending 15 km northeast to the northern side of Lake Kirvesjärvi (Fig. 1). The chromite-rich layer varies in thickness from a few centimeters up to 160 m in the Elijärvi area, where the whole complex is at its thickest (Fig. 10). Economically the most important portion of the chromitite layer extends from the Elijärvi orebody in the west to the Pohjois-Viia orebody in the east. Average thickness of the chromitite layer is about 40 m in this area. The total length of the mineable portion of

the layer is about 1.5 km. The chromitite layer is cut into several ore bodies by numerous faults, and these are treated as separate units for the purposes of mining, beneficiation, and metallurgy. The whole ore field with its nine orebodies is depicted in Figure 10. The chromite-rich unit has an average dip of 70° to northwest.

The mine's proven ore reserves total some 50 million tons. In addition, it is estimated that there are 90 million tons of mineral resources. The average chromium oxide content of the ore is 26 percent and its chrome-iron ratio is 1.6.

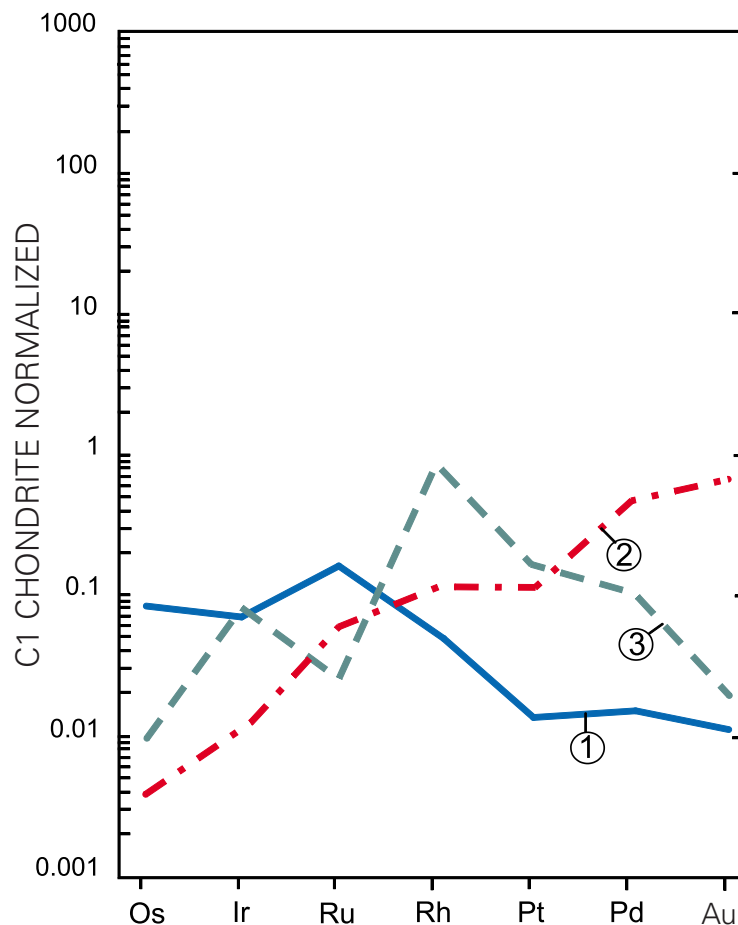


Fig. 9. Chondrite normalized metal patterns for the Kemi rock samples. 1, The main chromitite, average of three samples; 2, A sulfide-bearing, chromite-poor rock type in the middle of the main chromitite; 3 A chromitite-rich layer about 130 m above the main chromitite, average of two samples.

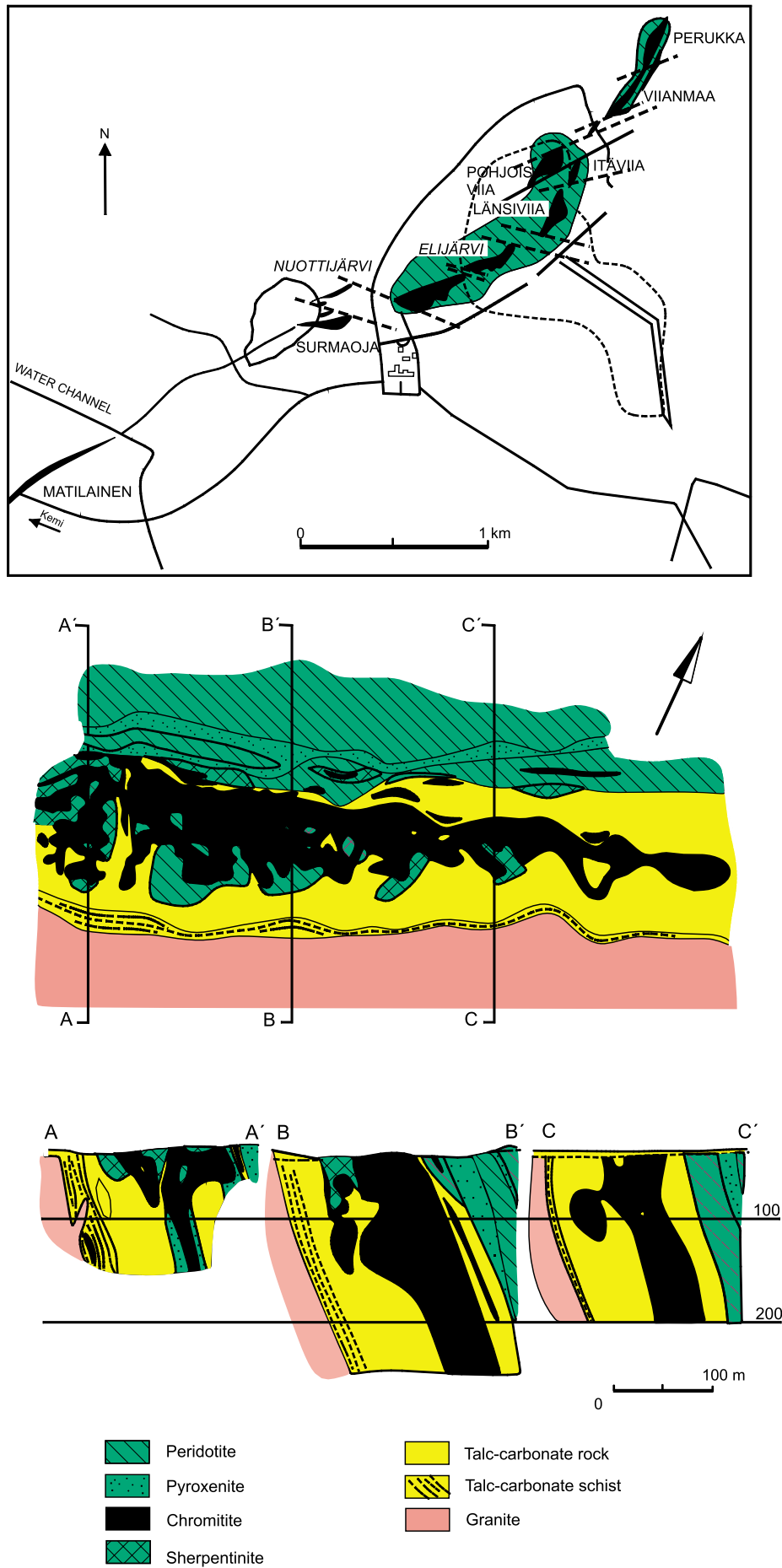


Fig. 10. Surface plan and three cross-sections of the Elijärvi orebody, after Alapieti et al. 1989a.

## STRUCTURE AND TEXTURE OF THE CHROMITE ORES

In the central part of the Kemi Intrusion the basal chromitite layer widens into a thick chromitite accumulation, which can be divided into three structurally different units. From bottom to top, these are the main chromitite unit, the altered unit, and the uppermost unit.

The basal contact with the Archean basement is tectonic, and a mylonitic talc-chlorite-carbonate schist, varying in thickness from 5 to 50 m, is the lowest rock type of the layered complex. The main chromitite unit is locally in contact with the remobilized granitoid, which intersects and brecciates the chromite ore.

The thickness of the main chromitite unit averages 40 m, but it varies from a few meters to 160 m. The upper contact with the altered chromitite unit lies stratigraphically 100 to 150 m above the basal contact of the complex, but its position has been altered by several strike-slip faults. The top of the main chromitite unit is layered in structure, but the lower part is non-layered and brecciated and the chromite ore contains abundant barren ultramafic inclusions. The best preserved structurally is the part of the layered unit between the Matilainen and Surmanoja orebodies where its thickness varies from a few meters to 30 m. The inhomogeneous Elijärvi orebody is depicted in Figures 10.

An intensely altered ultramafic rock with abundant thin chromite layers exists above the main chromitite unit. This rock type was primarily pyroxenite but now consists of talc and carbonates. Some of the chromite layers

can be traced for several tens of meters, but most of the layers extend for only a few meters. Innumerable small faults cut the layering and make it difficult to trace individual layers.

Sparse chromitite layers occur in the well-preserved peridotitic cumulate above the intensely altered ultramafic rock. The uppermost chromitite layer in the stratigraphy, about 0.5 m thick, exists as high as about 500 m above the basal contact of the intrusion.

In addition to the thick chromitite layer, the Cr content is also high in the pyroxenes in the middle part of the intrusion. This is surprising, since a vast amount of chromite must have crystallized out from the magma before these pyroxenes. One explanation for this is the entry of fresh magma pulses into the crystallizing chamber, mixing with the earlier, more or less contaminated liquid. According to the model proposed by Huppert *et al.* (1986), the new magma pulse would have been able to form a plume in the earlier liquid, resulting in the formation of chromite crystals during mixing. These crystals would have been taken up in the plume and would have spread sideways at the top of the liquid layer. After the discovery of the granophyre in the Penikat Intrusion, it would seem probable that it has also occurred above the Kemi Layered Series, and the plume has also reached this granophyric layer, where the salic contamination has triggered the chromite precipitation. The chromite grains will then have rained out of the plume to form the chromite pile at the base, preferentially around the vent, which would explain the



Fig. 11. Aerial photo of the Kemi open pit.

great thickening of the main chromitite in the central part of the intrusion. In addition, quite thick vertical chromitite has also been encountered in the probable feeder channel in the granite gneiss about 100 m below the intrusion, as mentioned earlier. The occurrence of this chromitite could be explained by flow differentiation, i.e. when the liquid with suspended chromite crystals flowed through this conduit, the chromites must have migrated into the region of higher velocity flow and concentrated in the center of the dike. The significance of the small spherical silicate inclusions rich in alkalis which commonly oc-

cur in chromite grains for the formation of the chromite-rich layers still remains poorly understood, although they could be indicative of sodium-rich fluids occurring during the crystallization of chromite.

The Kemi chromitite mine is a good example of the exploitation of a low-grade ore, distinctly lower in grade than in the stratiform deposits in southern Africa. The success of the operation is due to the convenient location of the deposit combined with advanced mineral processing and ferro-chrome production technology.



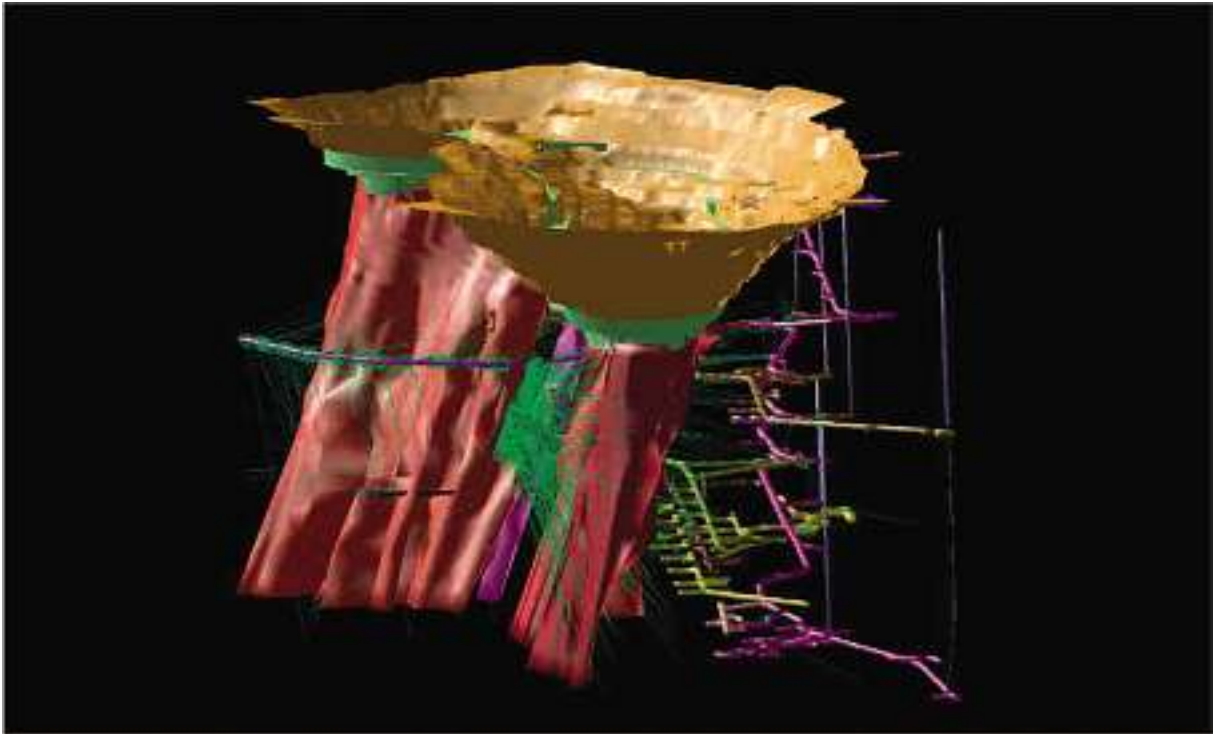


Fig. 12. 3-D model of the Kemi Mine

## EXCURSION SITES

1. The Kemi open pit
2. Underground mine
3. Upper contact of the Kemi Intrusion

## REFERENCES

ALAPIETI, T. T., 1982. The Koillismaa layered igneous complex Finland - its structure, mineralogy and geochemistry, with emphasis on the distribution of chromium: Finland Geol. Survey Bull. 319, 116 p.

ALAPIETI, T.T., KUJANPÄÄ, J., LAHTINEN, J.J. and PAPUNEN H., 1989a. The Kemi stratiform chromitite deposit, northern Finland. *Econ. Geol.* 84:1057-1077.

ALAPIETI, T. T., LAHTINEN, J., HUHMA, H., HÄNNINEN, E., PIIRAINEN, T., and SIVONEN, S., 1989b. Platinum-group element-bearing copper-nickel sulphide mineralization in the Marginal Series of the early

Proterozoic Suhanko-Konttijärvi layered intrusion, northern Finland, *in* Prendergast, M. and Jones, M.J., eds., *Magmatic sulphides – Zimbabwe Volume*. The Institution of Mining and Metallurgy, London, p. 177-187.

CAMERON, E.N., 1977. Chromite in the central sector of the Eastern Bushveld Complex, South Africa. *Am. Mineralogist* 62: 1082-1096.

HÄRME, M., 1949. On the stratigraphical and structural geology of the Kemi area, northern Finland. *Comm. Géol. Finlande Bull.* 147, 60 p.

- HUPPERT, H. E., SPARKS, R. S. J., WHITEHEAD, J. A. and HALLWORTH, M. A., 1986. The replenishment of magma chambers by light inputs. *Jour. Geophys. Research*, 91:6113-6122.
- IRVINE, T. N., 1975. Crystallization sequences in the Muscox intrusion and other layered intrusions - II. Origin of chromitite layers and similar deposits of other magmatic ores. *Geochim. et Cosmochim. Acta*, 39: 991-1020.
- JACKSON, E. D., 1961. Primary textures and mineral associations in the ultramafic zone of the Stillwater Complex, Montana. U.S. Geol. Survey Prof. Paper 358, 106 p.
- JACKSON, E.D. 1966. Liquid immiscibility in chromite seam formation - a discussion: *Econ. Geol.*, 61: 777-780.
- MANHES, G., ALLEGRE, C. J., DUPRE, B., and HAMELIN, B., 1980. Lead isotope study of basic-ultrabasic layered complexes: Speculation about the age of the earth and primitive mantle characteristics: *Earth Planet. Sci. Letters*, 47: 370-382.
- MCDONALD, J. A., 1965. Liquid immiscibility as one factor in chromitite seam formation in the Bushveld Igneous Complex, *Econ. Geol.*, 60: 1674-1685.
- MIKKOLA, A., 1949. On the geology of the area north of the Gulf of Bothnia: *Comm. Géol. Finlande Bull.* 146, 64 p.
- PATCHET, P., KOUVO, O., HEDGE, C. E., and TATSUMOTO, M., 1981. Evolution of continental crust and mantle heterogeneity: Evidence from Hf isotopes. *Contr. Mineralogy Petrology*, 78: 279-297.
- SAKKO, M, 1971. Varhais-karjalaisten metadiabaasien zirkoni-ikiä. With English summary: Radiometric zircon ages on the early Karelian metadiabases. *Geologi, Helsinki*, 23: 117-118.
- TARKIAN, M. and MUTANEN, T., 1987. Loveringite from the Koitelainen layered intrusion, northern Finland. *Miner. Petrol.* 37: 37-50.
- VON GRUENEWALD, G. 1973. The modified differentiation index and the modified crystallization index as parameters of differentiation in layered intrusions. *Trans. geol. Soc. S. Afr.* 76: 53-61.



## Chapter 3

### THE SOMPUJÄRVI, ALA-PENIKKA AND PAASIVAARA PGE REEFS IN THE PENIKAT LAYERED INTRUSION, NORTHERN FINLAND

Halkoaho, T.<sup>1)</sup>, Alapieti, T.<sup>2)</sup> and Huhtelin, T.<sup>3)</sup>

<sup>1)</sup>Geological Survey of Finland, Eastern Finland Office, P.O.Box 1237, FIN-70211, Kuopio, Finland, [tapio.halkoaho@gtk.fi](mailto:tapio.halkoaho@gtk.fi)

<sup>2)</sup>Department of Geosciences, University of Oulu, FIN-90014, Oulu, Finland, [tuomo.alapieti@oulu.fi](mailto:tuomo.alapieti@oulu.fi)

<sup>3)</sup>Outokumpu Chrome Oy, Kemi Mine, P.O.Box 172, FIN-94101, Kemi, Finland, [timo.huhtelin@outokumpu.com](mailto:timo.huhtelin@outokumpu.com)

#### INTRODUCTION

The Penikat Layered Intrusion is located in northern Finland, about 20 km to the north-east of the Gulf of Bothnia and 70 km to the south of the Arctic Circle (Fig. 1). It forms part of a discontinuous early Palaeoproterozoic layered intrusion zone about 300 km in length which begins in Sweden and continues eastwards to Näränkåvaara in Koillismaa and on from there into Russia, as the Oulanka Layered Complex. This zone, known as the Tornio-Näränkåvaara belt (Alapieti & Lahtinen 1986), contains almost 20 intrusions varying in size from a few kilometres up to 30 km across. Other formations in the same age category include the Koitelainen Layered Intrusion with its satellites and Akanvaara Layered Intrusion in Central Lapland and the Burakovsky Layered Intrusion on the eastern shore of Lake Onega, and the Mt. Generalskaya, Monchegorsk, Imandra Lopolith and Fedorova Tundra - Pana Tundra Layered Intrusions on the Kola Peninsula, all in Russia. These intrusions mentioned above have previously been described by e.g. Kujanpää (1964, 1980), Alapieti et al. (1979a,b, 1989a,b, 1990), Lavrov (1979), Mutanen (1981, 1989, 1997), Alapieti (1982), Dokuchayeva et al. (1982), Söderholm and Inkinen (1982), Alapieti and Piirainen (1984), Lahtinen (1985), Alapieti and Lahtinen (1986, 1989, 2002), Tarkian and Mutanen (1987).

Age determinations for the early Palaeoproterozoic layered intrusions in Finland carried out by the U-Pb method for zircon and the Pb-Pb whole rock and Sm-Nd methods have given results varying from 2346 m.y. to 2474 m.y.,

the mean being 2440 m.y., see Kouvo (1977), Puustinen (1977), Manhes et al. (1980), Patchet et al. (1981), Alapieti (1982) and Huhma et al. (1990). The initial  $\epsilon_{Nd}(2440)$  of the Penikat Layered Intrusion is  $-1.6 \pm 0.6$  (Huhma et al. 1990).

A number of ore mineralizations of various types have been found in the Tornio-Näränkåvaara belt, the most significant of which are the large chromitite deposit in the Kemi Layered Intrusion (Kujanpää 1980, Alapieti et al. 1989a) and the Mustavaara vanadium ore deposit in the Koillismaa Layered Complex (Juopperi 1977), while mineralizations containing base metal sulphides and platinum-group elements (PGE) have been discovered in many of its intrusions, including the Koillismaa Layered Complex (Isohanni 1976, Piirainen et al. 1977, Alapieti & Piirainen 1984, Lahtinen 1985), the Portimo Layered Complex (Vuorelainen et al. 1982, Lahtinen 1985, Alapieti et al. 1989b, Iljina et al. 1989, Huhtelin et al. 1989c, Iljina 1994, Alapieti & Lahtinen 2002) and the Penikat Layered Intrusion, where the sequence contains at least seven separate PGE-enriched zones. Three major zones, the Sompujärvi (SJ), Ala-Penikka (AP) and Paasivaara (PV) PGE Reefs have been identified for almost the entire length of the intrusion. The layered series of the Penikat Intrusion is divided into five megacyclic units. The SJ Reef being located in the boundary zone between the third and fourth megacyclic units, 500 to 1000 m above the base of the Penikat Layered Intrusion, and its PGE mineralizations have been found to occur in

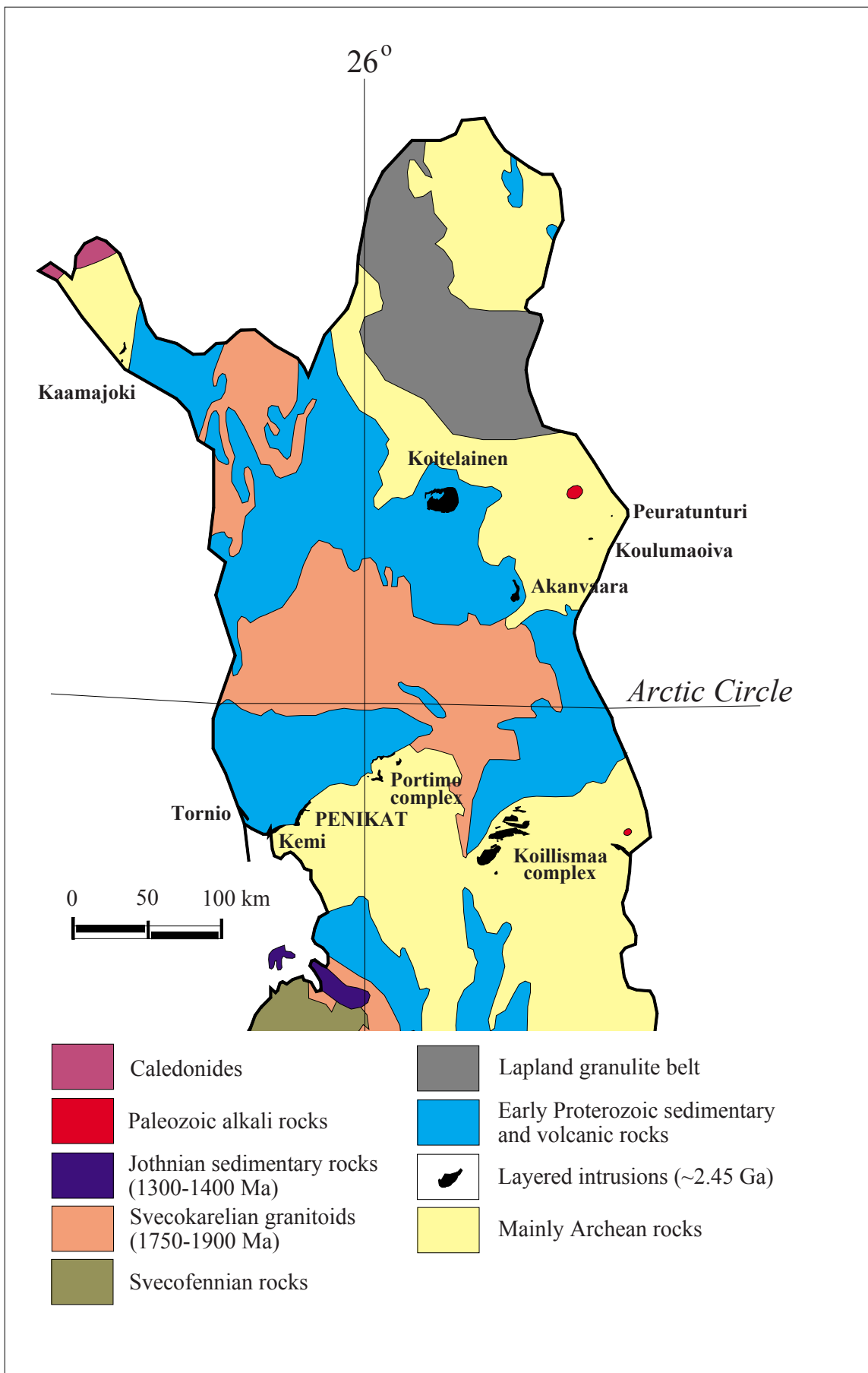


Fig. 1. Generalized geological map of Northern Finland showing the location of the early Palaeoproterozoic layered intrusions, about 2440 Ma in age. Modified after Alapieti and Lahtinen (1989) and Alapieti et al. (1990).

association with either base metal sulphide or chromite disseminations or to be concentrated in silicate rocks which do not contain any base metal sulphides or chromite. The base metal sulphide-bearing AP Reef is located 250-450 m above the SJ Reef in the lower part of megacyclic unit IV, and the base metal sulphide-bearing PV Reef about 700-1000 m above this, in the transition zone between megacyclic units IV and V. These PGE reefs have previously been described by Alapieti (1984), Alapieti and Lahtinen (1986, 2002), Alapieti et al. (1989), Halkoaho (1989, 1993), Halkoaho et al. (1989a, 1989b, 1990a,b), Huhtelin (1989) and Huhtelin et al. (1989a, 1990).

There are two popular hypotheses at present to explain the origin of PGE concentrations. The first, which was the most widely favoured at the beginning, is that PGE concentrations are associated with base metal sulphide-bearing

zones near the bases of cyclic units in sequences of cyclic layering (cf. Naldrett & Duke 1980, Campbell et al. 1983, Irvine et al. 1983, Naldrett et al. 1986, Campbell & Turner 1986). However, as shown in the case of the Penikat Intrusion, this traditional concept of platinum genesis cannot explain all PGE deposits, because the platinum-sulphide association is by no means ubiquitous and platinum-group minerals may or may not occur in association with chromite and silicate. Some other mechanism is needed to explain the particular aspect of the SJ PGE Reef in the Penikat Intrusion. In this case the second hypothesis, the concept of later or post-magmatic volatile activity, may be invoked to explain these features (cf. Elliott et al. 1982, Kinloch 1982, Schiffries 1982, Volborth & Houstley 1984, Buntin et al. 1985, Ballhaus & Stumpff 1985, 1986, Boudreau et al. 1986, Ballhaus et al. 1988, Boudreau 1988, Mathez et al. 1989, Willmore et al. 2000).

## PENIKAT LAYERED INTRUSION

The description of the Penikat Layered Intrusion is based mainly on the papers of Alapieti and Lahtinen (1986, 1989), Alapieti et al. (1990) and Halkoaho 1993. The intrusion is 23 km long and 1.5 to 3.5 km wide and its foot-wall rocks consist of late Archaean/early Palaeoproterozoic granitoids. The hanging wall rocks, which are younger than the intrusion, are either tholeiitic volcanics, subvolcanic sills or in places a polymictic conglomerate. The original intrusion was broken up by tectonic movements to form five westward-dipping blocks, the borders of which are bounded by roughly east-west-trending faults. These are designated as the Ala-Penikka, Keski-Penikka, Yli-Penikka, Kilkka and Sompujärvi blocks (Fig. 2). The intrusion may be divided into two principal units: the marginal series and the layered series.

The marginal series of the Penikat Intrusion is composed, from the base upwards, of a fine-grained chilled margin, subophitic, non-cumulate-textured gabbroids, and gabbro-noritic and bronzitic cumulates. The layered series is composed of alternating sequences of ultramafic, gabbro-noritic, gabbroic and anorthositic cumulates and it has been divided into megacyclic units I - V, starting from the base, which are abbreviated MCU I - MCU V (Fig. 3). The chemical composition of megacyclic units I - III is boninitic (Cr-rich) and the megacyclic units IV and V tholeiitic (Cr-poor). These are interpreted as being attributable to repeated influxes of new magma into the Penikat chamber during solidification (Alapieti & Lahtinen 1986). A general cumulus stratigraphy for the Penikat Intrusion is presented in Fig. 3.

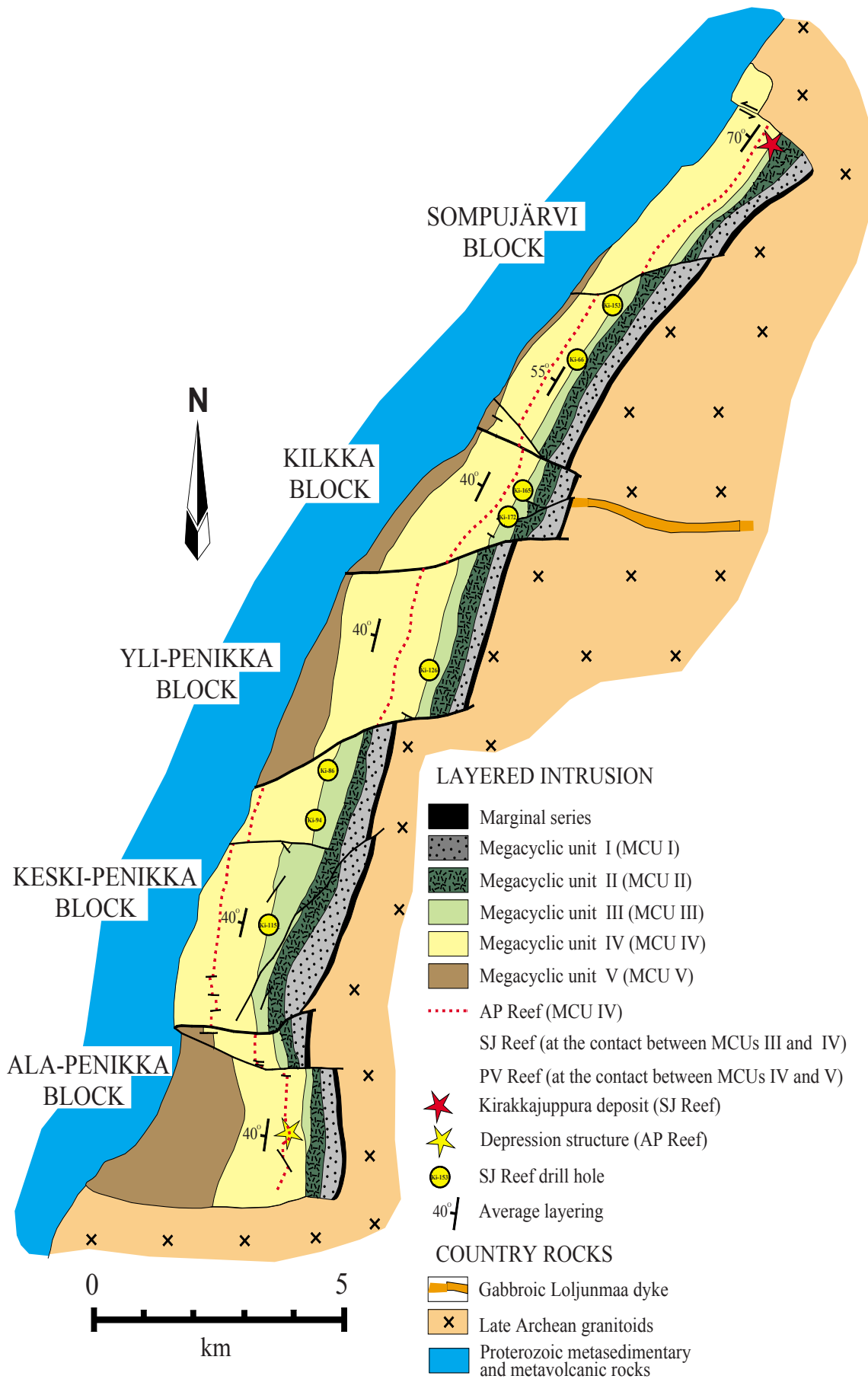


Fig. 2. Generalized geological map of the Penikat Layered Intrusion showing the locations of the megacyclic units, PGE reefs and drill holes in the SJ Reef discussed in the text. Modified after Alapieti and Lahtinen (1986, 1989) and Alapieti et al. (1990).

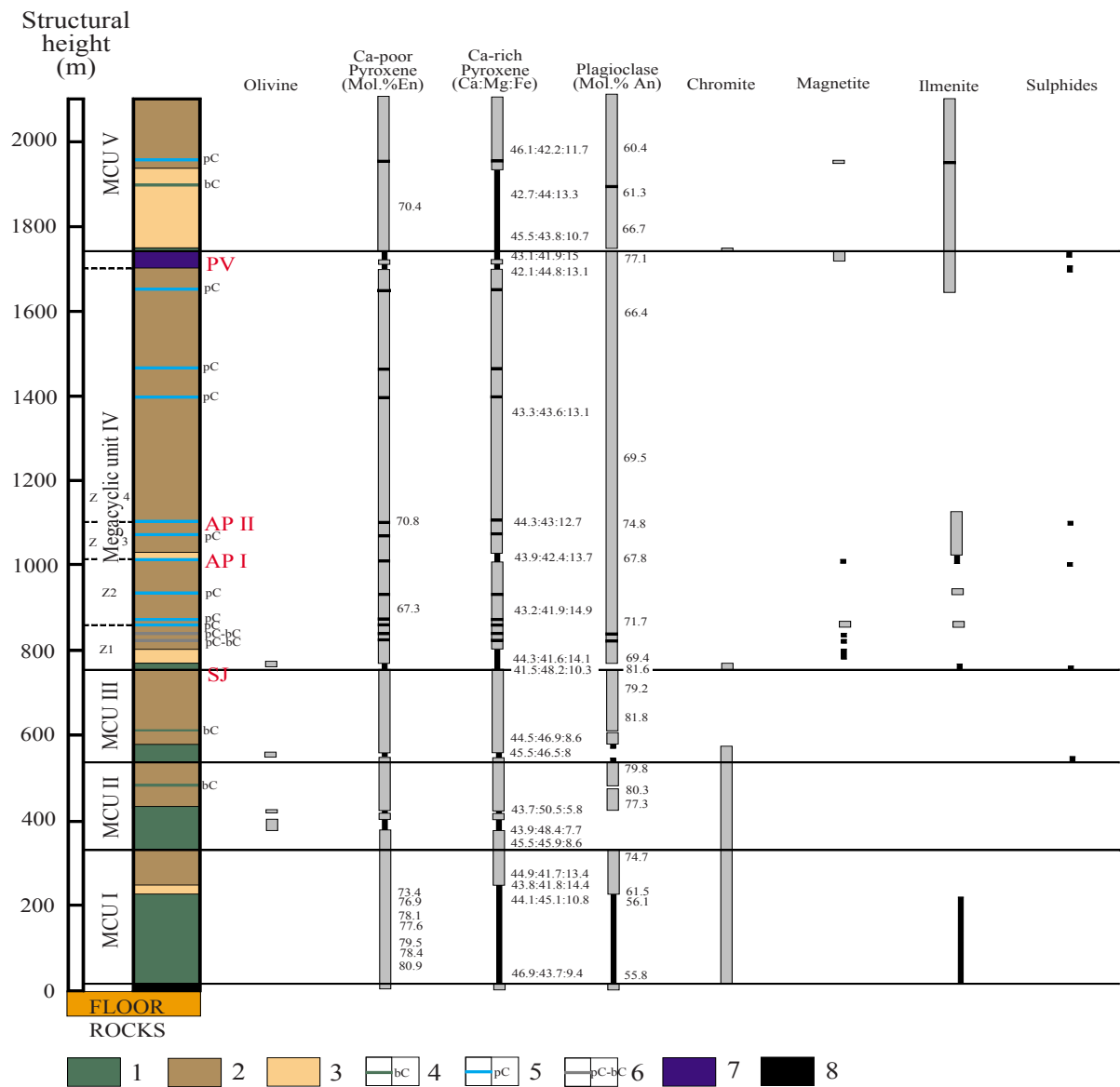


Fig. 3. General stratigraphic sequence and cryptic variation in minerals in the Penikat Intrusion. Thick vertical lines indicate cumulus minerals and thin vertical lines intercumulus minerals. Z1 – Z2 represent zones 1 – 4 (Halkoaho 1989, Halkoaho et al. 1989b, 1990b). 1) Ultramafic cumulates, 2) Plagioclase-augite-bronzite cumulate, 3) Plagioclase-bronzite with intercumulus augite or poikilitic plagioclase-bronzite cumulate with intercumulus augite, 4) Narrow pyroxenitic interlayer, 5) Narrow anorthositic interlayer, 6) Narrow anorthosite-pyroxenite pair interlayer, 7) Anorthositic-gabbronoritic transition zone, 8) Marginal series. SJ – Sompujärvi PGE Reef, API – Ala-Penikka I PGE Reef, AP II – Ala-Penikka II PGE Reef, PV – Paasivaara PGE Reef. Modified after Halkoaho 1993.

### Chilled margin and marginal series

Below the Penikat Intrusion is a potassium-rich granite containing large amounts of fluorite and galena in places. The contact between the intrusion and this granite is sharp featuring a distinct chilled margin. The total thickness of the marginal series is 10-20 m, and as no clear boundary has been observed between the marginal series and the layered series, the lowermost chromite layer is taken

to represent this boundary. The gabbronorite of the marginal series on top of the chilled margin is ophitic at first, but soon assumes a distinct cumulus structure, and the upper part grades into bronzitite. The chilled margin is slightly contaminated with granite, containing large amounts of biotite. Narrow rheomorphic granite dykes are to be found in the marginal series in places, an indicator of the low mobility of the granitic basement material (Alapieti 1984).

### Megacyclic unit I

The thicknesses of MCU I (see Figs 2 and 3) in the Penikat Intrusion varies between 270-410 m (average is about 330 m). The ultramafic layer of MCU I is formed by bronzitite (b(c)Cpa), which contains accessory cumulus chromite, intercumulus plagioclase and augite, with granophyric material, biotite, ilmenite and Cl-rich apatite commonly occurring as accessories in the intercumulus spaces. The bronzitite is overlain by 25 to 60 m of gabbronorites, plagioclase-bronzite mesocumulate (pmMca(q)) with intercumulus augite and a small amount of quartz, followed by plagioclase-augite-bronzite adcumulate (pabAC).

### Megacyclic unit II

The thicknesses of MCU II in the Penikat Intrusion varies between 160-230 m (average is about 200 m). The ultramafic layer of MCU II begins with websterite (ab(c)C), above which is lherzolite (o(c)Cab) containing thin chromitite streaks. Above the lherzolite one again finds websterite (abC or ab(c)C) with lherzolite and gabbronorite interlayers. The upper part of MCU II contains two gabbronorite layers (apbC or apb(c)C) that contain chromite disseminations in places and are separated by websterite.

### Megacyclic unit III

The thicknesses of MCU III in the Penikat Intrusion varies between 75-330 m (average is about 200 m). The ultramafic layer at the bottom of MCU III mainly consist of websterite (ab(c)C), which has chromite disseminations in places. Anyway some areas in the middle part of websterite occurs a lherzolite (o(c)Cab or ob(c)Ca). The main rock type above the ultramafic layer is a homogeneous gabbronorite, plagioclase-augite-bronzite adcumulate (pabAC). In some places of the upper part of MCU III between the plagioclase-augite-bronzite adcumulate and the ultramafic layer at the base of MCU IV features a thin poikilitic plagioclase-bronzite orthocumulate

(pbOCa\*) with poikilitic intercumulus augite, commonly with associated discontinuous gabbronoritic pegmatoids. This rock type is sometimes characterized by pronounced chromite dissemination or even chromitite interlayers, the disseminated chromite grains usually being corroded.

### Megacyclic unit IV

Megacyclic unit IV is the most important sequence as far as PGE mineralization is concerned. The thicknesses of MCU IV in the Penikat Intrusion varies between 760-1110 m (average is about 920 m). The contact between units IV and III does not follow the original uppermost layers of the latter, since the upper cumulates of unit III were quite deeply obliterated by magmatic erosion in many places (see Figs 11 and 12, Halkoaho et al. 1989a, 1990a).

The lower part of MCU IV may be divided into four zones, mainly by reference to the cryptic variation in augite (Halkoaho 1989, Halkoaho et al. 1989b, 1990b). The first zone, which is 100 m thick, begins with a layer of ultramafic cumulates, generally ranging in thickness from 10 to 20 m. The lowermost part of the ultramafic sequence is generally composed of about a 1 m thick layer of a bronzite cumulate (b+(c)Ca) with intercumulus augite. The base of the bronzite cumulate is formed by a thin chlorite schist layer. These rocks are in turn overlain by olivine cumulates (oCb\*a\* or o(c)Cb\*a\*) in which bronzite and augite occur as the intercumulus phases and tend to be poikilitic in texture. The uppermost part of the ultramafic layer is again composed of a bronzite cumulate with intercumulus augite. The ultramafic rocks are overlain by a sequence of gabbronoritic cumulates, the lower part of which consists of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*) and plagioclase-bronzite mesocumulate (pbMca) in which augite occurs as the main intercumulus mineral. Above this layer augite becomes a cumulus phase and maintains this status from this point upwards with the exception of certain interlayers. The upper part of the first zone is



characterized by pronounced rhythmic layering, which also reveals two, about 20 m thick, macrorhythmic units. These units begin with a poikilitic bronzite cumulate, followed by a plagioclase-bronzite mesocumulate (pbM<sub>Ca</sub>), a plagioclase-augite-bronzite adcumulate (pabAC) and another plagioclase-bronzite mesocumulate, the uppermost parts being composed of poikilitic plagioclase mesocumulate (pM<sub>Ca</sub>\*b\*) (Fig. 3 and see Figs 14 and 15).

**The second zone**, which is 150 m thick, is composed of homogeneous plagioclase-augite-bronzite adcumulates and two narrow plagioclase cumulate interlayers. At the base of this zone ilmenite is also encountered as a cumulus mineral together with those mentioned above (Fig. 3).

**The third zone** begins with a poikilitic plagioclase mesocumulate (pM<sub>Ca</sub>\*b\*) layer in which augite and bronzite occur in the form of large, poikilitic oikocrysts enclosing numerous plagioclase grains, thus giving this layer its characteristic mottled appearance (see Figs 8, 17 and 19). The thickness of this layer is normally 3 to 30 cm, but in the area of the depression/pothole structure in the Ala-Penikka block, which will be described in the end of this chapter, it attains a thickness of as much as 2 to 20 m (see Figs 8B, 19 and 20). This poikilitic plagioclase mesocumulate is overlain by 1 m of poikilitic plagioclase-bronzite mesocumulate (pbM<sub>Ca</sub>\*) in which augite occurs as poikilitic oikocrysts. This rock is in turn characterized by a spotted appearance caused by glomerophyric clusters of plagioclase grains visible as light spots; it is overlain by a 13 m thick gabbro-norite or norite (pb<sub>Ca</sub> or pbC(a)) in which augite still occurs as the intercumulus mineral but is no longer poikilitic in texture (Halkoaho et al. 1989b, 1990b). The plagioclase-bronzite cumulate with intercumulus augite is followed by about 80 m of a fairly homogeneous plagioclase-augite-bronzite adcumulate which contains a pair of narrow anorthosite interlayers 5 to 10 cm in thickness and 20 cm apart. On both sides of these anorthosite layers one finds 1.5 m of plagioclase-bronzite mesocumulate in which augite is the main intercumulus mineral.

The fourth zone is about 300 m thick and is mainly composed of plagioclase-augite-bronzite adcumulates, with the exception of a thin layer of poikilitic plagioclase adcumulate at its base and some anorthositic interlayers (Fig. 3).

Above the fourth zone the upper part of MCU IV is composed of a relatively homogeneous plagioclase-augite-bronzite adcumulate, a thin plagioclase orthocumulate layer being encountered about 90 m below the border between MCU's IV and V. At the top of MCU IV there is a 40 to 60 m thick transition zone (see Figs 3, 9 and 21, Huhtelin 1989, Huhtelin et al. 1989a, 1990) which is highly complex, containing plagioclase-augite-(bronzite) cumulates, anorthositic plagioclase mesocumulates, pegmatoidal rocks and a mixed rock composed of a plagioclase adcumulate matrix and darker irregular patches of poikilitic plagioclase and/or plagioclase-bronzite cumulate in which augite occurs as the main intercumulus mineral. The uppermost layer of the transition zone is composed of an anorthositic plagioclase mesocumulate which contains 5 to 10 % intercumulus augite (Fig. 3) (Huhtelin et al. 1989a, 1990).

**A depression structure or 'pothole'** which is about 300 m long and 100 m deep and interrupts the underlying cumulates is encountered at the boundary between the second and third zones in the Ala-Penikka block (Halkoaho 1989, Halkoaho et al. 1989b, 1990b, Halkoaho & Alapieti 1993) (Figs 2, 13 and 18). This structure has been broken up by northwest-southeast trending faults to form three separate parts on the present erosional surface, the southernmost one representing the shallowest section of the original structure whereas the northernmost one is the deepest. In addition, the pothole is cut by a younger diabase dyke in the middle part, which shows distinct chilled margins against the wall rocks (Halkoaho 1989, Halkoaho et al. 1989b).

The cumulus stratigraphy of this depression/pothole structure greatly resembles that of the lower part of the normal third zone, but the

vertical thicknesses of the layers are distinctly greater. The poikilitic plagioclase mesocumulate (pMCa\*b\*) with intercumulus augite and bronzite, for example, is now 2 to 20 m thick, whereas outside the structure it is only 3 to 30 cm thick, as mentioned earlier. Similarly the plagioclase-bronzite mesocumulate (pbMCa) with intercumulus augite overlying this plagioclase mesocumulate is now 50 m thick, whereas its thickness elsewhere is only about 13 m (see Fig. 18).

The area of the depression/pothole structure also features large amounts of gabbroic pegmatoids, which are concentrated in certain layers. These pegmatitic rocks are encountered particularly in connection with a poikilitic plagioclase mesocumulate in the central part of the depression structure and in a zone located about 120 m above this mesocumulate; there numerous gabbroic pegmatitic rocks run perpendicular to the prevailing igneous layering, and they are generally accompanied by plagioclase adcumulate fragments 20 to 50 cm in diameter having narrow margins which are more fine-grained than the cores (Halkoaho 1989, Halkoaho et al. 1989b) (see Fig. 18).

## PGE REEFS

### Sompujärvi PGE Reef

The Sompujärvi (SJ) PGE Reef is located at the boundary zone between the third (boninitic, Cr-rich) and the fourth (tholeiitic, Cr-poor) MCUs, 500-1000 m above the base of the Penikat Layered Intrusion (Figs 2 and 3), and is known to occur over the entire 23 km of the intrusion. The SJ Reef has previously been described by Alapieti (1984), Alapieti and Lahtinen (1986, 2002), Halkoaho et al. (1989a, 1990a) and Halkoaho 1993.

As described earlier, the main rock type in the gabbroic upper parts of MCU III is a homogeneous plagioclase-augite-bronzite adcumulate, usually overlain by a thin layer

### Megacyclic unit V

The original thickness of MCU V is not known, as its upper part has been eroded away to various extents, being absent entirely in the Keski-Penikka block, for instance (Fig. 2). There are 900 m of it remaining in the Ala-Penikka block and 600 m in the Yli-Penikka block, but only 10 m in the Sompujärvi block.

The bronzitite (b(c)Ca) at the base of MCU V is overlain by 190-250 m thick noritic, relatively homogeneous poikilitic plagioclase-bronzite cumulate in which augite occurs as oikocrysts. Quartz, apatite and ilmenite occur commonly as accessory minerals. The upper part of the poikilitic plagioclase-bronzite cumulate contains a bronzitite layer a few m thick, while above the cumulate is a plagioclase-augite-bronzite adcumulate with a narrow anorthosite layer 10 cm thick and containing cumulus magnetite. The uppermost sample about 300 m above the poikilitic plagioclase-bronzite cumulate, no longer contains any orthopyroxene, so it is a plagioclase-augite adcumulate (not shown in Fig. 3).

of poikilitic plagioclase-bronzite orthocumulate with intercumulus augite (see Figs 4-7), commonly with associated discontinuous gabbroic pegmatoids. The plagioclase-bronzite orthocumulate is also normally characterized by pronounced chromite dissemination or even chromitite interlayers (see Fig. 5B), the disseminated chromite grains usually being corroded.

The uppermost gabbroic layer of MCU III is not continuous due to magmatic erosion caused by the entry of new magma. The upper part of MCU III has quite deeply obliterated in many places (Halkoaho et al. 1989a, 1990a), e.g. at the southern and northern ends of the Penikat Intrusion (see Figs 2, 11 and 12).



As mentioned earlier, MCU IV commences with a layer of ultramafic cumulates, generally ranging in thickness from 10 to 20 m. The lowermost part of this ultramafic sequence is generally composed of a 1 metre layer of bronzite cumulate (b+(c)Ca), at the base of which is a thin chlorite schist layer, usually markedly deformed and schistose, whereas the original cumulus textures are generally clearly visible in the rocks on both sides. The chlorite of the schist is aluminium-rich (about 21 wt.%  $\text{Al}_2\text{O}_3$ ) and relatively MgO-rich (about 23 wt.%) and is sometimes accompanied by a considerable proportion of corroded chromite grains. The high total  $\text{Al}_2\text{O}_3$  content of the chlorite schist is almost the same as in the uppermost plagioclase-bearing cumulates of MCU III, whereas the CaO content is only 0.5 wt.% on average. If the chlorite schist once contained plagioclase, which is quite probable, it must have lost large amounts of Ca either through various reactions at the time of crystallization (e.g. under the influence of fluids) or in the course of later metamorphic events. The bronzite cumulate (bCa) is overlain by olivine cumulates in which bronzite and augite occur as the intercumulus phases and tend to be poikilitic in texture. The topmost part of ultramafic layer is again composed of a bronzite cumulate with intercumulus augite.

The SJ Reef is erratic in its distribution. Platinum-group minerals (PGMs) are usually concentrated in the basal portion of MCU IV, but they can occur in the overlying peridotitic cumulates in places (Fig. 7A), or in the gabbronoritic cumulates at the top of MCU III, or the mineralized zone can continue from these gabbronoritic cumulates upwards through pyroxenitic ones as far as the peridotitic cumulates (Figs 5B, 7B and 12). The SJ Reef varies in thickness from a few decimetres to several metres, the average being about 1 metre.

It will be focused here on elements, such as S, Cr, Cu, P and Zr, that are assumed to be significant for the generation of the SJ Reef. The SJ Reef has been divided into four groups based on the occurrence of PGMs relative to base metal sulphides, chromite and silicates:

1) chromite type, 2) composite chromite and base metal sulphide type, 3) base metal sulphide type and 4) PGE only type (Halkoaho 1993, Alapieti & Lahtinen 2002).

Drill holes containing the chromite type have been encountered only in the Kilkka and Sompujärvi blocks (Fig. 2). As mentioned earlier, this type is usually richer in PGE than the SJ Reef on average. Drill holes Ki-172 in the Kilkka block and Ki-66 in the Sompujärvi block (Fig. 2), as presented in Fig. 4, were selected as representatives of the chromite type. The highest PGE concentration in drill hole Ki-172 is encountered approximately in the middle of a poikilitic plagioclase-bronzite-(chromite) orthocumulate (pb(c)OCa\*) about 2.5 m thick located below the ultramafic layer at the base of MCU IV, in which the highest Cr concentration of 0.81 wt.% in the drill hole is also recorded. The concentrations of the other elements examined here, S, Cu, P and Zr are low, and certainly no higher than in the cumulates occurring above and below this layer. The highest PGE concentration in drill hole Ki-66 in the Sompujärvi block is found in an interlayer containing chromite disseminations located approximately in the middle of a websteritic layer (bCa) about 3 m thick in the lower part of the ultramafic cumulates at the base of MCU IV. Half a metre below the websteritic layer there is again about 30 cm of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*), but its PGE content is markedly lower than that in the ultramafic rock with chromite disseminations above it. There are three chromite-bearing interlayers detectable in the drill hole, the middle one of which is the richest in PGE. As in the previous drill hole, the concentrations of the other elements examined are low and remain below those found in the cumulates above and beneath them.

Composite chromite and base metal sulphide type mineralization drill holes have been observed in all the blocks except from Keski-Penikka, usually with the base metal sulphide type in the upper part of the chromite type or above it. Sometimes the two types occur together, but there is no case in which the base

metal sulphide type exists below the chromite type. The drill holes selected to represent the composite chromite and base metal sulphide type were Ki-126 in the Yli-Penikka block and Ki-153 (Fig. 2), in the Sompujärvi block. These two profiles are presented in Fig. 5. The highest PGE content in drill hole Ki-126 is encountered in a websteritic layer (b(c)Ca) about a metre thick and containing chromite disseminations occurring in the lower part of the ultramafic layer at the base of MCU IV, beneath which there is again about 30 cm of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*). The sulphide disseminations begin at the point of maximum PGE concentrations, but are most pronounced about half a metre above this (0.77 wt.% S), where there is no more than a PGE anomaly. Copper concentrations follow those of sulphur throughout and reach a maximum of 0.38 wt.%. In drill hole Ki-126 the main component in the sulphide (pyrite-pentlandite-chalcopyrite) paragenesis is chalcopyrite (about 50 %). The P and Zr concentrations in the 1.5 m thick gabbronoritic cumulates lying below the ultramafic layer at the base of MCU IV are considerably higher than in the cumulates above and beneath them. The highest Zr concentration, 170 ppm, is found in a narrow layer of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*). The PGEs in drill hole Ki-153 are mainly concentrated in the 10 m of poikilitic, chromite-bearing plagioclase-bronzite orthocumulate (pb(c)OCa\*) to be found at the top of MCU III, in connection with which one also finds pyroxenite, and also a narrow pegmatite band and chromite disseminations and layers in the lower part. The base metal sulphide disseminations in the drill hole are encountered in the olivine cumulate that makes up the lower part of the ultramafic layer at the base of MCU IV, where the maximum sulphur content is 0.39 wt.%. At this point Cu concentrations do not entirely follow those of S; the highest Cu value of 0.08 wt.% is found in the lower part of the base metal sulphide disseminations, below the maximum S concentration. The sulphide paragenesis here is pyrrhotite-pentlandite-chalcopyrite, which is markedly poorer in chalcopyrite than in the previous

drill hole. The PGE concentrations in the cumulates with base metal sulphide disseminations are considerably lower than those in the cumulates with chromite disseminations lying below them. Higher P and Zr concentrations occur only in the lower part of the poikilitic plagioclase-bronzite orthocumulate and in the pegmatite.

The base metal sulphide type has been found in all the blocks and is by far the most common type. The PGEs are concentrated mainly in the bronzite and/or olivine cumulates in the lower part of the ultramafic layer at the base of MCU IV, but the peaks for sulphur and PGEs do not usually coincide entirely, the sulphur peak being normally slightly above the PGE peak. On the other hand, the maximum PGE concentrations mostly correlate fairly well with those of copper. The drill holes chosen to represent the base metal sulphide type were Ki-115 in the Keski-Penikka block and Ki-165 in the Kilkka block (Fig 2). These type profiles are presented in Fig. 6. The maximum PGE concentration in drill hole Ki-115 is encountered in a websteritic (bCa) layer about 30 cm thick in the lower part of the ultramafic layer at the base of MCU IV and continuing to a weaker extent for about a metre into the olivine cumulate above the websteritic layer. As in the chromite type, this drill hole shows a narrow layer of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*) about 50 cm thick below the ultramafic layer at the base of MCU IV, as is common in connection with the base metal sulphide type, although it may be absent in some of the present drill holes. The base metal sulphide dissemination (pyrite-pentlandite-chalcopyrite paragenesis) begins at the point of highest PGE content but reaches its maximum, 0.26 wt.% S, about a metre further up, where the PGE concentration constitutes no more than an anomaly. Again copper does not entirely follow the pattern of sulphur but is highest in the lower part of the base metal sulphide dissemination, and low in the area of peak S values in the upper part. The maximum Cu content is now recorded immediately above the layer that is richest in PGE. P and Zr are markedly elevated in the zone

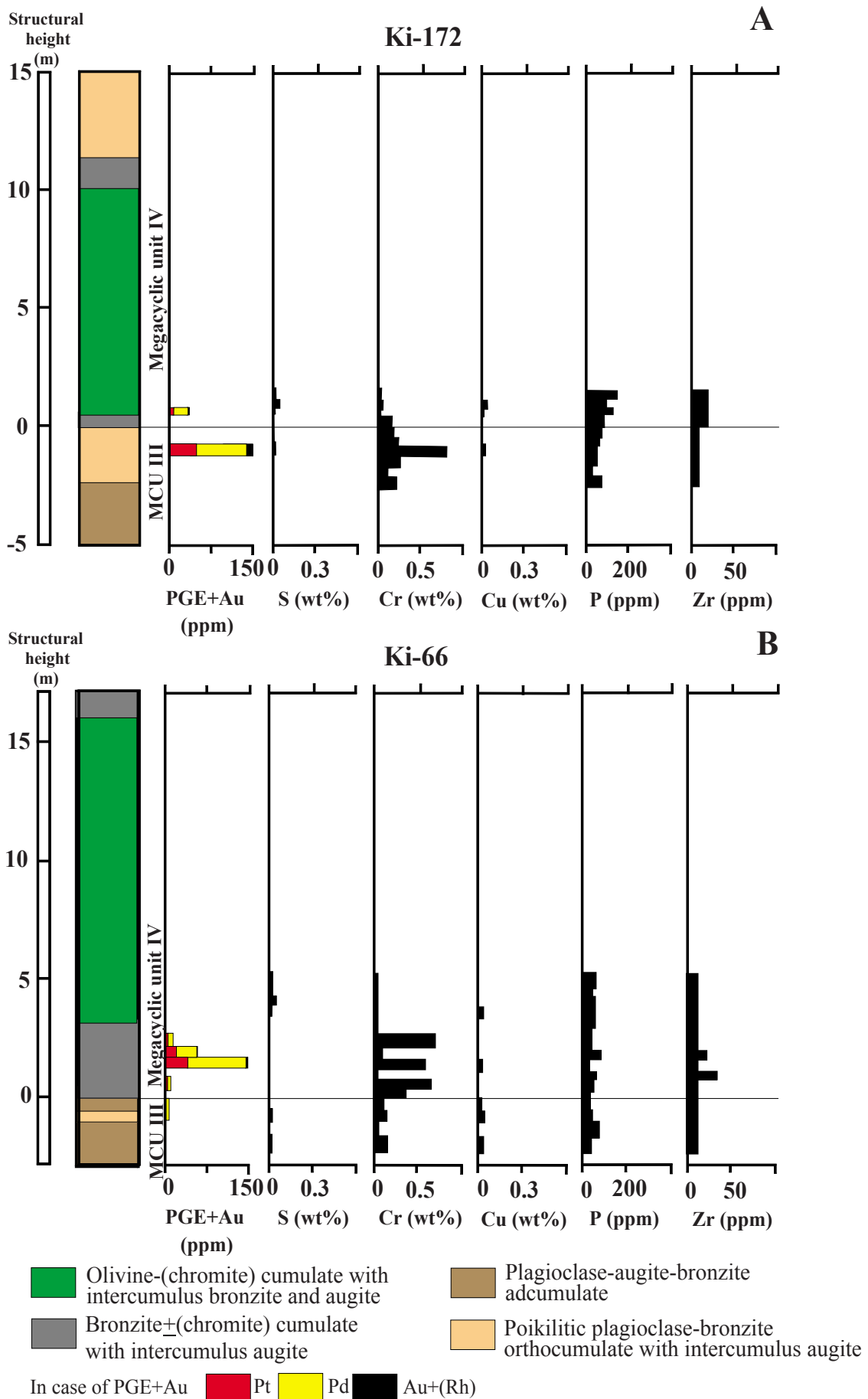


Fig. 4. Stratigraphic sequences for the chromite type in the SJ Reef, showing variations in Pt+Pd+Rh+Au, S, Cr, Cu, P and Zr (slightly modified from Halkoaho, 1993 and Alapieti & Lahtinen, 2002).

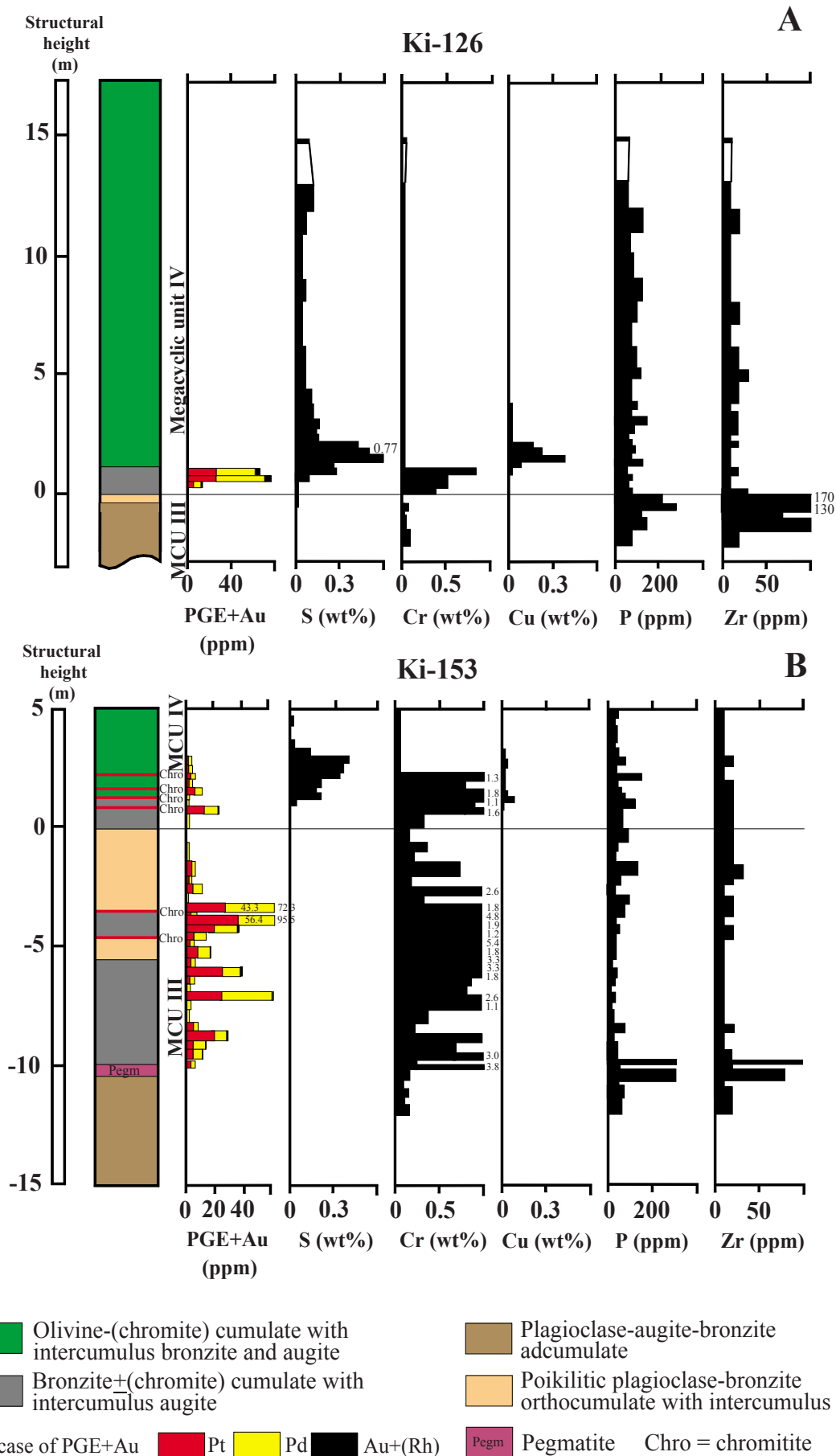


Fig. 5. Stratigraphic sequences for the composite chromite and base metal sulphide type in the SJ Reef, showing variations in Pt+Pd+Rh+Au, S, Cr, Cu, P and Zr (slightly modified from Halkoaho et al., 1989a, 1990a, Halkoaho, 1993 and Alapieti & Lahtinen, 2002).

olivine cumulates in the lower part of ultramafic layer at the base of MCU IV and in the narrow poikilitic plagioclase-bronzite orthocumulate (pbOCa\*) about 50 cm thick located below it. The highest PGE concentration is found in a websteritic layer approx. 50 cm thick in the lower part of the ultramafic layer at the base of MCU IV. The base metal sulphide dissemination (pyrite-pentlandite-chalcopyrite paragenesis) begins slightly below the point of maximum PGE content, but reaches its maximum of 0.24 wt.% S about half a metre above the maximum PGE concentration. Copper does not entirely follow the pattern found in sulphur, and is highest at the PGE maximum in the lower part of the base metal sulphide dissemination. P and Zr concentrations are no higher than in the cumulates lying above and below this layer.

The last type, with PGE alone, is the most significant type of mineralization as far as the genetic model for the SJ Reef is concerned, because it contains considerable concentrations of PGEs, but it does not have any of the base metal sulphides or chromites regarded generally as PGE collectors (see Hiemstra 1979, Naldrett & Duke 1980, Campbell et al. 1983, Irvine et al. 1983, Naldrett et al. 1986, Campbell & Turner 1986, Irvine 1977, Irvine & Sharpe 1982). This type has been found in all the blocks except for Yli-Penikka and Kilikka, but the best drill holes are those in the Keski-Penikka block (Fig. 2).

The PGEs are concentrated mainly in the bronzite and/or olivine cumulates of the lower part of the ultramafic layer at the base of MCU IV, as in the case of the base metal sulphide type. However, they can occur as much as five metres above the basal contact of MCU IV. The drill holes selected to represent the PGE only type are Ki-94 and Ki-86 in the Keski-Penikka block (Fig. 2). These type profiles are presented in Fig. 7. The highest PGE concentration in Ki-94 occurs in a coarse, almost pegmatitic lherzolite about 5 m above the lower contact of MCU IV. The websterite of the lower part of the ultramafic layer in MCU IV is also practically pegmatitic in places, and

the upper part of MCU III contains at least three metres of poikilitic plagioclase-bronzite orthocumulate (pbOCa\*). Low S, Cr and Cu concentrations are characteristic of this type. A sequence of Ki-94 about 6 m in length has been analysed (Fig. 7A) in which it is seen clearly that phosphorus exceeds the 200 ppm mark and zirconium the 50 ppm mark in the PGE enrichment zone, with the peak P concentration of 720 ppm, occurring immediately above this zone. In drill hole Ki-86 (Fig. 7B), a sequence of about 4 m has been analysed. The PGE enrichment zone is located in the poikilitic plagioclase-bronzite orthocumulate (pbOCa\*) of the upper part of MCU III, continuing upwards for about 2 m as far as the olivine cumulate (lherzolite) in the lower part of the ultramafic layer at the base of MCU IV. Concentrations of S, Cr and Cu are again low, and only that of P exceeds 200 ppm in the upper part of the mineralization.

In the following the average whole-rock concentrations of nickel, copper, sulphur, PGEs and gold in the chromite and base metal sulphide types of the SJ Reef and the metal ratios for the same concentrations will be considered. The discussion will be based on the two types of mineralization mentioned above, as analytical data are available. The average whole-rock concentrations of nickel, copper, sulphur, PGEs and gold are presented in Table 1.

Nickel, copper and sulphur are quite low in all the reef types in the SJ Reef, the maximum values determined in drill hole Ki-165 (Fig. 6B) being 0.2, 0.1 and 0.4 wt.%, respectively (the Ni content also includes nickel bound to silicates). The recalculated sulphide fraction for the base metal sulphide type is relatively sulphur-rich, the mean for the drill hole Ki-165, for instance, being 43.2 wt.%, and this is reflected in a relatively high amount of pyrite. The calculated metal concentrations for the same sulphide fraction are iron 37.0 wt.%, copper 9.2 wt.% and nickel 10.6 wt.%, which indicates Ni dominance over Cu, the average Cu/Ni ratio in the base metal sulphide type is 0.3.

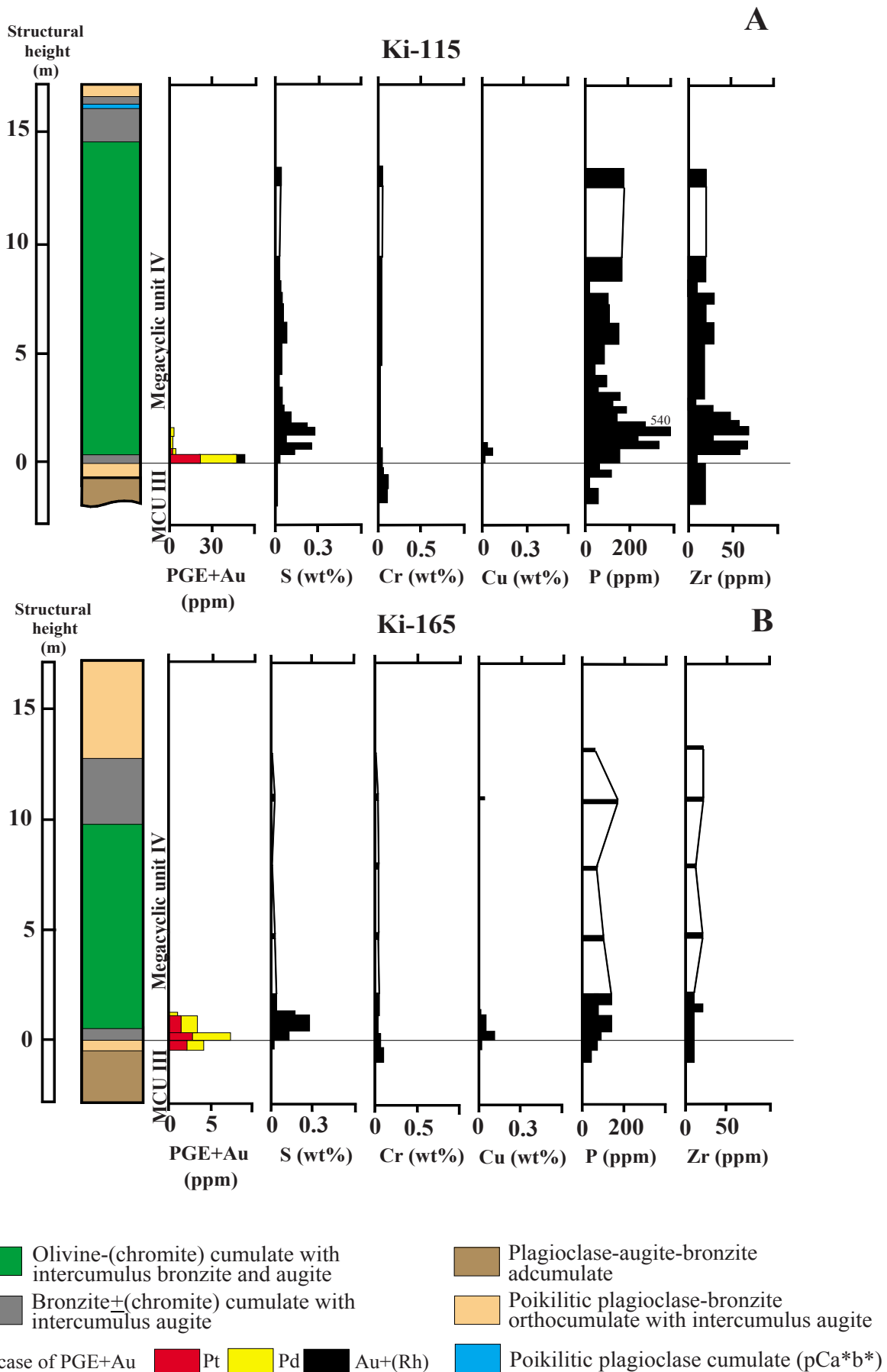
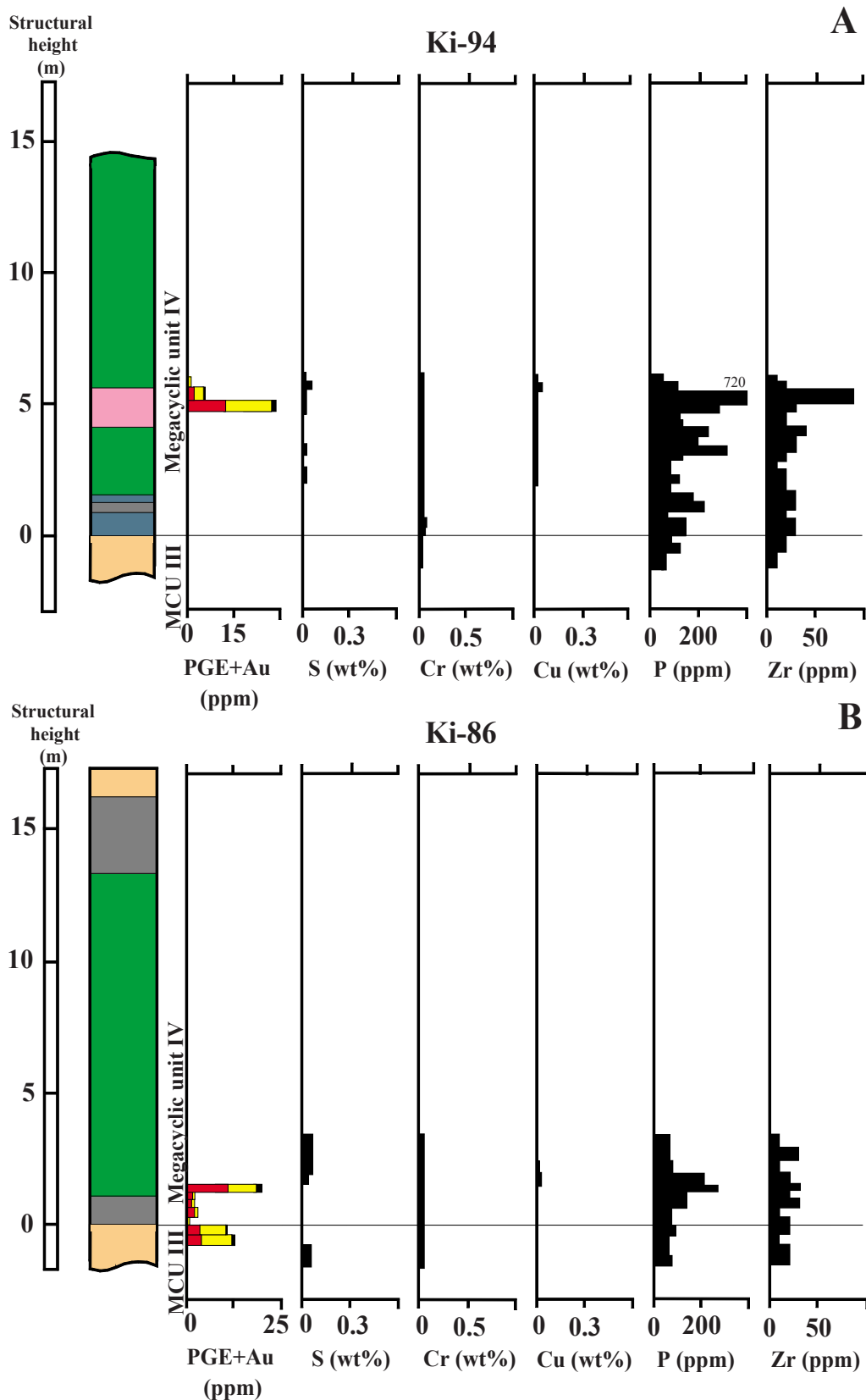


Fig. 6. Stratigraphic sequences for the base metal sulphide type in the SJ Reef, showing variations in Pt+Pd+Rh+Au, S, Cr, Cu, P and Zr (slightly modified from Halkoaho et al., 1989a,1990a, Halkoaho, 1993 and Alapieti & Lahtinen, 2002).





- Olivine-(chromite) cumulate with intercumulus bronzite and augite
- Bronzite+(chromite) cumulate with intercumulus augite
- Poikilitic plagioclase-bronzite orthocumulate with intercumulus augite
- Pegmatitic lherzolite
- In case of PGE+Au  Pt  Pd  Au+(Rh)  Pegmatitic websterite

Fig. 7. Stratigraphic sequences for the PGE only type in the SJ Reef, showing variations in Pt+Pd+Rh+Au, S, Cr, Cu, P and Zr (slightly modified from Halkoaho, 1993 and Alapieti & Lahtinen, 2002).

Table 1. Nickel, copper, sulphur, platinum-group element and gold concentrations in selected type samples representing the SJ Reef (Halkoaho et al. 1989a, 1990a, Halkoaho 1993), the AP Reefs (Halkoaho et al. 1989b, 1990b, Halkoaho 1993) and the PV Reef (Huhtelin et al. 1989, 1990). Standard deviations are given in parentheses. In the case of AP and PV Reefs A) is whole-rock content and B) recalculated to 100% sulphide. Metal concentrations in the Merensky Reef (Naldrett & Cabri 1976, Barnes et al. 1985), J-M Reef (Naldrett 1981, Barnes et al. 1985), the UG2 chromitite (Naldrett & Cabri 1976, McLaren & De Villiers 1982), the C1 chondrite (Barnes et al. 1985) and the mantle (Sun 1982, Barnes et al. 1988) are also shown.

Reef	Nbr of samples		Ni (wt.%)	Cu (wt.%)	S (wt.%)	Os (ppb)	Ir (ppb)	Ru (ppb)	Rh (ppb)	Pt (ppb)	Pd (ppb)	Au (ppb)
SJ Reef:												
Sulphide type	3		0.16 (0.06)	0.06 (0.05)	0.13 (0.11)	61 (26)	99 (40)	123 (59)	373 (153)	2667 (1193)	2700 (964)	83 (40)
Chromite type	6		0.08 (0.03)	0.04 (0.05)	0.03 (0.04)	354 (278)	1193 (890)	478 (416)	5528 (3492)	51967 (35688)	156567 (104734)	1143 (692)
AP I Reef:												
Normal Reef:												
GaNo/pabC	4	A	0.10 (0.01)	0.14 (0.06)	0.44 (0.12)	20 (6)	42 (25)	19 (7)	210 (160)	1965 (1150)	7125 (3440)	350 (260)
		B	6.9	11.1	36.7	1700	3500	1600	17300	162300	588400	28900
mAnor/pCa*b*	4	A	0.04 (0.03)	0.09 (0.03)	0.14 (0.06)	16 (2)	43 (20)	35 (20)	237 (140)	2615 (1500)	6150 (5000)	140 (20)
		B	8.3	22.7	34.8	4000	10900	8800	59800	660400	1553000	35400
Depression structure:												
GaNo/pbaC	4	A	0.18 (0.04)	0.47 (0.17)	0.97 (0.37)	8 (10)	15 (10)	15 (1)	73 (60)	975 (690)	2960 (2500)	216 (210)
		B	6.2	17.6	35.9	300	560	560	2700	36100	109600	8000
mAnor/pCa*b*	7	A	0.08 (0.05)	0.23 (0.14)	0.52 (0.31)	9 (7)	18 (14)	17 (8)	94 (70)	1083 (830)	3417 (2930)	144 (100)
		B	5.1	15.8	36.4	630	1300	1200	6500	75300	237400	10000
AP II Reef:												
GaNo/pabC	3	A	0.08 (0.02)	0.20 (0.15)	0.35 (0.26)	26 (20)	63 (50)	38 (30)	220 (80)	3400 (720)	11367 (2250)	607 (80)
		B	6.7	22.4	39.5	2900	7100	4300	24700	381200	1274300	68000
PV Reef:												
Upperm. plagioclase orthocumulate, transition zone	7	A	0.244 (0.123)	0.247 (0.155)	0.791 (0.499)	54 (50)	77 (74)	108 (87)	92 (78)	3913 (3783)	2317 (2080)	270 (167)
		B	11.16	11.30	36.18	2470	3520	4940	4210	178980	105980	12350
Bronzite orthocumulate	2	A	0.13 (0.039)	0.098 (0.089)	0.288 (0.278)	19 (10)	30 (12)	64 (20)	43 (16)	1620 (540)	775 (125)	244 (57)
		B	15.92	12.01	35.29	2330	3680	7840	5270	198500	94960	29900
Mixed rock, transition zone	1	A	0.05	0.085	3.06	5	11	12	8	920	120	85
		B	0.64	1.09	39.16	64	141	154	102	11770	1540	1090
Pegmatoid, transition zone	1	A	0.2	0.291	14611	1	3	4	2	290	140	4
		B	5.37	7.81	37.58	27	81	107	54	7780	3760	107
Merensky Reef	-		-	-	-	63	74	430	240	3740	1530	310
J-M Reef	-		-	-	-	22	19	50	150	5000	17300	640
UG2	12		0.13	0.02	-	53	60	1060	600	3200	1960	50
C1 chondrite						514	540	690	200	1020	545	152
Mantle			0.2	0.0028	0.02	4.2	4.4	6	2	9.2	4.4	1.4

The average Pd/Pt and Pd/Ir ratios in the chromite type are about 3 and 140, and those in the base metal sulphide type 1 and 28, respectively. The mantle-normalized metal pattern is presented in Fig. 10A, where the distribution patterns are compared with data on the UG2 chromitite. The chromite and base metal sulphide types in the SJ Reef differ markedly in this respect, the pattern for the chromite type being fairly steep and characterized by a peculiar, distinctly negative ruthenium anomaly (or positive iridium anomaly), whereas the base metal sulphide type has a more even PGE distribution with a smaller negative ruthenium anomaly.

The base metal sulphide type patterns resemble more closely the UG2 chromitite, although with lower ruthenium (Fig. 10A). If any conclusions regarding the PGE fractionation history can be reached from the above patterns in spite of the metamorphism, it would seem that the base metal sulphide type features less fractionation and the chromite type more.

The chromite will preferentially remove Os, Ir and Ru from the magma to produce a fractionated liquid and a cumulate enriched in these elements (cf. Oshin & Crocket 1982, Barnes et al. 1985, 1988). Thus the PGE in the chromite and base metal sulphide types may be considered as originating from slightly different sources, the chromite one from a magma containing chromite, which has already separated out, and the base metal sulphide type from a magma in which separation has not favoured any particular PGE. As compared with other PGE enrichment zones in the Penikat Intrusion such as the chromite type of the SJ Reef, the chromitite layers of MCUs II and III also show similar distinct negative Ru anomalies (cf. Huhtelin et al. 1989b). The AP Reefs (see Fig. 10B) exhibit a negative Ru anomaly intermediate between the chromite and base metal sulphide types of the SJ Reef (cf. Halkoaho 1989, Halkoaho et al. 1989b, 1990b), whereas the PV Reef (see Fig. 10C) shows little or no negative ruthenium anomaly (cf. Huhtelin et al. 1989a, 1990) and thus resembles the base metal sulphide type of the SJ Reef.

## Platinum-group minerals of the Sompujärvi PGE Reef

A total of 169 precious metal minerals from the Sompujärvi PGE Reef were analysed by electron microprobe (Halkoaho et al. 1989a, 1990a, Halkoaho 1993), resulting in about 40 different mineral species. The PGM grains investigated vary in size from 1 to 300  $\mu\text{m}$  in diameter, the mean being 9.5  $\mu\text{m}$ .

Except the Kirakkajuppura area, the PGMs in the chromite type can be classified into 9 groups, in descending order of abundance, as follows: (1) Pd-As-Sb minerals, e.g. isomertieite ( $\text{Pd}_{11}\text{As}_2\text{Sb}_2$ ) and stibiopalladinite ( $\text{Pd}_5(\text{Sb}_{1.6}\text{As}_{0.4})_2$ ), (2) sperrylite ( $\text{PtAs}_2$ ), (3) PGE-Fe-Cu-Mn hydroxides?, (4) PGE sulphides other than laurite, (5) alloys, e.g. hongshiite ( $\text{PtCu}$ ) and isoferroplatinum ( $\text{Pt}_3\text{Fe}$ ), (6) RhAsS-IrAsS minerals, e.g. hollingworthite ( $\text{RhAsS}$ ), (7) Sn and/or Pb-bearing PGE minerals, e.g. palarstanide ( $\text{Pd}_8(\text{Sn}_{1.0}\text{As}_{0.9}\text{Te}_{0.7}\text{Pb}_{0.4})_3$ ), (8) laurite ( $(\text{Ru,Os,Ir})\text{S}_2$ ) and (9) Pd-Te-(Bi) minerals, e.g. keithconnite ( $\text{Pd}_3(\text{Te}_{0.7}\text{Bi}_{0.3})$ ). In the Kirakkajuppura area 7 groups of PGM can be observed, which are in descending order of abundance: (1) PGE sulphides except laurite, e.g. braggite ( $(\text{Pd,Pt,Ni})\text{S}$ ), cuprorhodsite ( $(\text{Cu Pt}_{0.98}\text{Rh}_{0.94}\text{Ir}_{0.08})_3\text{S}_4$ ) and an unnamed mineral ( $\text{Pd}_{2.1}\text{Pt}_{0.75}\text{Cu}_{0.15}\text{S}_{0.9}\text{As}_{0.08}\text{Se}_{0.02}$ ), (2) Pd-Pb-Sn minerals, e.g. zvyagintsevite ( $\text{Pd}_3\text{Pb}$ ) and an unnamed mineral ( $\text{Pd}_{2.85}\text{Au}_{0.11}\text{Pt}_{0.04}\text{Pb}_{0.8}\text{Sn}_{0.2}$ ), (3) Pd-As-Te-Sn-Pb minerals, e.g. an unnamed mineral ( $\text{Pd}_5(\text{As}_{1.12}\text{Te}_{0.55}\text{Sn}_{0.23}\text{Pb}_{0.08}\text{Bi}_{0.02})_2$ ), (4) PGE-Fe-Cu-Mn hydroxides, (5) alloys, (6) laurite ( $(\text{Ru,Os,Ir})\text{S}_2$ ) and (7) sperrylite ( $\text{PtAs}_2$ ).

The PGMs in the base metal sulphide type can be classified into 7 groups, which, arranged in descending order of abundance, are: (1) sperrylite ( $\text{PtAs}_2$ ), (2) Pd-As-Sb minerals, e.g. isomertieite ( $\text{Pd}_{11}\text{As}_2\text{Sb}_2$ ) and stibiopalladinite ( $\text{Pd}_5(\text{Sb}_{1.6}\text{As}_{0.4})_2$ ), (3) Pd-Te-(Bi) minerals, e.g. kotulskite ( $\text{Pd}(\text{Te,Bi})$ ) and merenskyite ( $\text{Pd}(\text{Te,Bi})_2$ ), (4) RhAsS-IrAsS minerals, e.g. hollingworthite ( $\text{RhAsS}$ ) and irarsite ( $\text{IrAsS}$ ), (5) laurite ( $(\text{Ru,Os,Ir})\text{S}_2$ ), (6) alloys, e.g. isoferroplatinum ( $\text{Pt}_3\text{Fe}$ ) and (7) Au-Ag minerals.

Most of the above PGMs found in the chromite type occur in association with silicates, and a small amount on the edge of chromite or magnetite. Only laurite has been encountered as an inclusion in the chromite. In addition, braggite ((Pd,Pt,Ni)S), cuprorhodsite ((Cu,Rh,Pt)<sub>3</sub>S<sub>4</sub>) and zvyagintsevitte (Pd<sub>3</sub>Pb) have been encountered in a silicate inclusion in a chromite grain. The chromite type PGE mineralization is predominantly characterised by As, AsS and Te minerals, e.g. isomertieite (Pd<sub>11</sub>As<sub>2</sub>Sb<sub>2</sub>), sperrylite (PtAs<sub>2</sub>), hollingworthite (RhAsS) and kotulskite (Pd(Te,Bi)) together with PGE sulphides such as braggite ((Pd,Pt,Ni)S) and an unnamed mineral with the formula (Pt,Cu,Pd)<sub>5</sub>S<sub>3</sub>?, alloys such as isoferroplatinum (Pt<sub>3</sub>Fe) and hongshiite (PtCu) and Sn and Pb-bearing minerals such as palarstanide ((Pd,Pt)<sub>8</sub>(Sn,As,Pb)<sub>3</sub>) and zvyagintsevitte (Pd<sub>3</sub>Pb). Cu is a characteristic component of many of the PGMs in the chromite type mineralization (e.g. (Pt,Cu,Pd)<sub>5</sub>S<sub>3</sub>). The PGE mineralogy of the chromite type mineralization in the Kirakkajuppura area at the northern end of the Penikat Intrusion deviates from that of the normal chromite type, whereas the PGE sulphides are dominating, e.g. braggite and cuprorhodsite, particularly the Pb and Sn-bearing PGE minerals, e.g. zvyagintsevitte, (Pd<sub>2.9</sub>Au<sub>0.1</sub>)<sub>3</sub>(Pb<sub>0.8</sub>Sn<sub>0.2</sub>)? and Pd<sub>5</sub>(As<sub>1.1</sub>Te<sub>0.6</sub>Sn<sub>0.15</sub>Pb<sub>0.1</sub>Bi<sub>0.05</sub>)<sub>2</sub>?. Barkov et al. (1999, 2000, 2002, 2004a,b, 2005) have studied very detail the PGE mineralogy of the SJ Reef in the Kirakkajuppura area. They have found a lot of new mineral phases for example unnamed Pd-Pb oxide (Pd<sub>9</sub>PbO<sub>10</sub>), thiospinels of Cu-(Fe) and PGE, laflammeite (Pd<sub>3</sub>Pb<sub>2</sub>S<sub>2</sub>, a new PGM species) and a konderite-like sulphide of Fe, Pb, Cu, Rh, Pd and Ir.

The base metal sulphide type mineralization has PGMs associated with both silicates and base metal sulphides. The PGMs of the base metal sulphide type are chiefly As, Te and AsS minerals, e.g. isomertieite (Pd<sub>11</sub>As<sub>2</sub>Sb<sub>2</sub>), sperrylite (PtAs<sub>2</sub>), kotulskite (Pd(Te,Bi)) and hollingworthite (RhAsS).

The most significant difference between the chromite and the base metal sulphide types

of mineralization is that the former contains PGE sulphides and alloys, which are absent from the latter with the exception of laurite and isoferroplatinum. Almost all the unnamed PGMs found in the SJ Reef were similarly encountered in the chromite type mineralization. Kaukonen et al. (2004) have been observed that in case of the silicate or PGE only type the most common PGM phases are various Pd-Sb-As minerals such as isomertieite and mertieite-II, bismuthian kotulskite and hollingworthite. Even in the silicate type is high Pt values, they have not found any sperrylite grains.

#### Formation of the Sompujärvi PGE Reef

The formation of the Sompujärvi PGE Reef was a complex event, the elucidation of which is considerably hampered by the absence of any primary silicate minerals due to alteration, and in many cases also the lack of cumulus textures caused by the Svecofennian deformation, which was especially concentrated in the lower contact of the ultramafic layer at the base of MCU IV.

Halkoaho et al. 1989a, 1990a and Halkoaho 1993 suggest that when the magma from which MCU IV crystallized entered the Penikat chamber, it mixed with older residual liquid, resulting in the formation of the bronzite cumulates. In the course of crystallization the proportion of residual magma declined rapidly, resulting in the precipitation of olivine cumulates above the bronzite cumulates. The entry of the new magma pulse was probably quite powerful, and when this magma spread out over the uppermost, partly consolidated gabbro-noritic cumulate of MCU III, it caused pronounced local erosion in the uppermost crystal pile and excavated elongated channels and/or depressions, as associated with faulting, for instance. It has been suggested that these channels and depressions then trapped older PGE-enriched residual liquid, resulting in the crystallization of the poikilitic plagioclase-bronzite orthocumulate locally below the ultramafic rocks (see Figs 4A, 5B and 12). Since the trapped liquid became partly mixed with the overlying, less fractionated magma,

this process may have temporarily shifted the composition of the magma into the liquidus field of chromite, resulting in chromite saturation. These chromite grains settled at the base of MCU IV, yielding disseminations of varying grade, and in many places these grains also sank into the partly consolidated poikilitic plagioclase-bronzite cumulate which had crystallized from the trapped liquid mentioned above. These chromite grains were no longer in equilibrium with their gabbro-noritic surroundings, however, and they consequently became sintered and/or corroded. In addition there are some chromites which crystallized under the influence of a fluid phase.

It has been suggested that when the fourth magma pulse intruded into the Penikat magma chamber its lower part intermixed with the older residual magma (Halkoaho et al. 1989a and 1990a). This mixing of magmas was perhaps partly responsible for the precipitation and PGE enriched sulphides (cf. Campbell et al. 1983, Irvine et al. 1983, Naldrett et al. 1986, Campbell & Turner 1986) in the lower part of the ultramafic cumulates, accounting for the base metal sulphide mineralization type. This may not necessarily have been the main process by which this type of mineralization was formed, however, as the S and PGE concentrations do not always correlate exactly, so that as in the case of the PGE only type and the chromite type of PGE mineralization, which are discussed below, a fluid phase may have been the mineralization-forming factor for the base metal sulphide type.

Some mechanism other than magma mixing is clearly needed to explain the PGE only and chromite types of PGE mineralization, however. Since pegmatitic rocks and apatites are fairly common in association with these mineralization types, and high P and Zr concentrations also occur in places in the case of the PGE only type, volatile activity may explain their origin (cf. Elliott et al. 1982, Kinloch 1982, Schiffries 1982, Volborth & Housley 1984, Buntin et al. 1985, Ballhaus & Stumpff 1985 and 1986, Boudreau et al. 1986, Ballhaus et al. 1988, Boudreau 1988, Mathez et al.

1989). The chromite type of PGE mineralization appears to be spatially related to elongated channels and/or depressions or perhaps as a mega-/super-ripple marks probably caused by an influx of very volatile (and PGE) rich material to the Penikat chamber. In the same event local contaminations between the material of this influx and felsic roof and wall rocks caused abundant chromite precipitations. As mentioned above, the SJ Reef features chromites that crystallized under fluid phase influence, as "eroded" chromite grains have been found at the reaction interface between the gabbropegmatite and the plagioclase-augite-bronzite adcumulate of the upper part of MCU III in the Kirakkajuppura area. The chromite grains found in the poikilitic plagioclase-bronzite orthocumulate (pb(c)Ca\*) of the upper part of MCU III and in the pyroxenitic cumulates of the lower part of the ultramafic layer at the base of MCU IV may have been sintered or eroded under the influence of a fluid phase. The frequently chromite-disseminated poikilitic plagioclase-bronzite orthocumulate found in the upper part of MCU III may also have arisen as a consequence of recrystallization caused by a fluid phase.

One problem concerns the composition of the fluids, which is often regarded as being indicated by the occurrence of chlorine-bearing apatite and hydrous silicates. The Cl content of the SJ apatite seems to be quite modest, however, when compared with the values reported for the Merensky Reef and J-M Reef; also the Cl content of the whole-rock samples is quite low (10 ppm). The low Fe<sup>3+</sup> content of the chromite may suggest low oxygen fugacity. What was the role of any C-bearing fluids present? It is difficult to say at this stage whether any graphite exists in the SJ Reef, in view of the degree of metamorphism, but the ultramafic cumulates contain very large amounts of carbonates, so that carbon was evidently present.

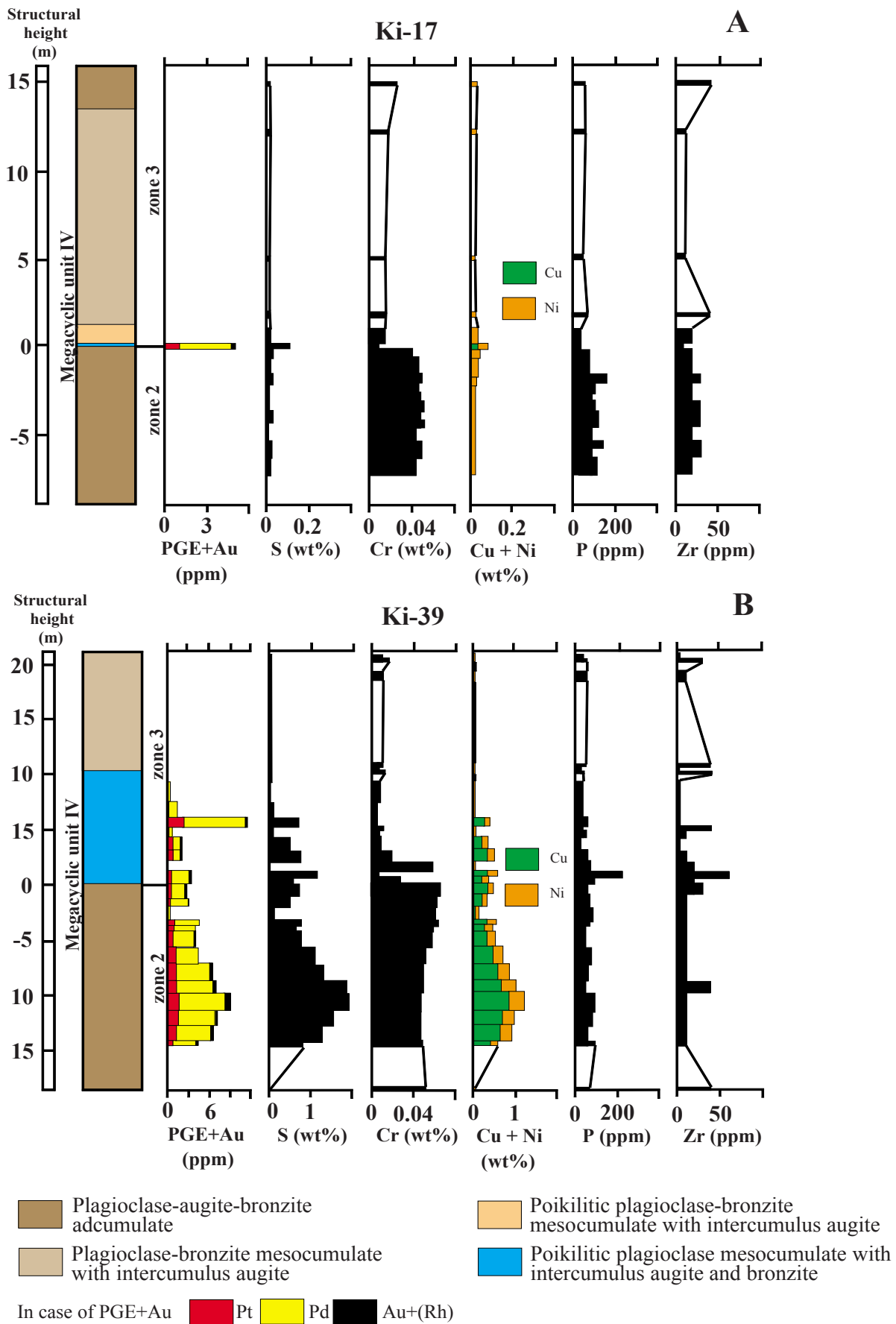


Fig. 8. Stratigraphic sequence of the normal API Reef (A) and the API Reef in the depression/pothole structure (B) showing variations in Pt+Pd+Au, S, Cr, Cu+Ni, P and Zr (slightly modified from Halkoaho et al., 1989b, 1990b, Halkoaho, 1993 and Alapieti & Lahtinen, 2002).



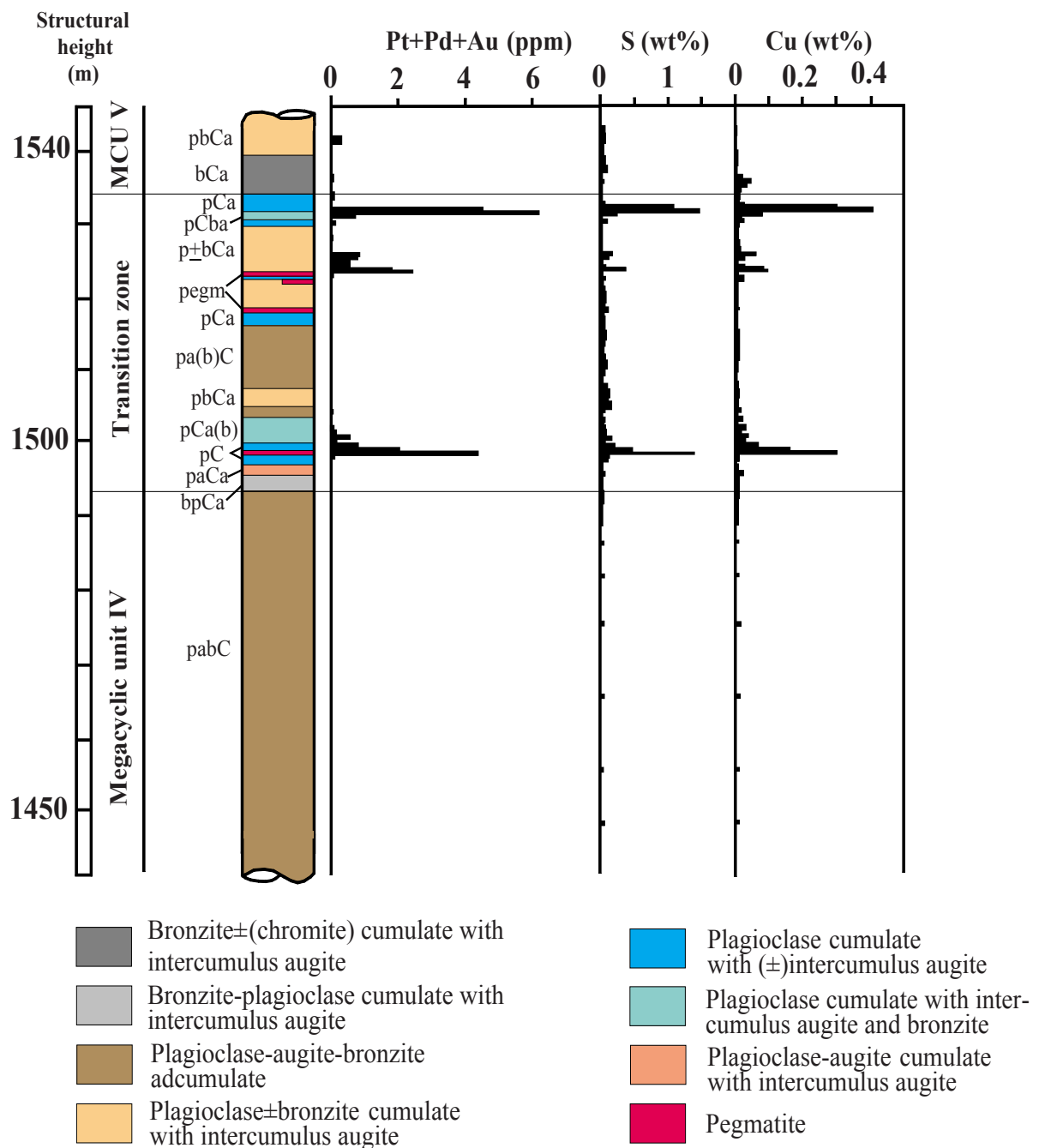


Fig. 9. Stratigraphic sequence of the Paasivaara Reef showing variations in Pt+Pd+Au, S, and Cu (slightly modified from Huhtelin et al. 1990 and Alapieti & Lahtinen, 2002).

### Ala-Penikka PGE Reefs

The PGE mineralizations referred to as the Ala-Penikka PGE Reefs (AP I and AP II) are located 250-450 and 350-450 m above the base of MCU IV (Fig. 3). Like the SJ Reef, these are known in broad outline for almost the entire 23 km of the intrusion (Fig. 2) (Alapieti 1984, Alapieti & Lahtinen 1986, 2002, Halkoaho 1989, Halkoaho et al. 1989b, 1990b, Halkoaho 1993).

The AP I and AP II Reefs are located at the border between the second and third zones and in the upper part of the third zone, respectively (Halkoaho 1989, Halkoaho et al. 1989b, 1990b, Halkoaho 1993). The AP I Reef is usually 20 to 40 cm thick, and the PGE mineralization is erratic in its distribution, being located in the uppermost part of the plagioclase-augite-bronzite adcumulate (pabAC) at the top of the second zone and continuing up-

wards into the poikilitic plagioclase mesocumulate (pM<sub>Ca</sub>\*b\*) at the base of the third zone (Figs 3 and 8A). The AP I Reef, with highly variable PGE values, has base metal sulphide disseminations closely associated with it. Base metal sulphides and PGMs usually occur in the interstices of the cumulus framework, together with magnetite and secondary minerals such as epidote and chlorite, but at the site of the depression/pothole structure they are concentrated over a wider zone, so that the mineralized rocks attain a vertical thickness of almost 20 m (Figs 8B, 18 and 20) (Halkoaho 1989, Halkoaho et al. 1989b, 1990b, Halkoaho & Alapieti 1993).

The PGE mineralization in the AP II Reef greatly resembles that in AP I. The base metal sulphides and PGMs are located in the uppermost part of the plagioclase-augite-bronzite adcumulate at the top of the third zone and continue upwards into the narrow poikilitic plagioclase adcumulate at the base of the fourth zone. This mineralization is generally poor in base metal sulphides, with the exception of certain concentrations where the base metal sulphide content rises to 1-2 vol.% and the PGE content to some tens of ppm (Table 1) (Halkoaho 1989, Halkoaho et al. 1989b, 1990b, Halkoaho 1993).

In the Ala-Penikka block of the Penikat Intrusion (Fig. 2) the Ala-Penikka PGE Reefs (AP I and AP II Reefs) are located 250 and 340 m above the base of MCU IV, respectively. Drill hole Ki-17 has been chosen to represent the normal AP I Reef and Ki-39 to represent the AP I Reef in the depression/pothole structure. The vertical variations in Pt, Pd, Au, S, Cr, Cu, Ni, P and Zr are depicted in Fig. 8. Data on both drill holes have been published earlier by Alapieti and Lahtinen (1986, 2002), Halkoaho (1989, 1993) and Halkoaho et al. (1989b, 1990b). The average whole-rock concentrations of nickel, copper, sulphur, PGEs and gold are presented in Table 1, together with concentrations recalculated to 100 % sulphide.

The normal AP I Reef and that of the depression/pothole structure are similar, but the

thicknesses of the layers are greater in the latter, and the poikilitic plagioclase-bronzite mesocumulate (pbM<sub>Ca</sub>\*) encountered above the poikilitic plagioclase mesocumulate of the normal AP I Reef has not yet been identified in the depression/pothole structure. The S, Cu, Ni and PGE concentrations parallel each other fairly well in both drill holes in the AP I Reef, and both feature a decline in the Cr content of the cumulates from 0.05-0.06 wt.% to 0.01-0.02 wt.% at the boundary between the second and third zones. This whole-rock Cr content rises again 10-15 m above the normal AP I Reef as augite becomes the cumulus mineral once more (Fig. 8A). Fairly high P and Zr concentrations are found in the area of the AP I Reef in the Ala-Penikka and Yli-Penikka blocks, and the cumulates of the upper part of the second zone in the normal AP I Reef drill hole (Fig. 8A) are slightly richer in P than those in the lower part of the third zone. Similarly, the highest P and Zr concentrations in the AP I Reef of the depression/pothole structure are found in the upper part (Halkoaho 1993).

The recalculated concentrations to 100 % sulphide indicate a clear dominance of Cu over Ni, the average whole-rock Cu/Ni ratio varying in the range of 1.4 to 2.7. Although the whole-rock S, Cu and Ni contents are higher in the depression/pothole structure than in the normal AP I Reef, the Ni and PGE contents in the recalculated sulphide fraction are generally lower in the depression/pothole structure (Table 1). The average Pd/Pt ratio in the AP I Reef is about 3 and in the AP II about 3.4. The average Pd/Ir ratio in the AP I Reef is about 170 and in the AP II about 240 (Halkoaho 1993).

The mantle-normalized metal pattern is presented and compared with data from the Merensky Reef and the J-M Reef in Fig. 10B. The noble metal patterns for the Merensky Reef seem to be flatter than those of the AP Reefs, and those of the J-M Reef are steeper. One conspicuous feature of all the metal patterns for the AP Reefs is the distinct negative ruthenium anomaly (or positive iridium

anomaly). This is slightly smaller than in the chromite type of the SJ Reef, but more significant than in the base metal sulphide type (see Fig. 10A).

#### Platinum-group minerals of the Ala-Penikka PGE Reefs

A total of 300 precious metal mineral samples were studied from the Ala-Penikka PGE Reefs (cf. Halkoaho 1989, Halkoaho 1993), resulting in 28 different PGM species. These minerals generally vary from 1 to 65  $\mu\text{m}$  in diameter, the mean being 7  $\mu\text{m}$ , and can be classified into eight groups, in order of descending abundance: (1) Pd-Te-(Bi) minerals, e.g. kotulskite (Pd(Te,Bi)) and merenskyite (Pd(Te,Bi)<sub>2</sub>), (2) sperrylite (PtAs<sub>2</sub>), (3) Pd-As-Sb minerals, e.g. palladoarsenide (Pd<sub>2</sub>(As,Sb)) and an unnamed Pd<sub>1.68</sub>As mineral, (4) Pd-Pt sulphides, e.g. cooperite (PtS), braggite ((Pd,Pt,Ni)S) and vysotskite (PbS), (5) RhAsS-IrAsS minerals, e.g. hollingworthite (RhAsS), (6) Pt-Pd-Te minerals, e.g. moncheite (PtTe<sub>2</sub>), (7) Pd-As-Te minerals and (8) Au-Ag minerals.

About 70 % of the PGM grains studied were found to occur in association with silicates in the AP I Reef, 23 % on the edge of base metal sulphide grains and only 7 % as inclusions in sulphides. About 87 % of the PGMs in the AP II Reef occur in silicates and 13 % in association with sulphides.

Pt-Te-(Bi) minerals account for about 40 % of all the PGMs in the AP I Reef and as much as 50 % in the AP II Reef. Two types of kotulskite are encountered in the AP II Reef, Bi-rich and Bi-poor, probably representing different stages of generation. Sperrylite (PtAs<sub>2</sub>) is the most common Pt carrier in the AP I Reef and the only one found in the AP II Reef. Pd-As-Sb minerals form the third most abundant PGM group in the AP I Reef, 15 %, and the second most abundant in the AP II Reef, 32 %. Pd-Pt sulphides have so far been identified only in the AP I Reef, where they are represented by cooperite (PtS), braggite ((Pt,Pd,Ni)S) and vysotskite (PdS), while RhAsS-IrAsS minerals are quite rare and are represented by

hollingworthite and irarsite. Pt-Pd-Te minerals include moncheite (PtTe<sub>2</sub>), merenskyite (PdTe<sub>2</sub>) and their unnamed intermediate forms. An almost complete solid solution of moncheite and merenskyite has been identified in the AP I Reef. The compositions of the Pd-As-Te minerals are located on a compositional line between Pd<sub>3</sub>Te<sub>2</sub> and Pd<sub>5</sub>As. Au-Ag minerals are quite rare in the AP Reefs.

#### Formation of the Ala-Penikka PGE Reefs

##### Normal Ala-Penikka PGE Reefs

The residual magma became intermixed with the new pulse, resulting in a hybrid magma which was probably slightly lighter than the new primitive magma and therefore moved upwards to produce zones two and three of MCU IV. One indication of this is that the residual magma was richer in Cr than the new one, and as a result the chromium content is higher in the second zone than in the other zones of MCU IV; a further indication is the decreasing Mg/(Mg+Fe+Mn) ratio in the augites. When the magma input ceased, the magma divided into convecting liquid layers (Halkoaho 1993).

The second and third zones of MCU IV (see Fig. 3) crystallized from a hybrid magma produced by the mixing of the fluid-rich residual magma from the lower pulses and the pulse which gave rise to MCU IV. The PGEs are derived chiefly from the residual magma and to some extent from the fourth magma pulse, the Cr, Pd and Cl concentrations in which were very much lower than those in the residual magma from the lower pulses. Thus the influence of the residual magma, which was rich in the above elements, is clearly visible in the form of higher than average Cr and Cl concentrations in the second and third zones of MCU IV (Halkoaho 1993).

In the case of the AP Reefs there are no indications of the entry of a new magma pulse, and only about 30 % of the PGM grains are associated with base metal sulphides, the rest occurring as inclusions in silicates. It has

been suggested that the AP Reefs should be interpreted as having been formed from an upward-migrating fluid-enriched intercumulus melt in which PGE, S, Ni, Cu and related elements occurred in the fluid phase (Halkoaho et al. 1989b, 1990b, Halkoaho 1993). A plagioclase-bronzite mesocumulate (pbMCa) about 10 to 20 m thick acted as a layer which trapped the upward-migrating intercumulus melt at its lower contact (see Fig. 8A), as is now seen in the low Ni content of the augite in the second zone and the low Pd content of the cumulates relative to the other zones in the lower part of MCU IV. The partial pressure of oxygen in the fluid phase of the intercumulus melt gradually increased, whereupon the oxidation grade of the iron, i.e. the ratio ( $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ ), also increased, so that eventually the point was reached at which titanomagnetite began to crystallize in the intercumulus space of the AP I Reef. This in turn reduced the solubility of sulphur in the intercumulus melt and the formation of a sulphide melt (cf. Shima & Naldrett 1975), leading to dispersal of the PGE-bearing complexes. The higher Cl and Pd concentrations in the cumulates of the third zone of MCU IV may well be attributable to the fact that some of the second-stage fluids bypassed the AP I Reef, causing an accumulation of sulphide components and PGEs at the level of the AP II Reef in places. The poikilitic plagioclase mesocumulate (pMCa\*b\*) of the AP I Reef may, as in the case of the SJ Reef be a poikilitic plagioclase-bronzite orthocumulate (pb( $\pm$ c)OCa\*), a product of recrystallization brought about by the fluids (Halkoaho 1993).

#### Depression/pothole structure in the Ala-Penikka I PGE Reef

The large depression/pothole structure in the Ala-Penikka block (Figs 2 and 18) is a remarkable feature as far as ore potential is concerned. Halkoaho (1989) and Halkoaho et al. (1989b, 1990b) suggest that it has developed as the result of a disturbance in the magma chamber causing the unconsolidated cumulate layers to collapse. The currents of the convection cells in the third zone then reworked the structure and smoothed it down, resulting in

the formation of a regular channel-like structure. On the other hand, Ballhaus et al. (1988) and Stumpfl and Ballhaus (1986) came to the conclusion that the potholes of the Merensky Reef are primary disturbances and were formed where high concentrations of volatiles locally suppressed the liquidus temperature of the plagioclase so that no footwall anorthosite cumulates were formed. Large amounts of discontinuous gabbro-noritic pegmatoids are also encountered in the area of the depression structure, so that one possibility is that high volatile activity may also have interfered with the normal crystallization process there (Halkoaho et al. 1990b).

Buntin et al. (1985) postulate that the potholes of the Merensky Reef represent scars of late magmatic fumarole activity. Boudreau (1991) also notes that these potholes show morphological similarities to the sedimentary features known as pockmarks and suggests an origin of the same kind for potholes in layered intrusions, i.e. an escape of overpressured gas from underlying sediments and cumulates, respectively. Halkoaho (1993) suggest that the extensive depression structure occurring in the AP I Reef may thus be an outlet hole for fluid material being squeezed out of the crystallizing magma chamber from below. The poikilitic anorthosite of the depression structure and the plagioclase-augite-bronzite adcumulate below it contain PGE-bearing gabbro-noritic pegmatites (Fig. 20), and there are gabbro-noritic pegmatites perpendicular to the layering together with anorthositic fragments about 200 m above the poikilitic anorthosite (Fig. 18). In addition the apatites of the second and third zones of MCU IV near the depression structure in the Ala-Penikka block are very much richer in Cl than the corresponding zones in the other blocks.

#### Paasivaara PGE Reef

The PV Reef is located about 700-1000 m above the AP Reefs in the inhomogeneous uppermost portion of MCU IV, often referred to as the transition zone between MCUs IV and V (Figs 3, 9 and 21). Like the other PGE reefs in the Penikat Intrusion, the PV Reef is known



in broad outline for almost the entire 23 km of its length, except in the case of the Keski-Penikka block, where it has been eroded away (Alapieti 1984, Alapieti & Lahtinen 1986, 2002, Huhtelin 1989, Huhtelin et al. 1989a, 1990).

Similar to the other PGE reefs in the intrusion, the PV Reef is erratic in its distribution, and PGE-bearing layers can be encountered as much as 30 m below the main enrichments and occasionally even in the lowest bronzitic cumulates of MCU V. The best PGE concentrations are generally encountered in the plagioclase orthocumulate of the transition zone close to the upper contact of MCU IV, but sometimes also in other rocks of this zone, such as the lowermost plagioclase orthocumulate and some of the pegmatoids (Figs 9 and 21). The PV Reef, with highly variable PGE values, has base metal sulphide disseminations closely associated with it, which together with the PGMs, usually occur in the interstices of the cumulus framework. The average thickness of the mineralized zone is about 1 metre.

Most elements have highly variable concentrations in the transition zone between MCUs IV and V. One especially noteworthy feature is the increase in Cr content in the transition zone about 40 m below the upper contact of MCU IV, where the whole-rock Cr content increases from 0.007 to about 0.04 wt.%. Whole-rock SiO<sub>2</sub>, MgO, FeO, Cr and Ni are higher and CaO, S and V lower in MCU V than in the upper part of MCU IV.

The average whole-rock concentrations of nickel, copper, sulphur, PGEs and gold are presented in Table 1, together with concentrations recalculated to 100 % sulphide. The average whole-rock Cu/Ni ratio in the PV Reef is 1.2, which indicates only a slight dominance of Cu over Ni, while the average Pd/Pt ratio is about 0.5 and the Pd/Ir ratio about 28. The PV Reef has the lowest Pd/Pt ratio of any of the reefs in the Penikat Intrusion.

The mantle-normalized metal pattern is presented and compared with data from the Merensky Reef and the J-M Reef in Fig. 10C. Its

noble metal pattern correlates well with that of the Merensky Reef (Huhtelin et al. 1989a, 1990) just as it represents also the PGE reef in the Penikat Intrusion that most clearly shows the noble metal pattern of the base metal sulphide type in the SJ Reef.

#### Platinum-group minerals of the Paasivaara PGE Reef

The precious metal minerals identified in the Paasivaara PGE Reef, which is located in the uppermost part of MCU IV, can be classified according to Huhtelin (1989) and Huhtelin et al. (1989a, 1990) into four groups, arranged in order of descending abundance: (1) sperrylite (PtAs<sub>2</sub>), (2) Pd-Te-(Bi) minerals, e.g. kotulskite (Pd(Te,Bi)) and merenskyite (PdTe<sub>2</sub>), (3) Au-Ag minerals and (4) Pd-As-Sb minerals, e.g. isomertieite (Pd<sub>11</sub>Sb<sub>2</sub>As<sub>2</sub>) and stibiopalladinite (Pd<sub>5</sub>Sb<sub>2</sub>). The PGMs vary in size from 1 to 70 µm, and about 50 % of the PGM grains studied occur in association with silicates, 26 % on the edge of base metal sulphide grains and 24 % as inclusions in sulphides (Huhtelin 1989, Huhtelin et al. 1989a, 1990). Törmänen (1994) and Törmänen & Alapieti (1996) have observed that PV Reef has a fairly simple PGE-mineralogy, mainly sperrylite, PdAsSb-minerals and Pd-tellurides.

#### Formation of the Paasivaara PGE Reef

Huhtelin et al. (1989a and 1990) suggest that the PV Reef was formed in the mixing process when the fifth magma pulse intruded into the chamber. Mixing of the new magma with the older residual magma in the chamber accounted for the sulphide precipitation. Mixing and convection were probably turbulent at first, and the sulphides were thus able to “scavenge” PGE from a large amount of silicate melt (cf. Campbell et al. 1983, Irvine et al. 1983, Naldrett et al. 1986, Campbell & Turner 1986). Cooling of the magma and diminish of the turbulent convection caused the sulphides and the associated PGM to sink within the Reef. On the other hand, pegmatitic rocks (Huhtelin et al. 1989a and 1990), apatite and biotite are fairly common in the upper part of MCU IV. Huhtelin et al. (1990) believe that volatiles

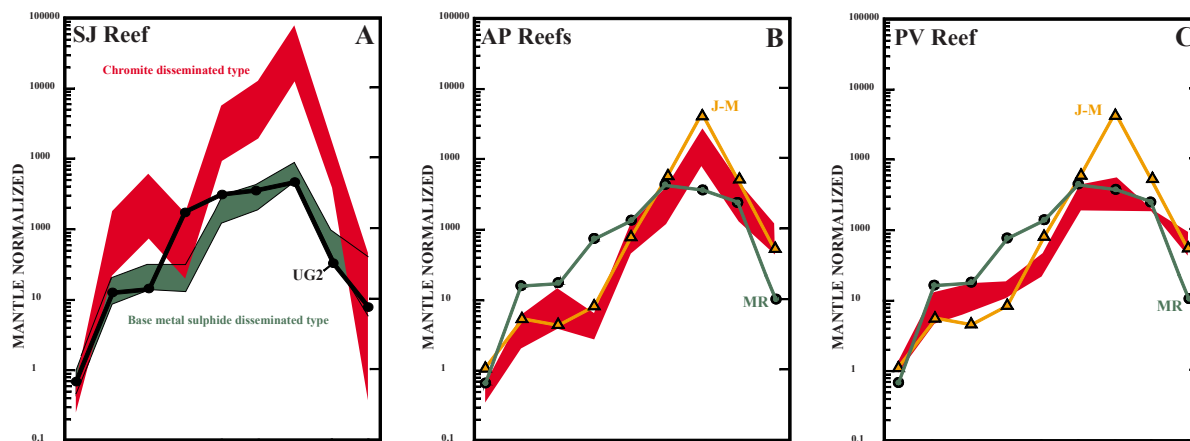


Fig. 10. (A) Average mantle-normalized platinum-group element, Au, Ni and Cu data of the SJ Reef (A, 1 Chromite type, 2 Base metal sulphide type, Halkoaho et al. 1989a, 1990a), the AP Reefs (B, AP I N. = normal AP I Reef, AP I D. = AP I Reef in depression structure, and AP II = AP II Reef, Halkoaho et al. 1989b, 1990b) and the PV Reef (C, Huhtelin et al. 1990). The SJ Reef is compared with UG2 (data from McLaren & DeVilliers 1982, Naldrett & Cabri 1976). The AP Reefs and PV Reef are compared with the Merensky Reef (MR, data from Naldrett & Cabri 1976) in the Bushveld Complex and the J-M Reef (J-M, data from Naldrett 1981) in the Stillwater Complex.

could have played some role in the formation of the PV Reef, and suggest that fluids could have migrated and redistributed the PGE, although they note that this question is still open to speculation.

Halkoaho (1993) suggest that the material contained in the transition zone in the upper part of MCU IV could be residual fluid and PGE-rich magma from the pulses of boninitic composition (I-III) which was lifted close to the ceiling of the magma chamber at the time as the magma of MCU IV penetrated the Penikat chamber. This interpretation would be supported by the fact that the transition zone is richer in Cr than is the fourth magma pulse on average, as would be likely if it was composed of residual magma from earlier Cr-rich pulses. Furthermore, as chlorine has a power-

ful tendency to become enriched in residual fluids, the residual magma can be assumed to have been Cl-rich as well. Although Cl concentrations in the area of the PV Reef are not especially high, the apatites and biotites of the approx. 200 m of poikilitic plagioclase-bronzite mesocumulate in the lower part of MCU V are Cl-rich. This may be a consequence of the mixing of a Cl-rich residual fluid with the lower part of the magma forming MCU V, causing fractionation of the complexes that transported the sulphide components and PGEs in the fluids and the formation of a PGE-rich sulphide melt. The PGEs of the PV Reef, like those of the other PGE reefs in the Penikat Intrusion must then have originated from the residual magmas of the pulses that formed the underlying layers that in chemical terms resemble boninites (MCU I-III).

## SUMMARY AND CONCLUSIONS

The Penikat Layered Intrusion was formed about 2440 million years ago of five megacyclic units, which are interpreted as representing separate discharges of magma into the magma chamber. The magmas forming the lowermost three MCUs resemble boninites in composi-

tion, while the fourth is very much poorer in MgO and Cr. The original composition of the magma that formed the fifth MCU is difficult to deduce, because it may contain a considerable amount of residual magma from the lower pulses. This complex pattern of intrusion gains



support from the cryptic variation in the minerals and the chemical variation in the cumulates.

Hamlyn and Keays (1986) assumed that the second-stage melt affinity magmas which mainly formed the Bushveld, Stillwater and Jimberlana intrusions were derived from markedly depleted PGE-enriched mantle material. In the case of the Penikat Intrusion there were evidently also two magma types, at least one of which was boninitic, or a second-stage affinity magma, and was enriched in PGEs.

At least seven PGE-enriched zones have been discovered in the Penikat Intrusion, but only three of these are of any significance: the SJ, AP and PV Reefs. All three are located in conjunction with MCU IV, the SJ Reef also occurring in the upper part of MCU III in places. The SJ Reef concentrations have been found to occur mainly in association with either chromite or base metal sulphide disseminations or to be concentrated in silicate rocks which do not contain such disseminations. On the other hand, the AP and PV Reef are clearly connected with base metal sulphide disseminations.

One popular hypothesis for explaining the origin of the PGE concentrations is associated with base metal sulphide-bearing zones within the basal units of cyclicly layered sequences. This traditional concept of platinum genesis cannot explain all the PGE deposits, because the platinum-sulphide association is by no means ubiquitous and PGMs may or may not occur in association with chromite and silicate. In the case of the SJ Reef in the Penikat Intrusion, for example, some other mechanism is needed to explain particular aspects of the mineralization. Processes such as late or post-magmatic volatile activity may played an additional important role.

It is obvious that the Cl content will generally be high in layered intrusions which contain PGE deposits, but the Cl contents of the whole-rock or of apatite are not necessarily high within a PGE reef or in its immediate vicinity, as in the case of the SJ and PV Reef.

The apatites which are richest in Cl in the Penikat Intrusion occur in the bronzitite of the lower part of MCU I, several hundred metres below the first significant PGE enrichment, the SJ Reef. Furthermore, Cl-rich apatites are to be found in the Ala-Penikka block 250-350 m above the SJ Reef, in the area of the AP Reefs and in the lower part of MCU V where it overlies the PV Reef. This may be attributable to the tendency for chlorine to escape upwards when PGMs are precipitated. Although Cl-rich fluids are considered significant transporters of PGEs (Boudreau et al. 1986, Boudreau & McCallum 1986, Mathez et al. 1989, Boudreau & McCallum 1989), other components involved in the transport of PGEs may be as important as Cl. The significance of C-bearing fluids, for instance, may be greater than has previously been expected, as suggested by the results regarding the SJ Reef (cf. Halkoaho et al. 1990a).

The history of all three significant PGE reefs in the Penikat Intrusion appears at some stage to have involved a fluid phase which has played the major role in the processes leading to the formation of the mineralizations. Similarly, the PGE concentrations in the SJ, AP and PV Reefs are obviously connected, in the sense that where one of them is rich in PGEs the others are poor. The source of the PGEs in these reefs thus seems to be the PGE-enriched magmas (MCU I-III) of boninitic affinity, in which the PGEs will have migrated together with the volatile components in the fluids of the residual magma. The volatile components will then have dispersed under the favourable conditions prevailing in the Penikat Intrusion, releasing the platinum metals to form the three significant PGE reefs. It was the partial melting of the second stage magma in the (PGE-enriched) upper mantle about 2440 million years ago that led to the high initial PGE tenor of the Penikat Intrusion.-

## EXCURSION TARGETS OF THE PENIKAT LAYERED INTRUSION

### Site 1. Sompujärvi PGE Reef in the Kirakkajuppura area

The Sompujärvi (SJ) Reef is best exposed at the Kirakkajuppura area at the northern end of the Penikat Layered Intrusion (Fig. 2), where Outokumpu Oy has been carrying out experimental opencast mining during years 1987-1988.

#### Stop 1. General view to the exploratory mine

An anorthosite interlayer (5-30 cm thick) in the third megacyclic unit is visible in the NE wall of the mine. The anorthosite layer dips about 70° to the NW and it can easily be seen that the gabbroic cumulates of the megacyclic unit III are intersected by the ultramafic cumulates of the megacyclic unit IV. The intersecting structure is also seen in Fig. 11 and Fig. 12 which shows a cross-section for the interval A-B. The cross-section figure indicates that the SJ PGE Reef does not entirely follow the rock type boundaries but wanders between the gabbroic rocks of the megacyclic unit III and the middle part of the ultramafic layer of the megacyclic unit IV.

#### Stop 2. Intersecting pegmatitic gabbros in the upper part of the megacyclic unit III

In the outcrop can be seen that the pegmatitic gabbro intersects the cumulates of the megacyclic unit III as the 5 – 30 cm thick anorthosite layer (see Fig. 11). The pegmatitic gabbros occur in the same stratigraphic position in the upper part of the MCU III than the chromite-disseminated poikilitic plagioclase-bronzite orthocumulate, thus the pegmatitic gabbros may be linked genetically with the poikilitic plagioclase-bronzite orthocumulate. In places these pegmatitic gabbros contain PGE.

#### Stop 3. Ultramafic cumulates and the lower contact of the megacyclic unit IV

The ultramafic rocks of the lower part of the

megacyclic unit IV vary from peridotites to pyroxenites. In the area of this stop the ultramafic rocks are more peridotitic and contain less chromite-disseminations than in the main mine area. In this area Outokumpu Oy has mined a small, so called, “Kuprikka” mineralization (see Fig. 11). The host rocks of this mineralization are peridotitic cumulates and its PGE content was lower than the main mineralization. The position of the lower contact of the megacyclic unit IV sometimes fluctuates. In this kind of areas, like in the stop area, the plagioclase-augite-bronzite adcumulate of the megacyclic unit III contains pyroxenitic cumulates. The genetic relationship between these pyroxenitic cumulates and the ultramafic cumulates of the megacyclic unit IV is still open for discussion.

#### Stop 4. Ultramafic cumulates of the megacyclic unit III

The thickness of the megacyclic unit III in the Kirakkajuppura area is only 20 – 35 m as compared its maximum thickness (about 400 m) in the Keski-Penikka block (see Fig. 2). The ultramafic cumulates are mainly peridotites, which change upwards during distance less than 0.5 m via a pyroxenite to a homogeneous gabbroic orthocumulate (plagioclase-augite-bronzite adcumulate).

#### Stop 5. Northern end of the ultramafic cumulates of the megacyclic unit IV

The ultramafic cumulates of the megacyclic unit IV narrow off rapidly, and at this point the peridotitic layer ends completely. Only the thin pyroxenitic layer continues northwards. According to the drill hole Ki-173 (Fig. 11), where the ultramafic layer of the megacyclic unit IV is only 20 cm thick pyroxenite, a dip of the northern end of the peridotitic cumulates is towards the south or southwest. In this area the gabbroic cumulates of the megacyclic unit III contain the same kind of pyroxenitic material what we saw in the area

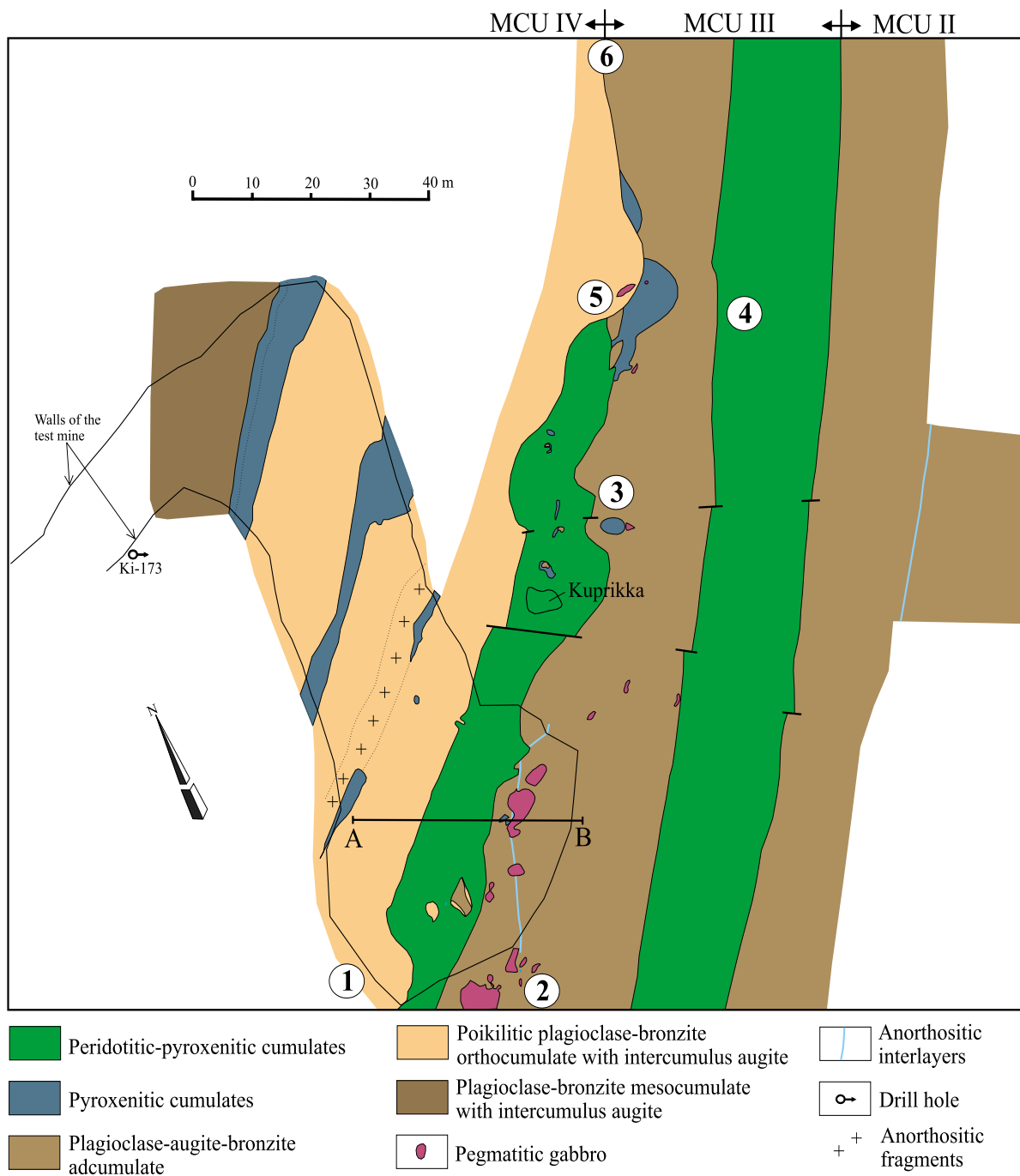


Fig. 11. Geological map of the Kirakkajuppura area, Penikat Intrusion and the stop (1 – 6) locations (modified after Halkoaho et al. 1989b, Alapieti & Lahtinen 1989). The outline of an exploratory mine is also shown.

of stop 3. This pyroxenitic material may contain a small amount of PGE. The granophyric dyke can also be seen at this stop.

**Stop 6.** Contact between the plagioclase-augite-bronzite adcumulate of the megacyclic unit III and the poikilitic plagioclase-bronzite orthocumulate with intercumulus augite of the megacyclic unit IV

In the area of our last stop (6) the ultramafic unit of the megacyclic unit IV is less than 0.5 m thick. In this outcrop the gabbro-norite (plagioclase-augite-bronzite adcumulate) of the megacyclic unit III is very close the poikilitic gabbro-norite (plagioclase-bronzite orthocumulate with poikilitic intercumulus augite) of the megacyclic unit IV.

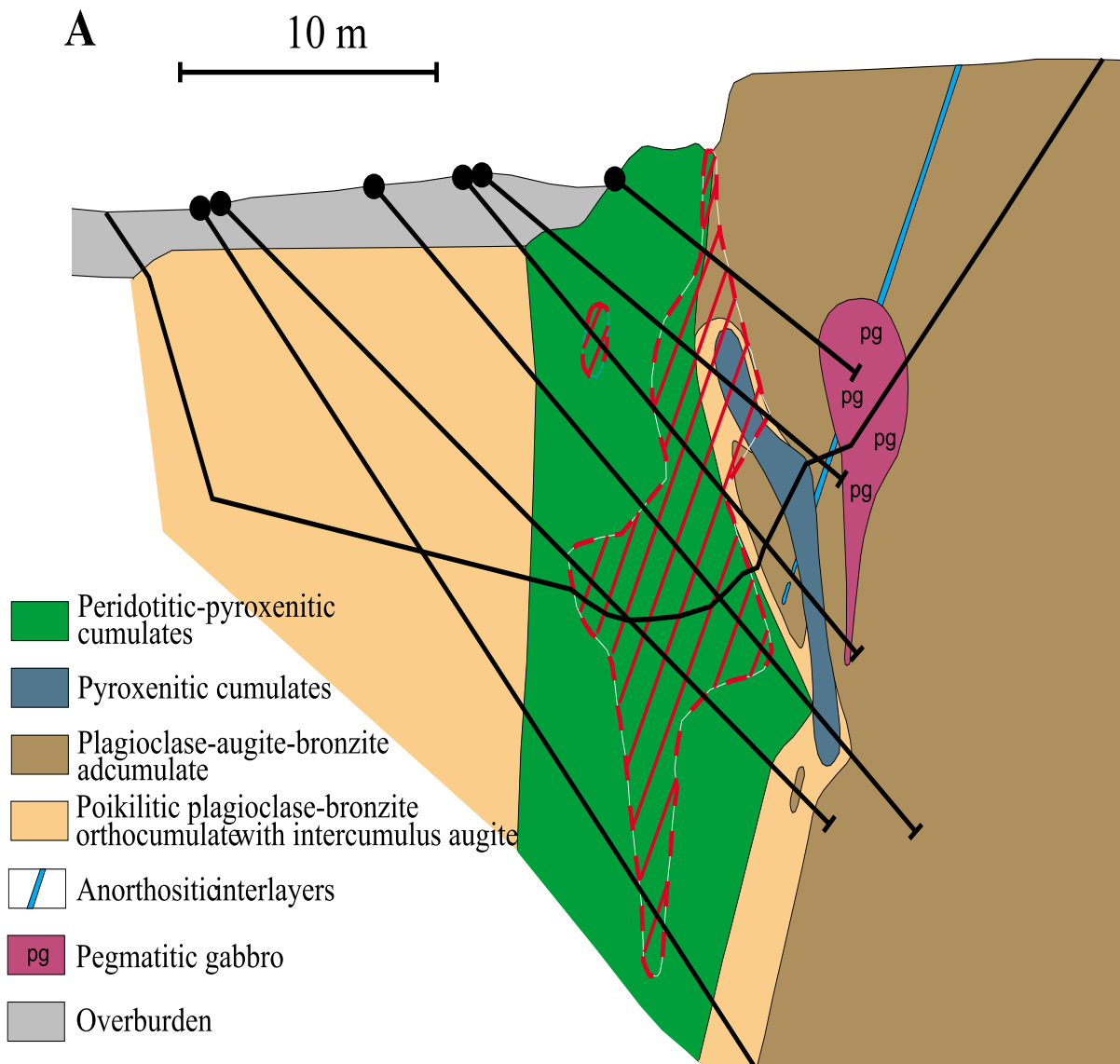


Fig. 12. Cross-section (A-B in Fig. 11) through the Kirakkajuppura PGE-mineralized zone. The outline of an exploratory mine is drawn in bold (modified after Halkoaho et al. 1989b, Alapieti & Lahtinen 1989). The location of the Kirakkajuppura PGE deposit (shown by the star) in the geological map of Penikat Intrusion is shown in Fig. 2.

## Site 2. Ala-Penikka PGE Reefs

The excursion area is divided into 3 stops (Fig. 13).

**Stop 1.** Border between zone 1 and zone 2 in the megacyclic unit IV

In the first outcrop can be seen uppermost anorthosite pyroxenite pair, which is together with next outcrop's poikilitic anorthosite, are most prominent mark horizons in the Penikat

Intrusion. Those layers can be follow from the southern end to the northern end of the intrusion. About 5 cm thick anorthosite layer is poikilitic plagioclase adcumulate (pACa\*) with intercumulus augite and about 1 m thick pyroxenite layer is poikilitic bronzite mesocumulate (bMCa\*p) with intercumulus augite and plagioclase. The pyroxenite begins the uppermost macrorhythmic unit of the zone 1.

In the next outcrop, about 20 m to the west, is the contact between zone 1 and zone 2 (Fig. 14).

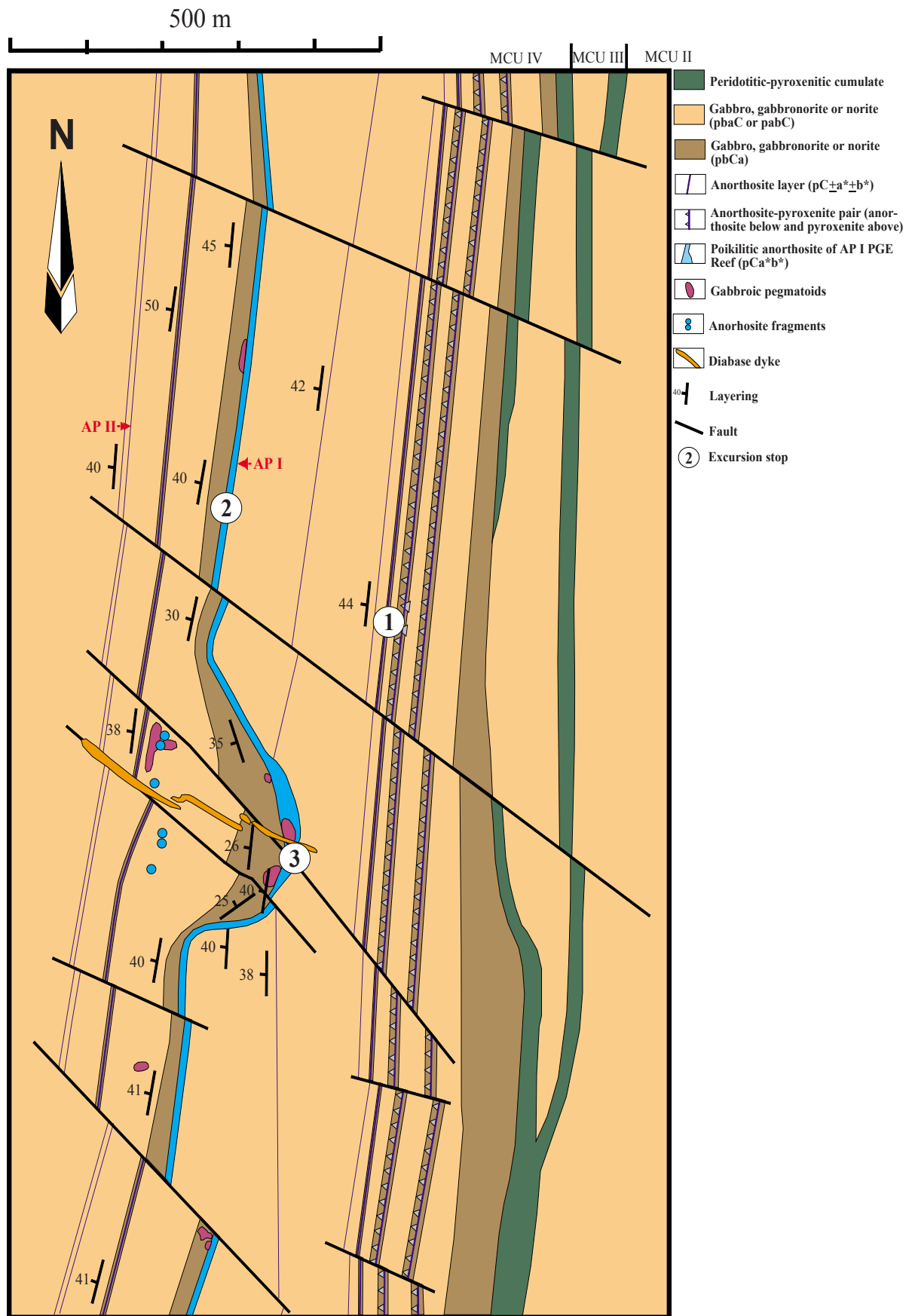


Fig. 13. Geological map of the Ala-Penikka area and the locations of the stops (slightly modified from Halkoaho 1989).





Fig. 14. Poikilitic plagioclase mesocumulate (pMCa\*b\*) in the contact between zones 1 and 2 (black line). Length of the white plate is 10 cm. Photo T. Halkoaho.

The uppermost rock type of the zone 1 is poikilitic plagioclase mesocumulate (pMCa\*b\*) with intercumulus augite and bronzite. The first rock type of the zone 2 is 0.5 m thick plagioclase-bronzite mesocumulate (pbMCa\*) with intercumulus augite. Above it also augite becomes a cumulus mineral. Variations of cumulus and intercumulus minerals, chemical compositions of minerals and cumulates are shown in Fig. 15.

**Stop 2.** Normal Ala-Penikka (AP) I PGE Reef in the border between zone 2 and zone 3

The AP I PGE Reef is situated in the border between zone 2 and zone 3 (see Figs 3, 8A and 17). It is closely associated with base metal sulphide dissemination (pyrrhotite, pentlandite, chalcopyrite ± pyrite, note the rusty colour on an outcrop). The AP I Reef occurs in a 3 to 30 cm thick poikilitic plagioclase mesocumulate with intercumulus augite and bronzite (pMCa\*b\*) and underlying a plagioclase-augite-bronzite adcumulate (pabAC). In the northern part of the outcrop about 1 m long piece of the poikilitic plagioclase mesocumu-

late has sunk down into the underlying plagioclase-augite-bronzite mesocumulate (Fig. 16). Above poikilitic plagioclase mesocumulate is about 1 m thick spotted poikilitic plagioclase-bronzite mesocumulate (pbMCa\*) with intercumulus augite and above it occur about 13 m thick plagioclase-bronzite mesocumulate (pbMCA) with intercumulus augite. Above that unit augite becomes again a cumulus phase. Variations of cumulus and intercumulus minerals, chemical compositions of minerals and cumulates are shown in Fig. 17.

**Stop 3.** Pothole structure of the AP I PGE Reef

In the area of the pothole structure the poikilitic plagioclase mesocumulate (mottled anorthosite, pMCa\*b\*) of the AP I Reef is much thicker than in the area of the normal AP I Reef. Maximum thickness of the poikilitic mesocumulate is about 20 m (see Figs 8B, 18, 19 and 20). In the pothole area the PGE mineralization is associated with the lower portion of the poikilitic plagioclase mesocumulate and the underlying plagioclase-bronzite-augite ad-



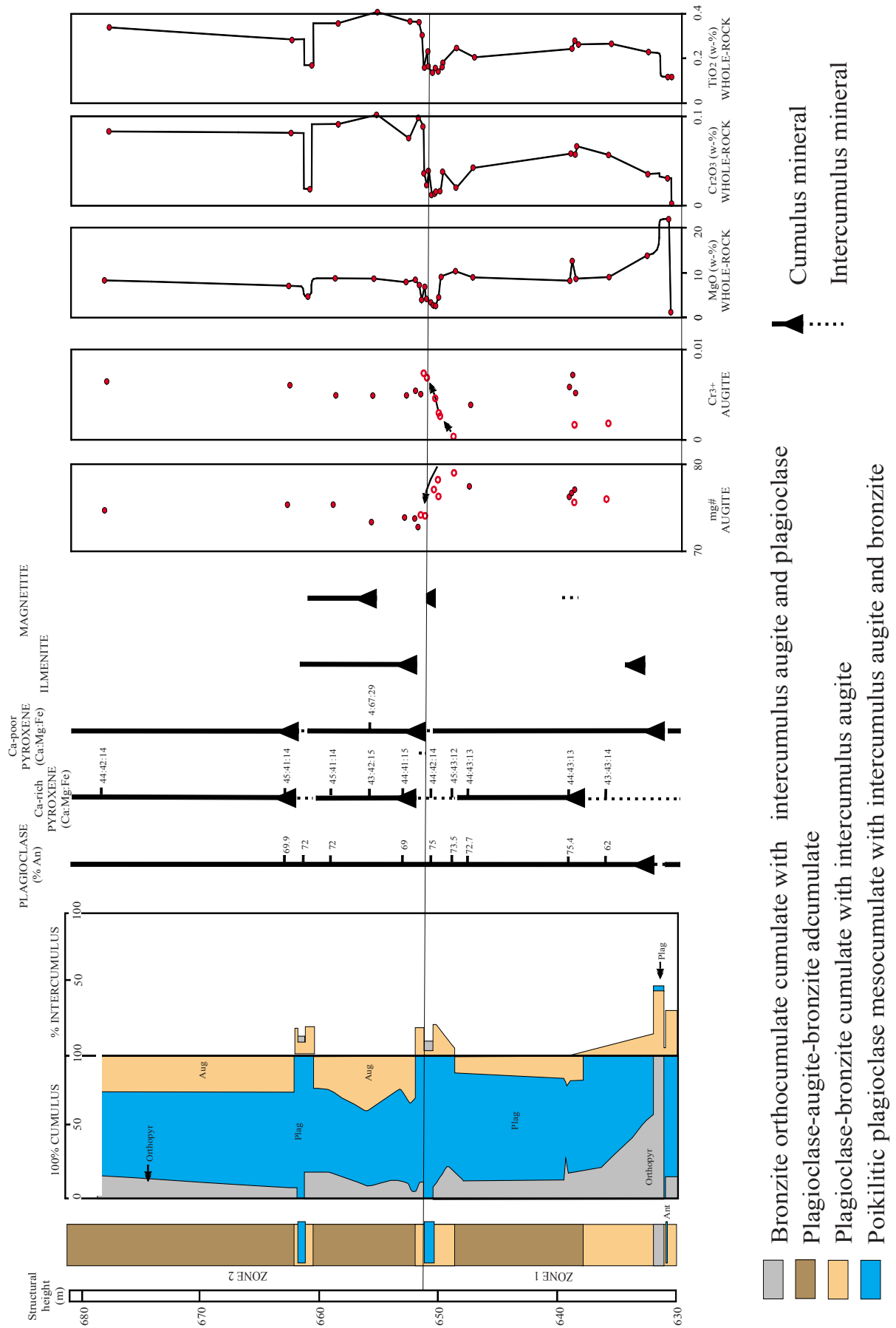


Fig. 15. Stratigraphic sequence and modal data on the proportions of cumulus and intercumulus minerals and cryptic variation in minerals, the 100Mg/(Mg+Fe+Mn) ratio (mg#) and Cr<sup>3+</sup> content of the augite (filled circle cumulus and open circle intercumulus) and MgO, Cr<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> for whole-rock samples at stop 1.



Fig. 16. Disturbance structure in the poikilitic plagioclase mesocumulate (anorthosite) of the API Reef. The anorthosite has “sunk” into the underlying plagioclase-augite-bronzite adcumulate (gabbronorite). Length of the compass is 12 cm. Photo T. Halkoaho.

cumulate (note the rusty colour on the outcrop). Above the poikilitic plagioclase mesocumulate locally spotted plagioclase-bronzite mesocumulate (see Figs 8A, 18 and 20). The poikilitic plagioclase-bronzite mesocumulate with intercumulus augite is missing in the pothole area. In the area of the pothole structure, especially in the middle part of the poikilitic

plagioclase mesocumulate and lower part of the plagioclase-bronzite mesocumulate occur a lot of gabbroic pegmatoids (Figs 18 and 20). When these pegmatoids occur in the poikilitic plagioclase mesocumulate or the underlying plagioclase-augite-bronzite adcumulate they contain PGE (Fig. 20).



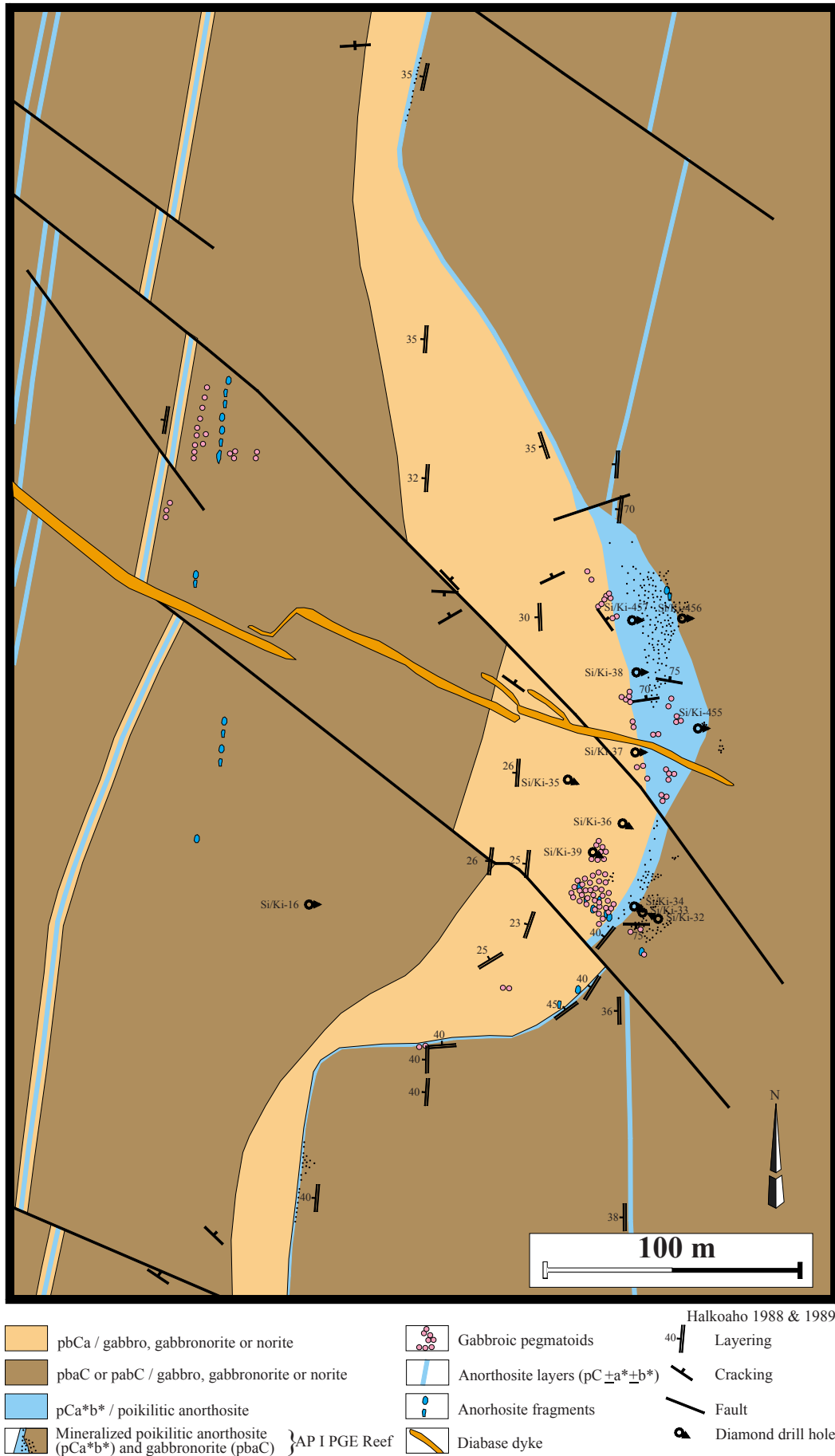


Fig. 18. Geological map of the depression structure of the AP I Reef. Modified after Halkoaho 1989.



Fig. 19. Poikilitic plagioclase mesocumulate (mottled anorthosite, pMCa\*b\*) in the area of the pothole structure of the AP Reef. Length of the compass is 12 cm. Photo T. Halkoaho.

### Site 3. Paasivaara PGE Reef

**Stop 1.** Contact between the bronzite orthocumulate of the basal part of MCU V and the uppermost plagioclase orthocumulate of the transition zone

Stop 1 (see Fig. 21) consists of the contact between the highly altered bronzite orthocumulate of the basal part of MCU V and the uppermost plagioclase orthocumulate of the transition zone, which is located between MCU's IV and V. The sulphides and the associated PGM most frequently occur in the interstices of the above mentioned plagioclase orthocumulate. The main sulphide paragenesis is chalcopyrite-pyrrhotite-pentlandite. The PGM identified are represented by spherulite, kotulskite, isomertieite, merenskyite, stibiopalladinite, cooperite and braggite. Gold

is also encountered in the PV mineralization, either as electrum or as native gold.

**Stop 2.** Mixed rock of the transition zone

Stop 2 (see Fig. 21) represents the mixed rock of the transition zone. The mixed rock is composed of white patches of plagioclase adcumulate and darker patches of plagioclase and/or plagioclase-bronzite cumulate in which intercumulus augite occurs in the form of oikocrysts. Pegmatoids and two narrow plagioclase orthocumulate layers are encountered within the mixed rock. Also the plagioclase orthocumulate layer approximately 1 m thick underlying the mixed rock will be seen. Sulphides and associated PGM are sometimes encountered in the mixed rock, in the plagioclase orthocumulate layers and in the pegmatoids.







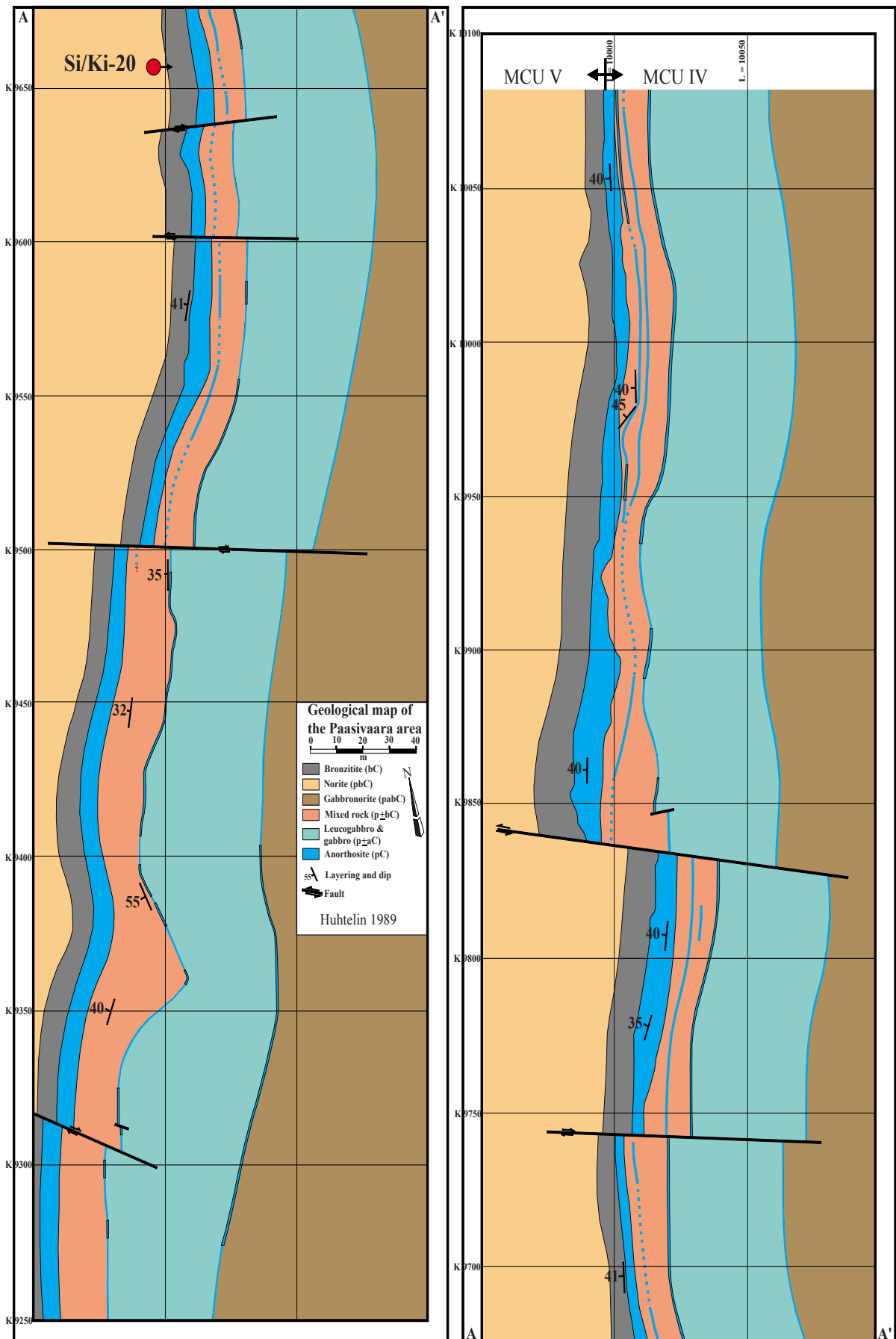


Fig. 21. Geological map of the Paasivaara area (slightly modified from Huhtelin 1989).

## REFERENCES

- ALAPIETI, T.T., 1982. The Koillismaa layered igneous complex, Finland - its structure, mineralogy and geochemistry, with emphasis on the distribution of chromium. Geological Survey of Finland Bulletin, 319, p. 1-116.
- ALAPIETI, T.T., 1984. Peräpohjan kerrosintrusiotutkimus. An unpublished report of the Outokumpu Oy Foundation, 55 pp. (in Finnish).
- ALAPIETI, T.T. and LAHTINEN J.J., 1986. Stratigraphy, petrology, and platinum-group element mineralization of the early Proterozoic Penikat layered intrusion, Northern Finland. Economic Geology, 81, p. 1126-1136.
- ALAPIETI, T.T. and LAHTINEN J.J., 1989. Early Proterozoic layered intrusions in the north-eastern part of the Fennoscandian shield. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 3-41.
- ALAPIETI, T.T. and LAHTINEN J.J., 2002. Platinum-group element mineralization in layered intrusions of Northern Finland and the Kola Peninsular, Russia. In The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-group Elements. Edited by L.J. Cabri. Special Volume 54, Canadian Institute of Mining, Metallurgy and Petroleum, p. 507-546.
- ALAPIETI, T.T. and PIIRAINEN, T.A., 1984. Cu-Ni-PGE mineralization in the marginal series of the early Proterozoic Koillismaa layered igneous complex, northeast Finland. In Sulphide deposits in Mafic and Ultramafic Rocks. Edited by D.L. Buchanan and M.J. Jones. The Institution of Mining and Metallurgy, London, p. 123-131.
- ALAPIETI, T.T., HUGG, R. and PIIRAINEN, T.A., 1979a. Structure, mineralogy and chemistry of the Syöte section in the early Proterozoic Koillismaa layered intrusion, northeastern Finland. Geological Survey of Finland Bulletin, 229, p. 1-43.
- ALAPIETI, T.T., HUGG, R., PIIRAINEN, T.A. and RUOTSALAINEN, A., 1979b. The ultramafic and mafic intrusion at Näränkävää, north-eastern Finland. Geological Survey of Finland Report of Investigation, 35, p. 1-31.
- ALAPIETI, T.T., KUJANPÄÄ, J., LAHTINEN, J.J. and PAPUNEN, H., 1989a. The Kemi stratiform chromitite deposit, Northern Finland. Economic Geology, 84, p. 1057-1077.
- ALAPIETI, T., LAHTINEN, J., HUHMA, H., HÄNNINEN, E., PIIRAINEN, T.A. and SIVONEN, S.J., 1989b. Platinum-group element-bearing Cu-Ni sulphide mineralization in the marginal series of the early Proterozoic Suhanko-Konttijärvi layered intrusion, Northern Finland. In Magmatic sulphides - Zimbabwe volume. Edited by M.D. Prendergast and M.J. Jones. London, Institution of Mining and Metallurgy, p. 177-187.
- ALAPIETI, T.T., FILÉN, B.A., LAHTINEN, J.J., LAVROV, M.M., SMOLKIN, V.F. and VOITSEKHOVSKY, S.N., 1990. Early Proterozoic layered intrusions in the northeastern part of the Fennoscandian shield. Mineralogy and Petrology, 42, p. 1-22.
- BALLHAUS, C.G. and STUMPFL, E.F., 1985. Occurrence and petrological significance of graphite in the Upper Critical zone, western Bushveld Complex, South Africa. Earth Planet Science Letters 74, p. 58-68.
- BALLHAUS, C.G. and STUMPFL, E.F., 1986. Sulfide and platinum mineralization in the Merensky Reef: evidence from hydrous silicates and fluid inclusions. Contributions to Mineralogy and Petrology, 94, p. 193-204.
- BALLHAUS, C.G., CORNELIUS, M. and STUMPFL, E.F., 1988. The Upper Critical Zone of the Bushveld Complex and the origin of Merensky-type ores -- a discussion. Economic Geology, 83, p. 1082-1085.
- BARKOV, A.Y., HALKOAHO, T.A.A., ROBERTS, A.C., CRIDDLE, A.J., MARTIN, R.F. and PAPUNEN, H., 1999. New Pd-Pb and Pb-V oxides from a bonanza-type PGE-rich, nearly BMS-free deposit in the Penikat layered complex, Finland. Canadian Mineralogist, 37, p. 1507-1524.

- BARKOV, A.Y., MARTIN, R.F., HALKOAHO, T.A.A. and POIRIER, G., 2000. The mechanism of charge compensation in Cu-Fe-PGE thiospinels from the Penikat layered intrusion, Finland. *American Mineralogist*, 85, p. 694-697.
- BARKOV, A.Y., MARTIN, R.F., HALKOAHO, T.A.A. and CRIDDLE, A.J., 2002. Laflammeite, Pd<sub>3</sub>Pb<sub>2</sub>S<sub>2</sub>, a new platinum-group mineral species from the Penikat layered complex, Finland. *Canadian Mineralogist*, 40, p. 671-678.
- BARKOV, A.Y., FLEET, M.E., MARTIN, R.F. and ALAPIETI, T.T., 2004a. Zoned sulfides and sulfarsenides of the platinum-group elements from the Penikat layered complex, Finland. *Canadian Mineralogist*, 42, p. 515-537.
- BARKOV, A.Y., FLEET, M.E., MARTIN, R.F. and HALKOAHO, T.A.A., 2004b. A potentially new konderite-like sulfide of Fe, Pb, Cu, Rh, Pd, and Ir from the Penikat layered complex, Finland. *Canadian Mineralogist*, 42, p. 499-513.
- BARKOV, A.Y., FLEET, E.L., MARTIN, R.F. and HALKOAHO, T.A.A., 2005. New data on "bonanza"-type PGE mineralization in the Kirakkajuppura PGE deposit, Penikat layered complex, Finland. *Canadian Mineralogist*, (in press).
- BARNES, S.-J., NALDRETT, A.J. and GORTON, M.P., 1985. The origin of the fractionation of platinum-group elements in terrestrial magmas. *Chemical Geology*, 53, p. 303-323.
- BARNES, S.-J., BOYD, R., KORNELIUSSEN, A., NILSSON, L.-P., OFTEN, M., PEDERSEN, R.B. and ROBINS, B., 1988. The use of mantle normalization and metal ratios in discriminating between the effects of partial melting, crystal fractionation and sulphide segregation on platinum-group elements, gold, nickel and copper: examples from Norway. In *Geoplatinum*. Edited by H.M. Prichard, P.J. Potts, J.Fw. Bowles and S.J. Cripp. Elsevier, London, p. 113-143.
- BOUDREAU, A.E., 1988. Investigations of the Stillwater Complex: part IV. The role of volatiles in the petrogenesis of the J-M Reef, Minneapolis Adit section. *Canadian Mineralogist*, 26, p. 193-208.
- BOUDREAU, A.E. and MCCALLUM, I.S., 1986. Investigations of the Stillwater Complex: Part III. The Picket Pin Pt/Pd deposit. *Economic Geology*, 81, p. 1953-1975.
- BOUDREAU, A.E. and MCCALLUM, I.S., 1989. Investigations of the Stillwater Complex: Part V. Apatites as indicators of evolving fluid composition. *Mineralogy and Petrology*, 102, p. 138-153.
- BOUDREAU, A.E. MATHEZ, E.A. and MCCALLUM, I.S., 1986. Halogen geochemistry of the Stillwater and Bushveld Complexes: evidence for transport of the platinum-group elements by Cl-rich fluids. *Journal of Petrology*, 27, p. 967-986.
- BUNTIN, T.J., GRANDSTAFF, D.E., ULMER, G.C. and GOLD, D.P., 1985. A pilot study of geochemical and redox relationships between potholes and adjacent normal Merensky Reef of the Bushveld Complex. *Economic Geology*, 80, p. 975-987.
- CAMPBELL, I.H. and TURNER, J.S., 1986. The role of convection in the formation of platinum and chromitite deposits in layered intrusions. *Mineralogical Association of Canada, short course handbook*, 12, p. 236-278.
- CAMPBELL, I.H., NALDRETT, A.J. and BARNES, S.J., 1983. A model for the origin of the platinum-rich sulfide horizons in the Bushveld and Stillwater Complexes. *Journal of Petrology*, 24, p. 133-165.
- DOKUCHAEVA, V.S., CHARGUROV, A.A., RADCENKO, M.K. and FEDOROV, C.A., 1982. Rannekarelskie magmatism. In *Imandra-Varzuga zona Karelid*. Edited by G.I. Gorbunov. NAUKA, Leningrad, p. 114-144 (in Russian).
- ELLIOTT, W.C., GRANDSTAFF, D.E., ULMER, G.C., BUNTIN, T. and GOLD, D.P., 1982. An intrinsic oxygen fugacity study of the platinum-carbon associations in layered intrusions. *Economic Geology*, 77, p. 1493-1510.
- HALKOAHO, T., 1989. Ala-Penikan platinametallimineralisaatiot Penikkain kerrosintruusion. Report 2 of the PGE Research Project, University of Oulu, Oulu, p. 1-173 (in Finnish).
- HALKOAHO, T., 1993. The Sompujärvi and Ala-Penikka PGE Reefs in the Penikat Layered Intrusion, northern Finland: implications for PGE reef-forming processes. *Acta Universitatis Ouluensis. Series A, Scientiae Rerum Naturalium*, 249, p. 1-122.

- HALKOAHO, T.A.A., ALAPIETI, T.T. and LAHTINEN, J.J., 1989a. The Sompujärvi PGE mineralization in the Penikat layered intrusion, Northern Finland. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 71-92.
- HALKOAHO, T.A.A., ALAPIETI, T.T. and LAHTINEN, J.J., 1989b. The Ala-Penikka PGE mineralizations in the Penikat layered intrusion, Northern Finland. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 93-122.
- HALKOAHO, T.A.A., ALAPIETI, T.T. and LAHTINEN, J.J., 1990a. The Sompujärvi PGE Reef in the Penikat layered intrusion, Northern Finland. *Mineralogy and Petrology*, 42, p. 39-55.
- HALKOAHO, T.A.A., ALAPIETI, T.T., LAHTINEN, J.J. and LERSSI, J.M., 1990b. The Ala-Penikka PGE Reefs in the Penikat layered intrusion, Northern Finland. *Mineralogy and Petrology*, 42, p. 23-38.
- HIEMSTRA, S.A., 1979. The role of collectors in the formation of the platinum deposits in the Bushveld Complex. *Canadian Mineralogist*, 17, p. 469-482.
- HUHMA, H., CLIFF, R.A., PERTTUNEN, V. and SAKKO, M., 1990. Sm-Nd and Pb isotopic study of mafic rocks associated with early Proterozoic continental rifting: the Peräpohja schist belt in northern Finland. *Contributions to Mineralogy and Petrology*, 104, p. 369-379.
- HUHTELIN, T., 1989. Paasivaaran platinamineräalisaatio Penikkain kerrosintruusiassa. Report 1 of the PGE Research Project, University of Oulu, Oulu, p. 1-70 (in Finnish).
- HUHTELIN, T.A., ALAPIETI, T.T. and LAHTINEN, J.J., 1989a. The Paasivaara PGE mineralization in the Penikat layered intrusion, Northern Finland. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 123-144.
- HUHTELIN, T.A., ALAPIETI, T.T., LAHTINEN, J.J. and LERSSI, J.M., 1989b. Megacyclic units I, II and III in the Penikat layered intrusion. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 59-69.
- HUHTELIN, T.A., LAHTINEN, J.J., ALAPIETI, T.T., KORVUO, E. and SOTKA, P., 1989c. The Narkaus intrusion and related PGE and sulphide mineralizations. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 145-161.
- HUHTELIN, T.A., ALAPIETI, T.T. and LAHTINEN, J.J., 1990. The Paasivaara PGE Reef in the Penikat layered intrusion, Northern Finland. *Mineralogy and Petrology*, 42, p. 57-70.
- ILJINA, M., 1994. The Portimo Layered Igneous Complex, with emphasis on diverse sulphide and platinum-group element deposits. *Acta Universitatis Ouluensis. Series A, Scientiae Rerum Naturalium*, 258, p. 1-158.
- ILJINA, M.J., ALAPIETI, T.T., LAHTINEN, J.J. and LERSSI, J.M., 1989. The Suhanko - Konttijärvi intrusion and related sulphide and PGE mineralizations. In 5th International Platinum Symposium. Guide to the post-symposium field trip. Edited by T.T. Alapieti. Geological Survey of Finland, Guide 29, p. 163-187.
- IRVINE, T.N., 1977. Origin of chromitite layers in the Muskox intrusion: a new interpretation. *Geology*, 5, p. 273-277.
- IRVINE, T.N. and SHARPE, M.R., 1982. Source rock compositions and depths of origin of Bushveld and Stillwater magmas. *Carnegie Institute Washington Yearbook*, 81, p. 294-303.
- IRVINE, T.N., KEITH, B.W. and TODD, S.G., 1983. The J-M platinum-palladium Reef of the Stillwater Complex, Montana: II. Origin by double-diffusive convective magma mixing and implications for the Bushveld Complex. *Economic Geology*, 78, p. 1287-1334.
- ISOHANNI, M., 1976. Porttivaaran ja Syötteen emäksisten kerrosintruusioiden sisäisestä sulfidimalmimuodostuksesta Koillismaalla. Unpublished Licentiate thesis. Manuscript at the Department of Geology, University of Oulu, p. 1-122 (in Finnish).

- JUOPPERI, A., 1977. The magnetite gabbro and related Mustavaara vanadium ore deposit in Porttivaara layered intrusion, northeastern Finland. Geological Survey of Finland Bulletin, 288, p. 1-68.
- KAUKONEN, R.J., TÖRMÄNEN, T.O. and ALAPIETI, T., 2004. Platinum-group mineralogy of the silicate type PGE mineralization in the Penikat layered intrusion, Northern Finland. 32nd International Geological Congress, Florence. Scientific Sessions: abstracts (part 2), p. 1269.
- KINLOCH, E.D., 1982. Regional trends in the platinum-group mineralogy of the Critical zone of the Bushveld Complex, South Africa. Economic Geology, 77, p. 1328-1347.
- KOUVO, O., 1977. The use of mafic pegmatoids in geochronometry. 5th ECOG meeting, Pisa, Italy (abst.).
- KUJANPÄÄ, J., 1964. Kemin Penikkain jakson rakenteesta ja kromiiteista. Unpublished Licentiate thesis. Manuscript at the Department of Geology, University of Oulu, p. 1-118 (in Finnish).
- KUJANPÄÄ, J., 1980. Geology of the Kemi chromite deposit. In Precambrian ores of Finland. Edited by T.A. Häkli. 26th International Geological Congress, Paris. Guide to excursions 078 A+C, p. 6-13.
- LAHTINEN, J., 1985. PGE-bearing copper-nickel occurrences in the Marginal Series of the early Proterozoic Koillismaa layered intrusion, Northern Finland. In Nickel-copper deposits of the Baltic shield and Scandinavian Caledonides. Edited by H. Papunen and G.I. Gorbunov. Geological Survey of Finland Bulletin, 333, p. 161-178.
- LAVROV, M.M., 1979. Giberbasity i rasslojenie peridotit-gabbro-noritovie intrusii dokembria Severnoi Karelii. NAUKA, Leningrad, p. 1-135 (in Russian).
- MANHES, G., ALLEGRE, C.J., DUPRE, B. and HAMELIN, B., 1980. Lead isotope study of basic-ultrabasic layered complexes: speculation about the age of the earth and primitive mantle characteristics. Earth Planet Science Letters 47, p. 370-382.
- MATHEZ, E.A., DIETRICH, V.J., HOLLOWAY, J.R., and BOUDREAU, A.E., 1989. Carbon distribution in the Stillwater Complex and evolution of vapor during crystallization of Stillwater and Bushveld magmas. Journal of Petrology, 30, p. 153-173.
- MCLAREN, C.H. and DE VILLIERS, J.P.R., 1982. The platinum-group chemistry and mineralogy of the UG-2 chromitite layer of the Bushveld Complex. Economic Geology, 77, p. 1348-1366.
- MUTANEN, T., 1981. A new type of platinum-bearing chromite ore in the Koitelainen mafic layered intrusion, Northern Finland. 3rd International Platinum Symposium, Pretoria, South Africa. Abstracts of papers, p. 28-29.
- MUTANEN, T., 1989. Koitelainen intrusion and Keivitsa-Satovaara complex. Excursion guide 5th International Platinum Symposium. Geological Survey of Finland, Guide 28, p. 49 p.
- MUTANEN, T., 1997. Geology and petrology of the Akanvaara and Koitelainen mafic layered intrusions and the Keivitsa-Satovaara layered complex, northeastern Finland. Geological Survey of Finland Bulletin, 395, p. 1-233.
- NALDRETT, A.J., 1981. Platinum-group element deposits. In Platinum-group elements: mineralogy, geology, recovery. Edited by L.J. Cabri. Canadian Institute of Mining and Metallurgy (CIM Special volume 23), p. 197-231.
- NALDRETT, A.J. and CABRI, L.J., 1976. Ultramafic and related mafic rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. Economic Geology, 71, p. 1131-1158.
- NALDRETT, A.J. and DUKE, J.M., 1980. Platinum metals in magmatic sulfide ores. Science 208, p. 1417-1424.
- NALDRETT, A.J., GASPARRINI, E.C., BARNES, S.J., GRUENEWALDT, G. VON and SHARPE, M.R., 1986. The upper critical zone of the Bushveld Complex and the origin of Merensky-type ores. Economic Geology, 81, p. 1105-1117.



- OSHIN, I.O. and CROCKET, J.H., 1982. Noble metals in the Thetford mines ophiolite Quebec, Canada. Part I distribution of gold, iridium, platinum and palladium in the ultramafic and gabbroic rocks. *Economic Geology*, 77, p. 1556-1570.
- PATCHETT, P., KOUVO, O., HEDGE, C.E. and TATSUMOTO, M., 1981. Evolution of continental crust and mantle heterogeneity: evidence from Hf isotopes. *Contributions to Mineralogy and Petrology*, 78, p. 279-297.
- PIIRAINEN, T., ALAPIETI, T., HUGG, R. and KERKKONEN, O., 1977. The marginal border group of the Porttivaara layered intrusion and related sulphide mineralization. *Geological Society of Finland Bulletin*, 49, p. 125-142.
- PUUSTINEN, K., 1977. Exploration in the north-east region of the Koitelainen gabbro complex, Sodankylä, Finnish Lapland. In *Prospecting in areas of glaciated terrain*. Edited by G.R. Davis. The Institute Mining and Metallurgy, London, pp. 6-13.
- SCHIFFRIES, C.M., 1982. The petrogenesis of a platiniferous dunite pipe in the Bushveld Complex: infiltration metasomatism by a chloride solution. *Economic Geology*, 77, p. 1439-1453.
- SHIMA, H. and NALDRETT, A.J., 1975. Solubility of sulfur in an ultramafic melt and the relevance of the system Fe-S-O. *Economic Geology*, 70, p. 960-967.
- STUMPFL, E.F. and BALLHAUS, C.G., 1986. Stratiform platinum deposits: new data and concepts. *Fortschr. Mineralogie*, 64, p. 205-214.
- SUN, S.-S., 1982. Chemical composition and origin of the earth's primitive mantle. *Geochimica et Cosmochimica Acta*, 16, p. 179-192.
- SÖDERHOLM, K. and INKINEN, O., 1982. The Tornio layered intrusion--a recently discovered intrusion with chromite horizons in northern Finland. *Geological Society of Finland Bulletin*, 54, p. 15-24.
- TARKIAN, M. and MUTANEN, T., 1987. Lovringite from the Koitelainen layered intrusion, Northern Finland. *Mineralogy and Petrology*, 37, p. 37-50.
- TÖRMÄNEN, T., 1994. Penikkain kerrosintrusion Sompujärvi-, Ala-Penikka- ja Paasivaara-mineralisaatioiden platinamineralogia. *Geologian ja mineralogian syventävien opintojen tutkielma 77260S*. University of Oulu, Department of Geology, Oulu, p. 1-106 (in Finnish).
- TÖRMÄNEN, T. and ALAPIETI, T., 1996. Platinum-group mineralogy of the Penikat layered intrusion, Finland. In *IGCP project 336 symposium in Rovaniemi, Finland, August 21-23, 1996: program and abstracts*. Turun yliopiston geologian ja mineralogian osaston julkaisuja 38, p. 83.
- VOLBORTH, A.A. and HOUSLEY, R.M., 1984. A preliminary description of complex graphite, sulphide, arsenide, and platinum-group element mineralization in a pegmatoid pyroxenite of the Stillwater Complex, Montana, U.S.A. *Tschermaks Mineralogische und Petrographische Mitteilungen*, 33, p. 213-230.
- VUORELAINEN, Y., HÄKLI, T.A., HÄNNINEN, E., PAPUNEN, H., REINO, J. and TÖRNROOS, R., 1982. Isomertieite and other platinum-group minerals from the Konttijärvi layered mafic intrusion, Northern Finland. *Economic Geology*, 77, p. 1511-1518.
- WILLMORE, C.C., BOUDREAU, A.E. and KRUGER, F.J., 2000. The halogen geochemistry of the Bushveld Complex, Republic of South Africa: implications for chalcophile element distribution in the lower and critical zones. *Journal of Petrology*, 41, p. 1517-1539.



## Chapter 4

### PORTIMO LAYERED IGNEOUS COMPLEX

Markku Iljina

Geological Survey of Finland, P.O.Box 77, FIN-96101, Rovaniemi, Finland

#### STRUCTURAL UNITS OF THE PORTIMO COMPLEX

The Portimo Layered Igneous Complex (later called Portimo Complex, Fig. 1) belongs to the Tornio-Näränkäväära Belt of c. 2.44 Ga old layered intrusions and is composed of four principal structural units (Iljina, 1994):

- the Narkaus Intrusion
- the Suhanko Intrusion
- the Konttijärvi Intrusion
- the Portimo Dykes

Each intrusion contains a marginal series and an overlying layered series (Fig. 2). The marginal series of the Suhanko and Konttijärvi Intrusions differ from that of the Narkaus Intrusions in thickness and prevailing rock types. The Narkaus marginal series generally varies from 10 to 20 m in thickness, while the Suhanko and Konttijärvi marginal series may reach several tens of meters. The Narkaus marginal series is mainly composed of pyroxenite with some plagioclase-bearing rocks in its lower parts, whereas olivine cumulates commonly constitute the upper half of the Suhanko and Konttijärvi marginal series. -In the course of the Konttijärvi and Ahmavaara mine development, a slightly different stratigraphic division was adopted by the Gold Fields Arctic Platinum Oy. In that division the olivine cumulate layer is called as 'Peridotite Marker', which is underlain by either Konttijärvi or Ahmavaara Proxenite and Marginal Gabbro further down in the stratigraphy (Figs. 17 and 19).

A striking difference between the layered series of the intrusions is the presence of marked reversals in the Narkaus Intrusion, as shown

by the thick ultramafic olivine-rich cumulate layers, whereas crystallization in the Suhanko and Konttijärvi Intrusions continued without notable reversals. The Suhanko layered series commences with plagioclase-bronzite orthocumulates (with poikilitic augite) that also contain some bronzite cumulate interlayers. This poikilitic rock is separated from the overlying, rather monotonous plagioclase-bronzite-augite adcumulates by a few-m thick pyroxenite. About midway in the stratigraphy, bronzite disappears as a cumulus mineral, but returns higher up in the Suhanko sequence. Four poikilitic anorthosite layers also occur in the upper Suhanko layered series. Granophyric material is limited to discontinuous patches and cross-cutting dykes in the upper Suhanko and Konttijärvi layered series.

The major reversals in the Narkaus layered series resemble those of the Penikat Intrusion and enable its layered series to be divided into three megacyclic units (Fig 2). The lowermost (MCU I) commences with a thick (~80 m) bronzite cumulate layer with a massive chromitite layer close to its top. The rest of MCU I as well as the gabbroic parts of MCU II and MCU III are composed mainly of plagioclase-bronzite-augite adcumulates with the exception of a poikilitic plagioclase cumulate layer above the ultramafic basal part of MCU III. MCU unit II, however, is found only in the Kilvenjärvi Block and fades away eastwards.

Mafic and ultramafic dykes, known as the Portimo Dykes, are found in the basement below the Konttijärvi Intrusion and in the Ahmavaara area of the Suhanko Intrusion.

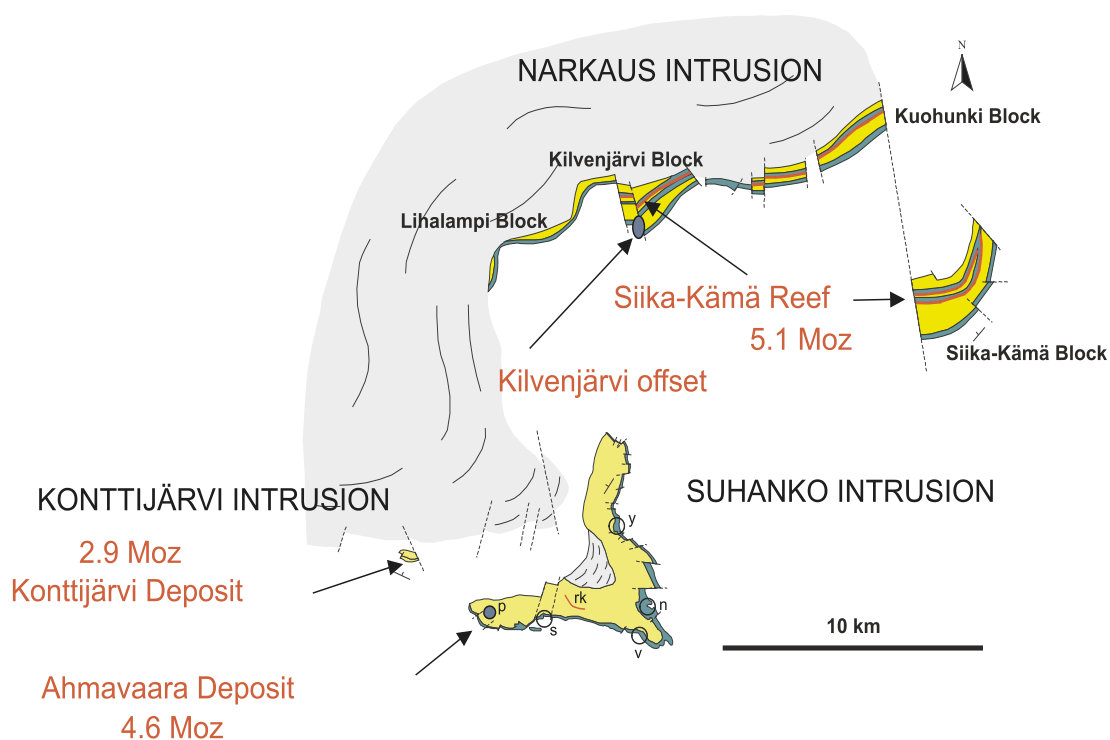


Fig. 1. General geological map of the Portimo layered Igneous Complex (Iljina, 1994) and published Pt-Pd-Au resources (Company press releases). p, ultramafic pipe and rk, Rytikangas PGE Reef. The massive sulphide deposits in the Suhanko Intrusion are also shown: s, Suhanko proper; v, Vaaralampi; n, Niittylampi and y, Yli-Portimojärvi. Archean Complex in white, Proterozoic supracrustal rocks in grey and layered intrusions in yellow. The marginal series (grey) borders the intrusions on the southern and eastern sides.

They have also been found as fragments in the marginal series of the Konttijärvi Intrusion. The dykes have not been dated and their association to the main intrusions is based on geochemical observations as discussed later. The dykes are subparallel to the basal contact of the intrusion and merge with it locally. In view of their location and original subhorizontal orientation, these dykes were previously referred to as ‘sublayer sills’ (Iljina *et al.*, 1989). The term ‘pre-intrusion dykes’ has also been used by Iljina *et al.*, 1992 to allude to the nominal age difference between them and the intrusions.

The cumulus sequences in the layered series of the small Konttijärvi Intrusion and the western end of the Suhanko Intrusion resemble each other. Pyroxenite, which separates the lowermost poikilitic orthocumulate from the overlying gabbroic adcumulate, attains a thickness of some tens of meters in both sections. The gabbroic rocks of the Konttijärvi marginal series, indicated in Fig. 3, are partly pyroxene cumulates with variable portions of felsic material introduced by floor rock

contamination. This and the thick layered series pyroxenite make the present-day Konttijärvi stratigraphy rather ultramafic when cumulus terminology is applied. The lower contact of the Konttijärvi intrusion is also rather unique. Below the lowermost more homogenous cumulate there is a thick *Mixing Zone*, which in some places is up to approx. 150 m wide (Fig. 8). The combined thickness of the Konttijärvi marginal and layered series is only slightly more (approx. 160 m) than this *Mixing Zone*.

*The Mixing Zone* (also called Transition Zone) is made up of a rock type termed ‘hybrid gabbro’ and of banded gabbro (Fig. 8). The ‘hybrid gabbro’ is characterized by grain size variations from fine to medium and also contains an almost assimilated felsic contaminant. Further away from the intrusion the hybrid gabbro turns into the banded gabbro, which according to outcrop evidence, is recrystallised banded Archean quartz dioritic gneiss which still has a primary folded texture but gabbroic mineralogy. Contacts between homogenous gabbro (of marginal series

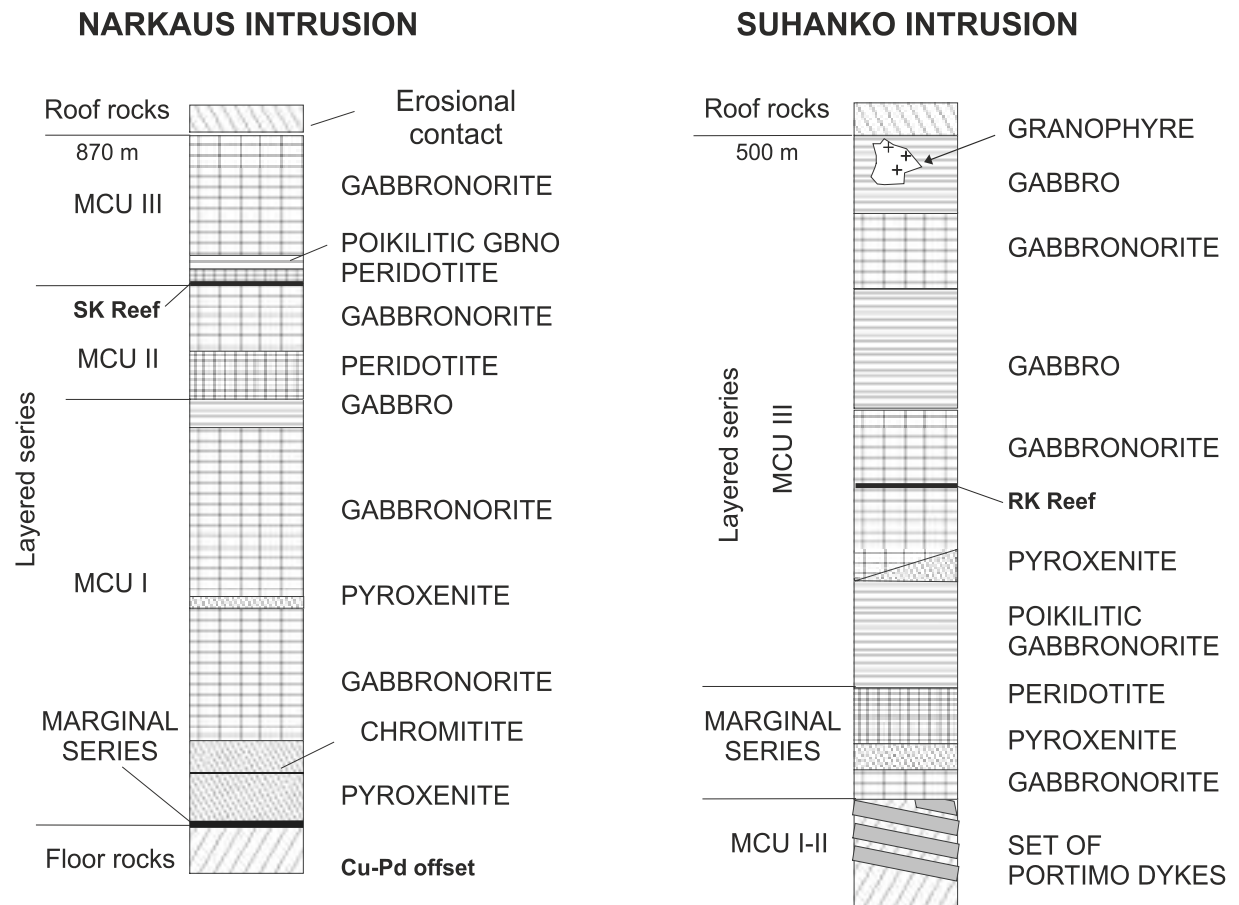


Fig. 2. Cumulus stratigraphies of the Narkaus and Suhanko Intrusions and the locations of the principal PGE occurrences. MCU, megacyclig unit. Modified after Iljina, 1994.

proper), hybrid gabbro and banded gabbro are arbitrary but the hybrid and banded gabbros are mapped to form a domain of its own. This division is due to the pattern that in many drill holes there are several sections of hybrid and banded gabbros (1 - 20 m in length) right next to each other, so that the two gabbro types together form a distinctive, mappable unit. This unit also contains basement gneiss blocks which are up to several tens of metres in size. The Mixing Zone 'gabbros' appears to be a result of the mechanical mixing of melted Archean gneiss and mafic magma and also the metasomatic recrystallization of the basement gneiss into mafic gneiss. The Mixing Zone seems to dip to form a depression structure, some tens of metres in diameter (Fig. 3) at the centre of the Konttijärvi igneous body.

Fine-grained, non-cumulate-textured gabbroic bodies up to a few tens of meters thick and several hundred meters long occur in the

Suhanko marginal series in many places. The chemical composition of these bodies seems to vary along the strike as the Ahmavaara bodies turned out to have distinctly higher Cr content than bodies in the SE tip of the Suhanko Intrusion, Niittylampi area (Table 3). The chemical composition of the Niittylampi bodies is similar to the mean composition of the Suhanko Intrusion, while the Ahmavaara one differs from it by higher chromium content. The chemical features and the mode of occurrence of these plagioclase-two pyroxene rocks have led to the interpretation that the bodies are autoliths and representatives of chilled margin rocks that were disrupted and entrained by subsequent magma pulses (Iljina, 1994).

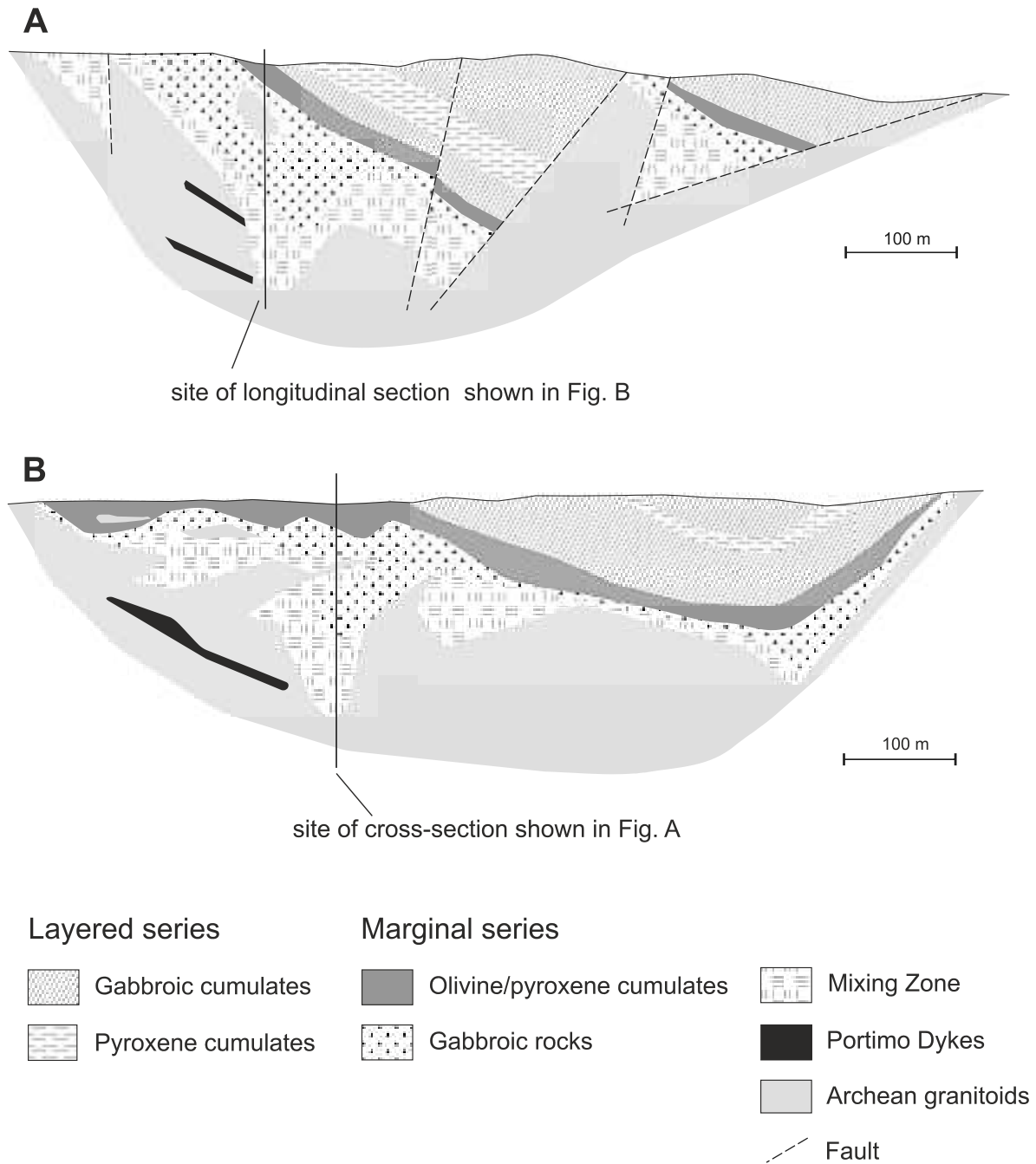


Fig. 3. Cross-section (A) and longitudinal section (B) of the Konttijärvi Intrusion. Modified after Iljina and Hanski, 2002.

An iron-rich ultramafic pegmatoidal mass two hundred meters in diameter is found in the western limb of the Suhanko Intrusion, (the Ahmavaara block, Fig. 1) where it is located above the ‘anticline’ of the base of the intrusion (Fig. 6). Magnetic measurements and drill hole evidence suggest that the

pegmatite forms a pipe-like body, which dips perpendicularly to the magmatic layering of the hosting cumulates. Comparable pegmatites have also been reported by Mutanen (1997) in the Koitelainen Intrusion, where ultramafic pegmatoids (clinopyroxenites rich in magnetite and ilmenite) occur as pipes and veins.

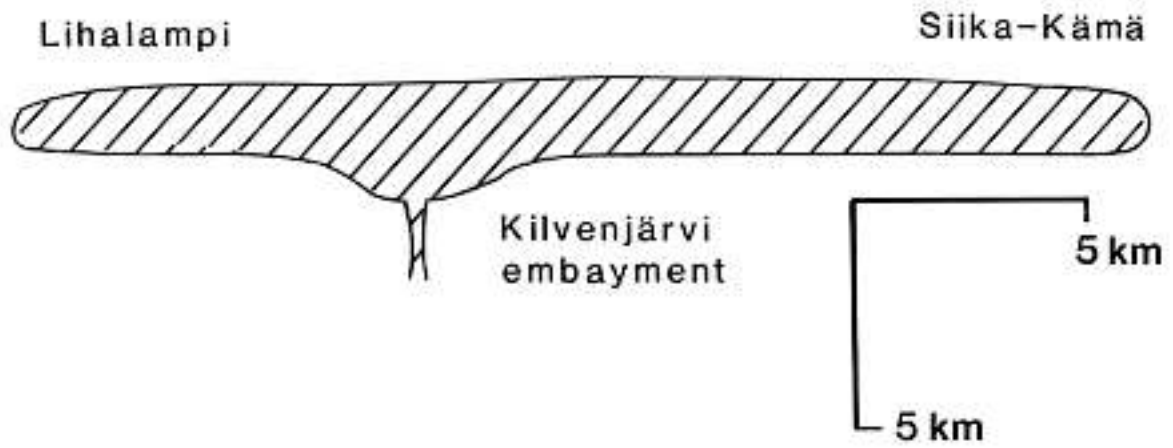


Fig. 4. Schematic cross-section of the initial Narkaus Intrusion. Modified after Iljina, 1994.

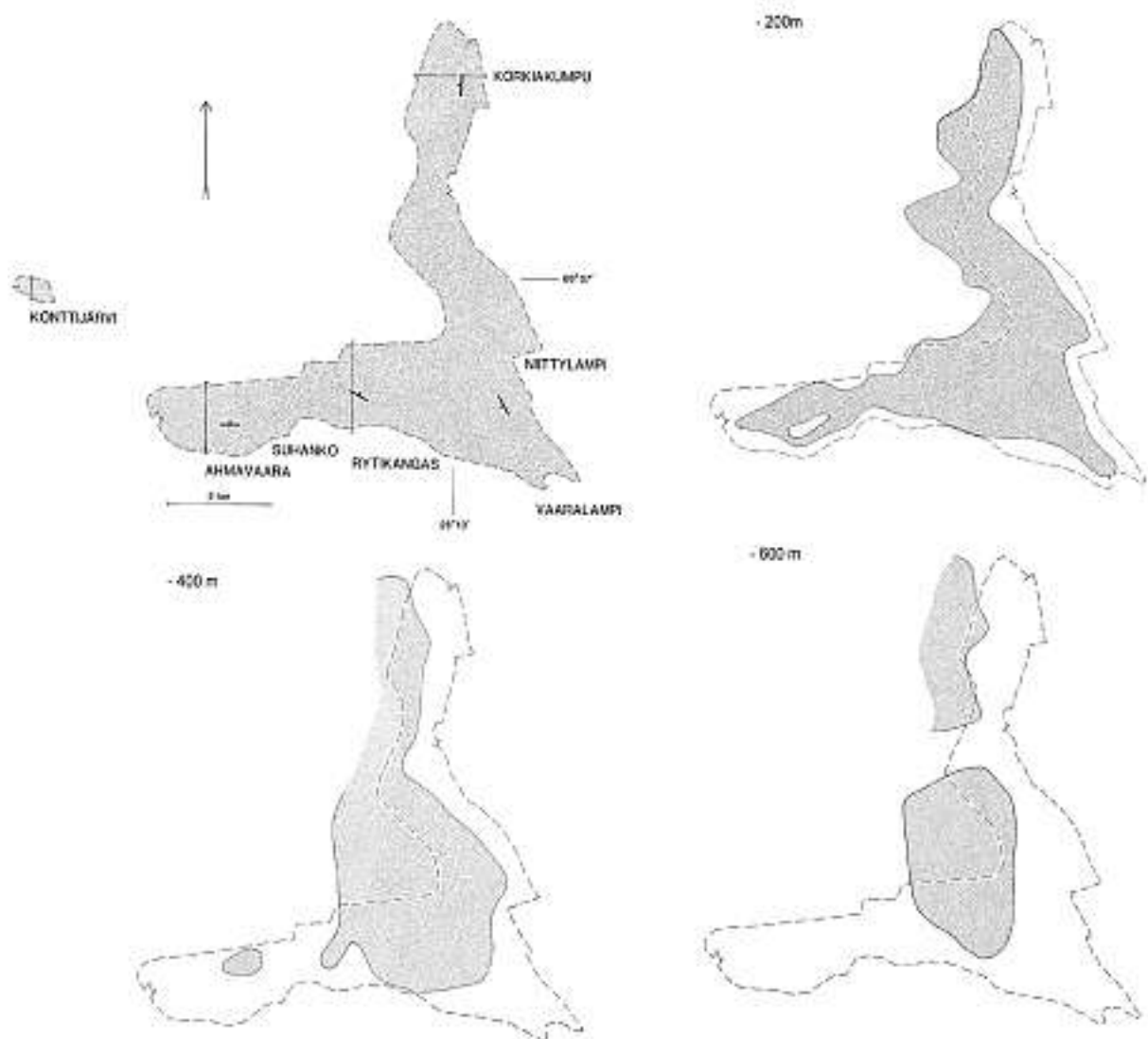


Fig. 5. Plan view and horizontal cross-sections at depths of 200, 400 and 600 metres of the Suhanko Intrusion. Sites of the vertical cross-sections depicted in the figure 6 are also shown. Modified after Pernu et al., 1986.



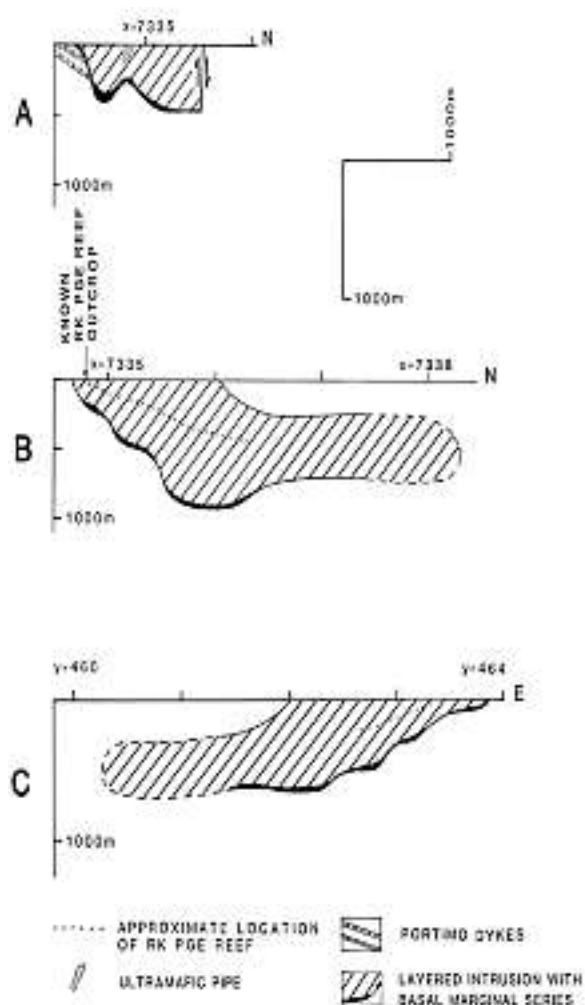


Fig. 6. Three vertical cross-sections through the Suhanko Intrusion. Sites marked on the figure 5. A, Ahmavaara; B, Rytikangas and C, Korkiakumpu. Modified after Pernu et al., 1986.

### Three-dimensional structure of the portimo complex

Various types geophysical measurements carried out on the Suhanko Intrusion reveal its three-dimensional structure fairly well, and this will be described below. Conversely, there are only few gravimetric profiles available which cross the Narkaus Intrusion, but these do serve to indicate that the intrusion blocks plunge beneath the roof rocks at a medium angle (corresponding to the dip of the layering), reaching the depth of almost one kilometre from the present erosion surface.

Figure 4 shows a hypothetical longitudinal cross-section for the Narkaus Intrusion. The cumulate layers are at their thickest in the Kilvenjärvi block, which seems to be a structural embayment in the Narkaus Intrusion, otherwise interpreted as sheet-like in form. The present cross-section of the Narkaus Intrusion resembles that of the Penikat Intrusion. Moreover, the feeder channel for the Narkaus Intrusion can be hypothesized beneath the Kilvenjärvi block.

The Suhanko Intrusion has estimated present-day volumes of about 10 km<sup>3</sup>. Figures 5 and 6 present horizontal sections through the Suhanko Intrusion at three depths and three

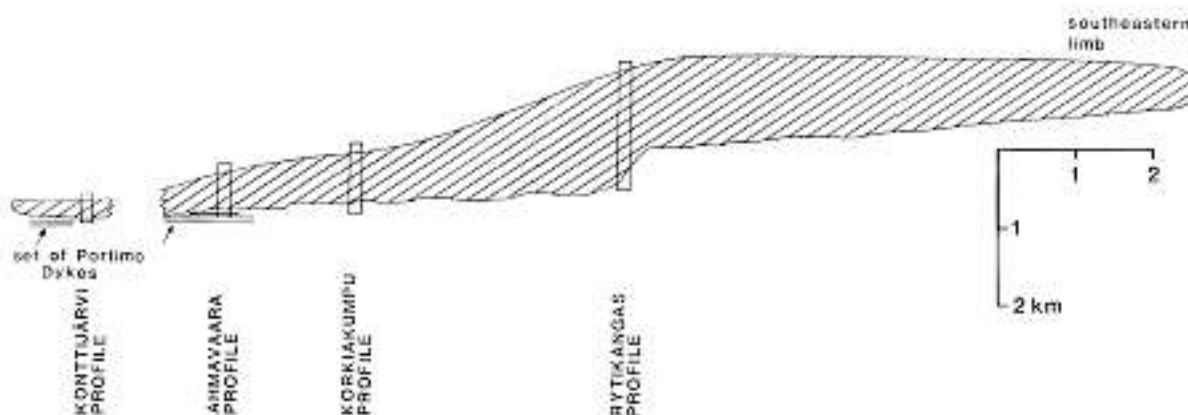


Fig. 7. Schematic cross-section of the initial Suhanko Intrusion. Modified after Iljina, 1994.



vertical cross-sections. The significant feature is that the central and northern parts of the Suhanko Intrusion plunge under the roof rocks at a low angle, reaching a depth of the order of one kilometre relative to the present erosional surface. The lower contact of the intrusion is 'transgressive', with the base of the southeastern tip was much higher than that of the western and northern limbs if we rotate the intrusion into its original position (Fig. 7). The western limb of the Suhanko Intrusion, the Ahmavaara block, is relatively shallow

and can be divided into southern and northern embayments, separated from each other by an east-west-trending 'anticline' (Fig. 6A). The southeastern tip of the Suhanko Body is even shallower, and only marginal series cumulates are preserved, the overlying cumulates having been eroded away.

In view of their cumulus stratigraphy and chemistry, the Ahmavaara section is interpreted as representing the deepest section of the original Suhanko Intrusion.

## DIVERSE CU-NI-PGE MINERALISATIONS IN THE PORTIMO COMPLEX

Among the layered intrusions, the Portimo Complex is exceptional in hosting a variety of PGE mineralisations (Figs. 8-13). The principal mineralisation types are:

- PGE-bearing Cu-Ni-Fe sulphide disseminations in the marginal series of the Suhanko and Konttijärvi Intrusions
- predominantly massive pyrrhotite deposits located close to the basal contact of the Suhanko Intrusion
- the Rytikangas PGE Reef in the layered series of the Suhanko Intrusion
- the Siika-Kämä PGE Reef in the Narkaus layered series
- the offset Cu-PGE mineralisation below the Narkaus Intrusion

The first two represent a mineralization type defined recently as a 'contact style' mineralization. Four other PGE enrichment types are depicted in Fig. 13. These are 1) the PGE enrichment in the Portimo Dykes below the Konttijärvi and Ahmavaara marginal series, 2) the PGE concentrations near the roof of the Suhanko Intrusion, associated mostly with pegmatites, 3) a Pt-anomalous pyroxenitic pegmatite pipe in the western limb of the Suhanko Intrusion and 4) chromite and silicate-associated PGE enrichments in the lower parts of the Narkaus Intrusion and MCU II.

### **Disseminated PGE-bearing base metal sulphide mineralisations**

Disseminated PGE-bearing base metal sulphide mineralisations, normally 10–30 m in thickness, occur throughout the marginal series of the Suhanko and Konttijärvi Intrusions (Figs 8 and 13). Their distribution is erratic and they generally extend from the lower peridotitic layer downwards for some 30 m into the basement. The PGE contents vary from only weakly anomalous values to 2 ppm in most places in the marginal series of the Suhanko Intrusion but rise to > 10 ppm in several samples in the Konttijärvi and Ahmavaara areas.

Fig. 8 depicts the variation of copper, precious metals and Se/S ratio in one representative drill hole of the Konttijärvi marginal series. Whole-rock PGE seems to have a good correlation with copper, Se and Se/S. At the depth of approx. 170 m, PGE drops and so do the elements and the ratio mentioned. The copper-deficient sulphide mineralization seems to continue further away from the intrusion. Further downhole the PGE kick associated with the high alkali dyke is accompanied by elevated Cu, Se and Se/S, but these components do not correspond to the higher S peak closer to the end of the hole.

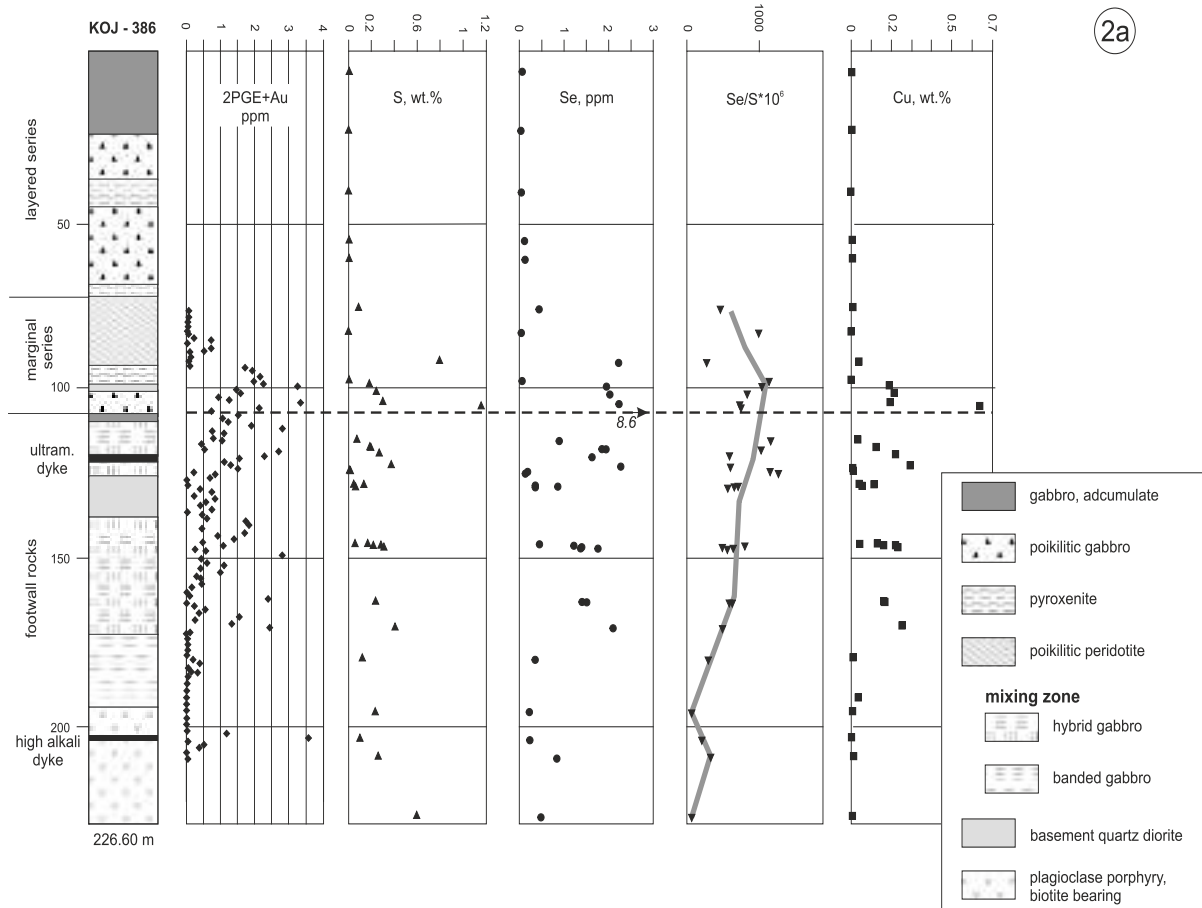


Fig. 8. Stratigraphic sequence of the Konttijärvi marginal series showing variations in bulk Pt+Pd+Au, S, Se, Se/S and Cu. For structural position see 2a in Fig. 13.

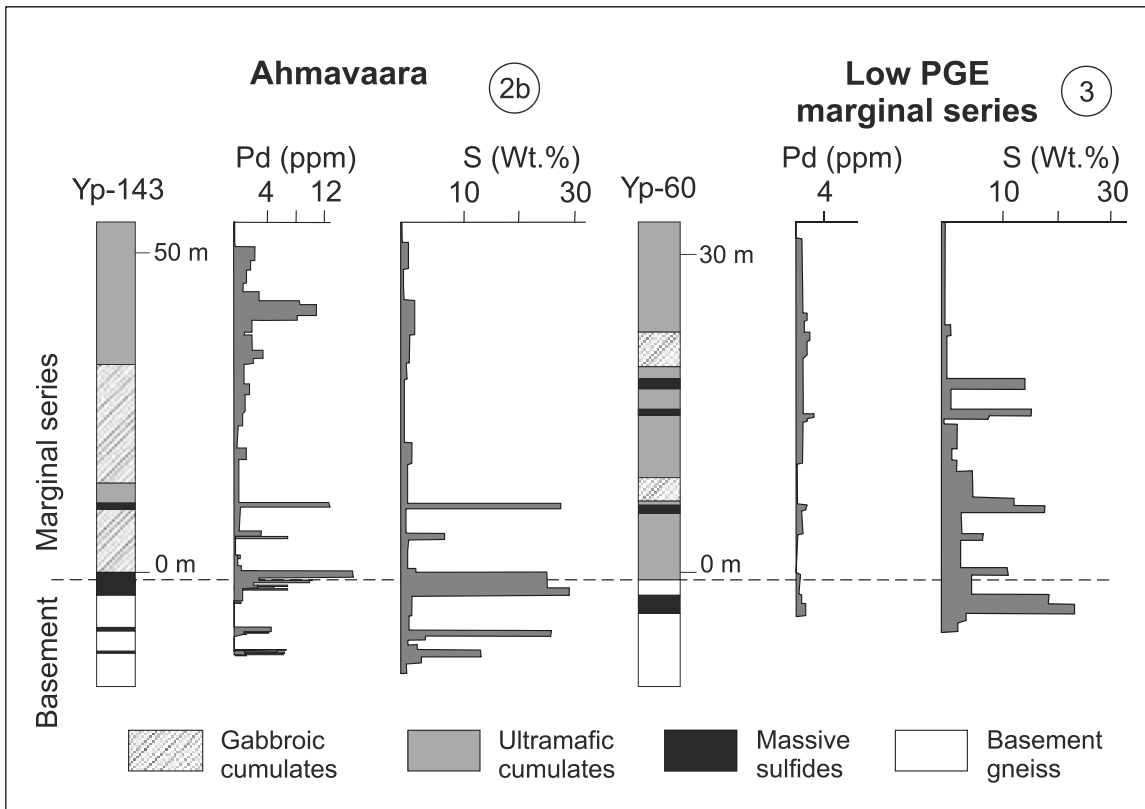


Fig. 9. Comparison of the Ahmavaara deposit and one low grade, disseminated and massive sulphide deposit of the Suhanko Intrusion (Suhanko proper, Fig. 1). For structural position see circles 2b and 3 in Fig. 13. Modified after Iljina et al., 1992.

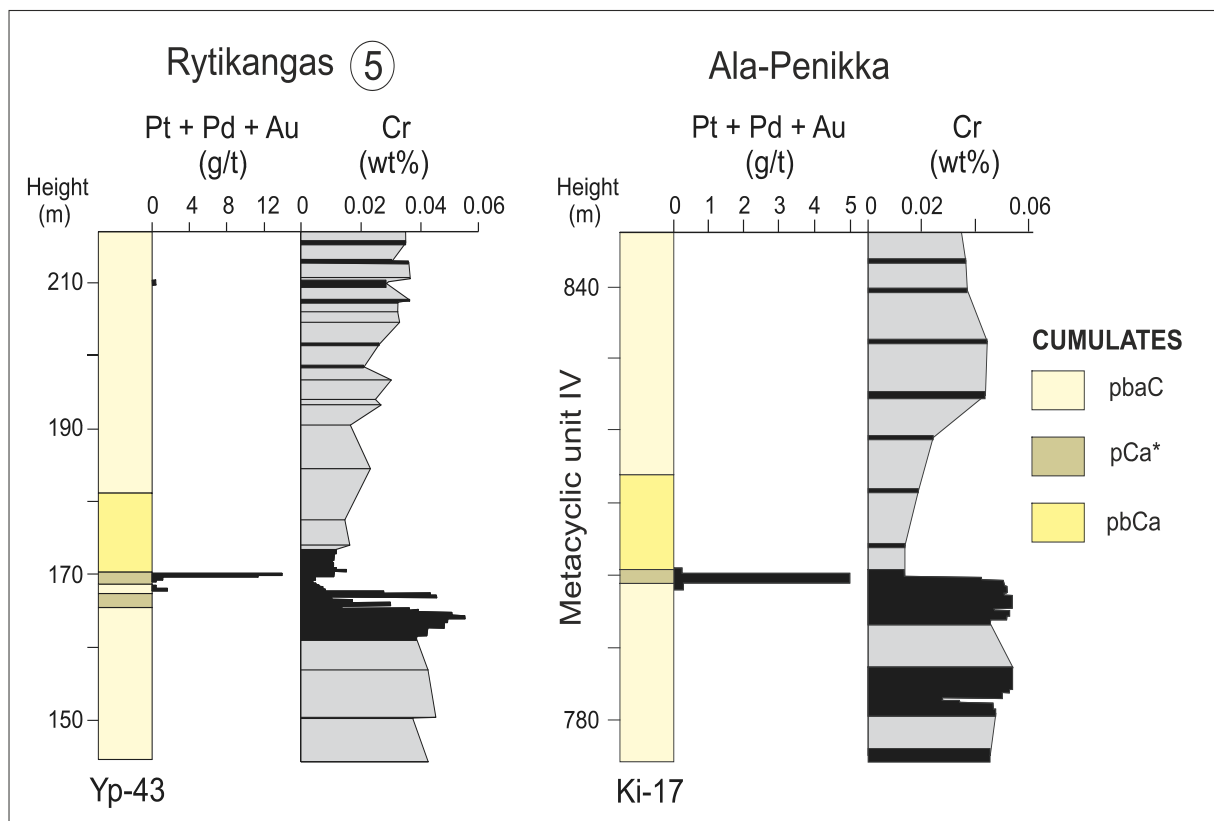


Fig. 10. Comparison of the Rytikangas (RK) and Ala-Penikka PGE Reefs from the Suhanko and Penikat Complexes, respectively. For structural position of the RK Reef see circle 5 in Fig. 13. Modified after Iljina *et al.*, 1992.

### Massive sulphide mineralisations

Massive sulphide mineralisations are characteristic of the marginal series of the Suhanko Intrusion. They are in the form of dykes and obviously also plate-like bodies conformable to layering and generally vary in thickness from 20 cm to 20 m. The mineralisations also vary in location from 30 m below the basal contact of the intrusion to a position 20 m above it and range in size from less than 1 million tonnes to more than 10 million tonnes. The sulphide paragenesis is composed almost exclusively of pyrrhotite, except in the Ahmavaara deposit, which also contains chalcopyrite and pentlandite. The massive pyrrhotite deposits show relatively low PGE values with the maximum Pt + Pd normally reaching a few ppm (exemplified by circle 3, Figs 9 and 13), however, similarly to the marginal series disseminated sulphide mineralisations of the same intrusion (see above), the PGE concentrations are generally much higher in the Ahmavaara deposit, attaining a level of 20 ppm (exemplified by circle 2b, Figs 9 and 13). The drilling results

shows also that the low-PGE grade Suhanko (proper) massive sulphide deposit locates physically above the Rytikangas Reef due to 'transgressive' nature of the Suhanko marginal series (Iljina *et al.*, 1992).

### Rytikangas PGE Reef

The Rytikangas PGE Reef represents the main PGE occurrence in the layered series of the Suhanko Intrusion (Figs 10 and 13), located in the middle of the western limb, ~170 m above the base of the intrusion. Its position is known over a distance of 1.5 km. The Rytikangas Reef is hosted by poikilitic plagioclase, plagioclase-bronzite, and plagioclase-bronzite-augite orthocumulates, all containing augite oikocrysts. This cumulate series overlies a 70 m sequence of monotonous plagioclase-bronzite-augite adcumulates and underlies 10 m of homogeneous plagioclase-bronzite mesocumulates with nonpoikilitic intercumulus augite. The orthocumulate layer varies in thickness from 30 cm to 10 m. The thickness of the Reef itself is 30–50 cm and it typically occurs on top of the poikilitic

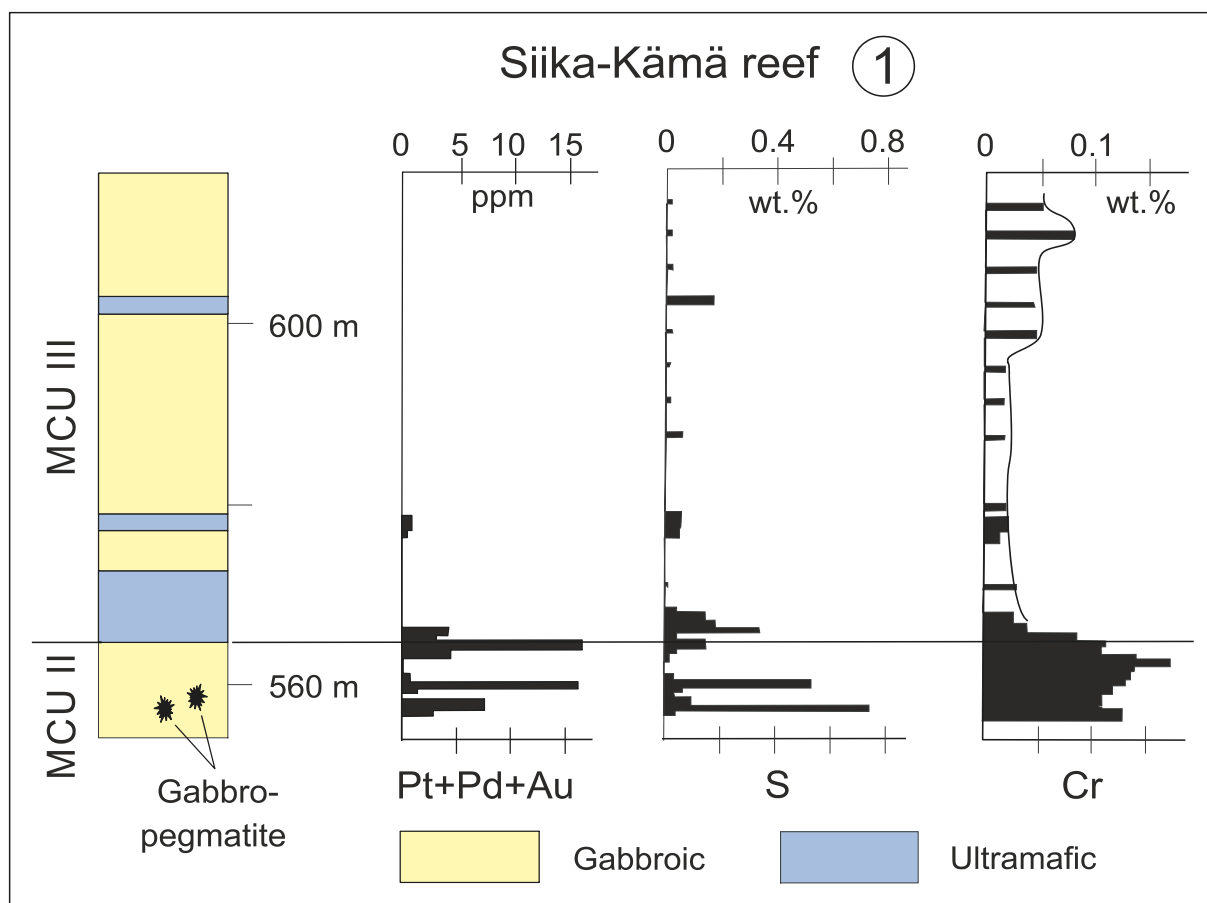


Fig. 11. Cumulus stratigraphy and variation of the precious metals and S and Cr, Siika-Kämä PGE Reef, Narkaus Intrusion. For structural position see circle 1 in Fig. 13. Metal data from Huhtelin et al., 1989.

orthocumulate layer. The cumulus stratigraphy and drop in the whole-rock Cr content across the Rytikangas Reef is practically identical to those of the Ala-Penikka Reef of the Penikat Intrusion (Fig. 10).

### Siika-Kämä PGE Reef

The Siika-Kämä PGE Reef of the Narkaus Intrusion is most commonly located at the base of MCU III (Figs 11 and 13), but it can lie somewhat below that or in the middle of the olivine cumulate layer of MCU III. Chlorite-amphibole schist similar to that at the Sompujärvi PGE Reef in the Penikat Intrusion commonly hosts the Siika-Kämä Reef. In some parts of the reef, the PGE mineralisation is accompanied by chromite seams or chromite disseminations. The thickness of the reef varies from less than one meter to several meters, and many drill holes penetrate a number of mineralized layers separated by PGE-poor layers, which can be several meters thick. The

PGE concentration varies from anomalous values of several hundred ppb to tens of ppm. Some gabbroic pegmatites, abundant in the uppermost gabbroic adcumulates tens of meters below MCU III, are also mineralized and can contain several ppm of Pd and Pt. The Siika-Kämä mineralisation is one of the most sulphide-deficient PGE mineralisations in the Portimo Complex, in some places containing no visible sulphides and rarely exceeding a whole-rock sulphur content of 1 wt%.

### Offset Cu-Pd mineralisation

The offset mineralisation is sporadically distributed in the basement gneisses and granites below the Narkaus Intrusion. The largest deposit, and also the best-known, is situated below the Kilvenjärvi Block (Figs 1, 12 and 13). This deposit is composed of a cluster of closely grouped smaller occurrences and is located in and near a N-trending major fault zone some tens of meters wide, against

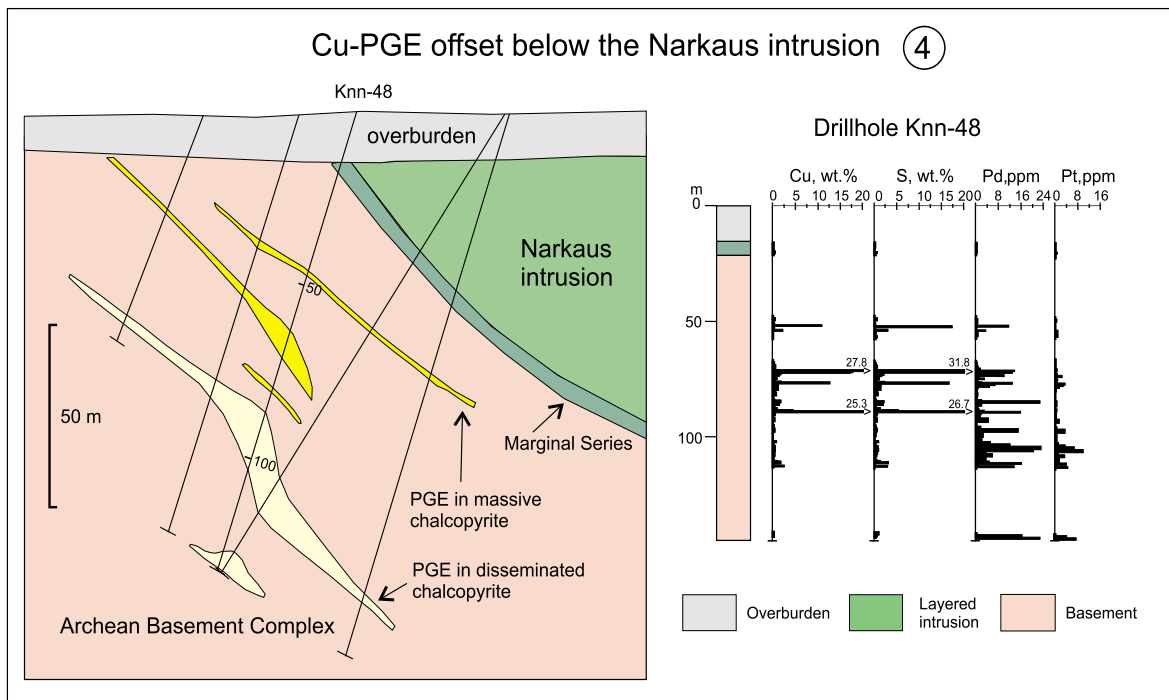


Fig. 12. Off-set Cu-Pd deposit at Kilvenjärvi below the Narkaus Intrusion. For structural position see circle 4 in Fig. 13. Metal data from Huhtelin et al., 1989.

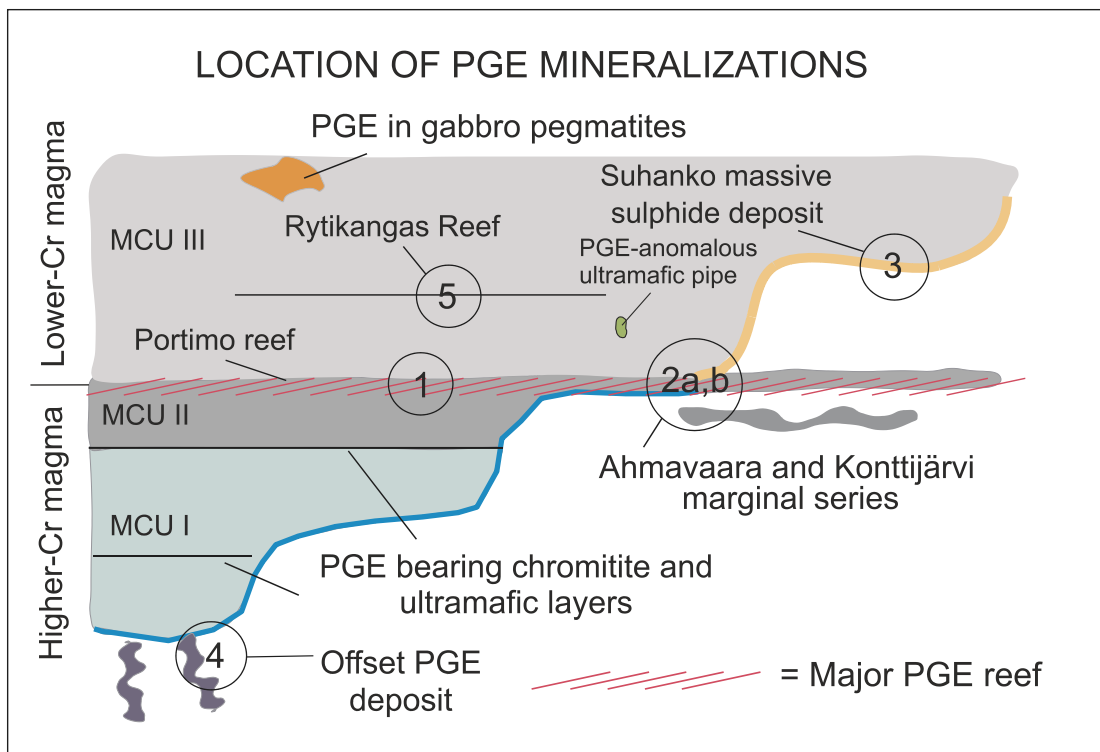


Fig. 13. Schematic presentation of the locations of the various PGE enrichments encountered in the Portimo Layered Igneous Complex. The circled numbers refer to the figures 8-12 in this paper. Modified after Iljina, 1994.

which the Kilvenjärvi Block terminates. The offset mineralisation represents the richest PGE deposit type within the Portimo area with Pt+Pd contents reaching up to 100 ppm. The offset mineralisation is predominantly a Pd deposit, as it has a much higher Pd/Pt ratio than the other Portimo deposits (or any other Tornio-Näränkäväära Belt PGE deposit) and is extremely low in Os, Ir, Ru, and Rh. Furthermore, it is extremely irregular in form, containing disseminated sulphide-PGM 'clouds', massive sulphide veins or bodies, and breccias, in which sulphide veins brecciate granitoids. The proportions of base metal sulphides and PGM are highly variable, but the massive sulphide bodies are always rich in PGE, while some samples containing almost no visible sulphides can carry several tens of ppm of Pd. In general terms, the more sulphide-rich occurrences are situated closer

to the basal contact of the intrusion and those poorer in sulphides are encountered in a wider zone below the intrusion (Fig. 12).

Figure 13 shows the structural model for the Portimo Complex and the positions of the mineralisations described above, as interpreted by Iljina (1994). Taking the boundary of the two parental magmas as a reference level, it can be seen that the Siika-Kämä Reef and the highly mineralized Ahmavaara and Konttijärvi marginal series are located in the same positions in terms of magmatic stratigraphy. Accordingly, as a group they were referred to by Iljina (1994) as the Portimo Reef. Pulses of the earlier, higher-Cr parental magma are represented in the Konttijärvi and Ahmavaara areas by the Portimo Dykes lying immediately below the marginal series.

## COMPOSITION OF THE SULPHIDE FRACTION

The concentrations of sulphur and base and noble metals in the type samples (A) and their values when recalculated to 100 % sulphides (B), are presented in Table 1. The recalculation is based on the mineral analyses and on the assumption that the Cu in the Rytikangas Reef is partitioned between bornite, chalcopyrite and chalcocite in the ratio 65:25:10 and Ni between pentlandite and millerite in the ratio 50:50. The mineral assemblage pyrrhotite-pentlandite-chalcopyrite was used for the other mineralizations. The element concentrations, also recalculated to 100 % sulphides, marked by C, represent means of large number of samples.

The massive sulphide deposits at the base of the Suhanko Intrusion, except for Ahmavaara, proved to be poor in nickel and copper, as their concentrations in the sulphide fraction ranged from 0.48 to 2.2 wt.% Ni and from 0.37 to 2.4 wt.% Cu. In places, the olivine cumulates above have an even higher nickel content than the massive sulphides below. Conversely, the Ahmavaara deposit have a markedly higher nickel content than the others, 2.7 wt.% in

sulphide fraction

The sulphide fraction of the Portimo Dykes, the Konttijärvi marginal series, the mineralized upper Suhanko layered series and the Siika-Kämä Reef show high copper concentrations, 17.9-27.7 wt.%, and moderate nickel concentrations, 2.7 to 6.2 wt.%, while the Rytikangas Reef sulphide fraction has an even higher copper content. The five type samples had a mean of 29.4 wt.% Cu, and the average of 54 other samples was 38.7 wt.% (C, Table 1). On the other hand, the sulphur content of the type samples is very low, 34.2 wt.%, and 33.0 wt.% in a large number of cases, resulting in a Cu:S ratio above one, 1.2. This high ratio for the Rytikangas Reef is not a surface oxidation phenomenon, since it was also detected in the deep boreholes.

A high copper concentration in the sulphide fraction, although very variable, is found in the offset mineralization located below the Narkaus marginal series, where almost pure massive chalcopyrite dykes are found.



Table 1. A: Average whole-rock Ni, Cu, S, PGE and Au concentrations for selected type samples, with standard deviation in parentheses; B: concentrations in the type samples (n, number of samples), recalculated to 100% sulphide; C: metal concentrations in a large number of samples, recalculated to 100% sulphide. See text for further information. Data from Iljina (1994) and references therein.

		Ni(wt.%)	Cu	S	Os(ppb)	Ir	Ru	Rh	Pt	Pd	Au
<b>Portimo Dykes and sulphide disseminated marginal series</b>											
Portimo Dykes, n=1	A	0.025	0.093	0.183	3.0	0.5	-	2.0	510	2200	47
	B	5.0	18.5	36.5	598	99.7	-	399	101 700	438 700	9370
Konttijärvi marginal series, n=5	A	0.056 (0.040)	0.239 (0.170)	0.323 (0.200)	8.6 (8.3)	19.0 (12.9)	14.2 (10.0)	92 (72)	1 300 (710)	4 070 (3 260)	240 (110)
	B	6.1	25.9	35.0	930	2 060	1 540	9 970	140 800	440 900	26 000
	C'	5.4	14.4	36.7							
<b>Massive sulphide deposits of marginal series</b>											
Ahmavaara, n=3	A	2.00 (0.46)	0.719 (0.400)	25.8 (4.5)	20 (11)	50 (18)	44 (23)	357 (81)	1 510 (710)	11 030 (2 870)	104 (90)
	B	3.0	1.1	39	30	76	67	540	2 280	16 700	160
	C	2.7	2.4	37					2 120	15 200	
Suhanko, n=3	A	0.919 (0.140)	0.807 (0.240)	20.7 (3.8)	30 (20)	64 (27)	64 (41)	222 (60)	207 (76)	1 230 (184)	7.3 (2.5)
	B	1.7	1.5	39.1	57	120	120	420	390	2 320	14
	C	1.5	2.4	37							
Vaaralampi <sup>1</sup> n=2	A	0.284 (0.010)	0.143 (0.060)	23.3 (7.2)	25 (2.8)	8.5 (3.5)	89 (22)	24 (21)	-	485 (21)	5.0 (2.8)
	B	0.48	0.24	39.5	42	14	151	41		820	8.5
	C	0.94	0.63	37							
Niittylampi, n=2	A	1.67 (0.06)	0.305 (0.030)	32.7 (0.7)	23 (5.7)	79 (9.9)	36 (11)	550 (14)	136 (83)	835 (7.1)	19 (11)
	B	2.0	0.37	39.2	28	95	43	660	160	1 000	23
	C	2.2	1.6	37					870	2 190	
Yli-Portimojärvi, n=2	A	0.456 (0.160)	0.575 (0.540)	24.9 (12.1)	-	111 (154)	-	199 (271)	171 (127)	930 (636)	7.0 (5.7)
	B	0.72	0.91	39.4		180		310	270	1 470	11
<b>Layered series</b>											
Siika-Kämä Reef <sup>2</sup> n=4	A	0.080 (0.074)	0.360 (0.191)	0.454 (0.229)	32 (14)	65 (35)	47 (36)	330 (151)	2 850 (1 125)	9 980 (6 120)	337 (324)
	B	6.2	27.7	34.9	2 460	5 000	3 610	25 370	219 000	766 900	25 910
Rytikangas Reef, n=5	A	0.063 (0.080)	0.249 (0.190)	0.291 (0.330)	28 (27)	32 (24)	24 (18)	171 (123)	1 630 (427)	7 240 (2 460)	207 (145)
	B	7.4	29.3	34.2	3 290	3 760	2 820	20 100	191 600	850 900	24 300
	C''	6.4	38.7	33.0							
Mineralized upper Suhanko layered series, n=2	A	0.035 (0.020)	0.231 (0.090)	0.492 (0.110)	23 (3.5)	27 (5.0)	76 (14)	53 (7.0)	605 (105)	1270 (290)	40 (0)
	B	2.7	17.9	38.2	1 790	2 100	5 900	4 120	47 000	98 600	3 100

Table 1 also shows the PGE and Au concentrations in the sulphide fraction, in rows B and C. The noble metal concentrations are seen to increase with increasing copper content. The palladium content of the sulphide fraction in the Konttijärvi marginal series, the Portimo Dykes, the Rytikangas Reef and the Siika-Kämä Reef (all copper-rich) ranges between 450 and 850 ppm. A good impression of how high these values are can be obtained

by comparing them with one of the main platinum sources in the world, the Merensky Reef, for example, which contains only 120 ppm Pd and 280 ppm Pt (Naldrett, 1989).

Among the massive sulphides, the highest palladium and platinum concentrations are found in the Ahmavaara deposit 15.2 ppm Pd and 2.1 ppm Pt, while the others have 0.8-2.3 ppm Pd and 0.2-0.9 ppm Pt, but there were

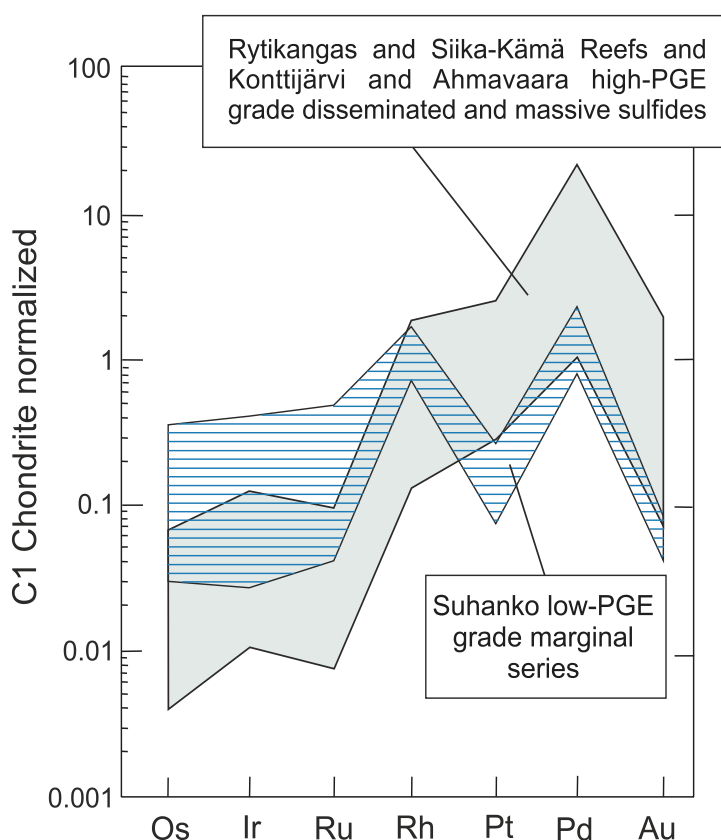


Fig. 14. Chondrite-normalized PGE and Au patterns of the Siika-Kämä and Rytikangas PGE reefs, Konttijärvi and Ahmavaara high-grade PGE disseminated and massive sulphide deposits and lower-grade PGE massive sulphide deposits of the Suhanko marginal series. Data from Iljina, 1994.

no essential differences in the concentrations of the other platinum-group elements. The sum of osmium, iridium, ruthenium and rhodium in the Ahmavaara deposit was 0.7 ppm, while elsewhere it was 0.2 to 0.8 ppm. As far as their PGE grade is concerned, the Ahmavaara deposit find their counterpart in the Noril'sk deposit in Russia, where the reported concentrations are 10.8 ppm Pd and

3.7 ppm Pt in 100% sulphides (cf. Naldrett *et al.*, 1992). On the other hand, the PGE in sulphide fraction of the less PGE mineralized Suhanko (proper), Vaaralampi, Niittylampi and Yli-Portimojärvi massive pyrrhotite deposits is close those values found in the Sudbury, where the reported averages are 1.15 ppm Pt and 1.25 ppm Pd (Levack West, Main ore, Naldrett, 1989).

## PGE RATIOS AND CHONDRITE-NORMALIZED DISTRIBUTION PATTERNS

The Pd/Pt, Pd/Ir and (Pt+Pd)/(Os+Ir+Ru) ratios are presented in Table 2. All the mineralizations are characterized by a predominance of palladium over platinum, and only the Siika-Kämä Reef shows platinum domination in some places, as well as in the chromite and silicate-associated PGE enrichments of the MCU II. The Konttijärvi high PGE-grade marginal series, the Ahmavaara massive sulphide deposit and the Rytikangas and Siika-Kämä PGE Reefs

have similar Pd/Ir and (Pt+Pd)/(Os+Ir+Ru) ratios. The above metal ratios were higher in the Portimo Dykes, where they were 3840 and >267, respectively, but were distinctly lower in the low PGE-grade massive sulphide ores and in the mineralized Suhanko upper layered series (Pd/Ir=6.3 to 43, and (Pt+Pd)/(Os+Ir+Ru)=2.3 to 14.2), while the offset mineralization showed extremely high ratios (>12 900 and >687, respectively).

The chondrite-normalized distribution patterns are presented in Fig. 14. Comparing the PGE mineralizations found on or slightly above the transition zone between the Cr-MgO richer and Cr-MgO poorer parental magmas, it is noted that the Portimo Dykes, Konttijärvi and Ahmavaara disseminated high PGE-grade marginal series, the Ahmavaara massive sulphides and the Rytikangas and Siika-Kämä

Reefs have very similar patterns, all possessing quite a steep positive slope and a depletion in ruthenium content, thus differing greatly from the low-PGE grade pyrrhotite deposits, which do not have such a steep positive slope. The low-PGE-grade massive sulphide deposits seem to have a negative platinum anomaly instead of the negative ruthenium anomaly.

Table 2. Pd/Pt, Pd/Ir and (Pt+Pd)/(Os+Ir+Ru) ratios in the various mineralizations. The limits of variation are in parenthesis. N, number of samples. Data from Iljina (1994) and references therein.

	N	Pd/Pt	Pd/Ir	(Pt+Pd)/(Os+Ir+Ru)
<b>Offset, Portimo Dykes and Konttijärvi marginal series</b>				
Offset	1	6.7	>12 900	>687
Portimo Dykes <sup>3</sup>	2	3.4 (2.6-4.3)	3 840 (3 270-4 400)	>267
Konttijärvi marginal series	5	3.0 (1.4-4.0)	212 (138-429)	141 (67-300)
<b>Massive sulphide deposits of marginal series</b>				
Ahmavaara	3	8.0 (6.2-10.3)	243 (114-335)	116 (64-175)
Suhanko	3	6.6 (4.5-9.3)	20.6 (15.2-24.3)	10.5 (6.6-14.2)
Vaaralampi	1	3.6	42.7	4.2
Niittylampi	2	7.6 (4.3-10.9)	10.7 (9.7-11.7)	7.1 (6.8-7.3)
Yli-Portimojärvi	1	5.3	6.3	2.3
<b>Layered series</b>				
Rytikangas Reef	5	4.4 (3.7-5.1)	270 (147-382)	132 (77-184)
Siika-Kämä Reef	8	1.7 (0.8-3.0)	83.6 (32.1-132)	62.2 (41.7-93.3)
Mineralized upper Suhanko layered series	2	2.1 (2.0-2.2)	46.6 (44.5-48.6)	14.9 (14.4-15.4)
Chromitite layer, MCU I	1	3.8	17.1	5.6
Chromite and, silicate-associated PGE, MCU II	3	0.9	49.8	43.1

## DISCUSSION ON PARENTAL MAGMA COMPOSITION

In order to evaluate the composition of 'Portimo' parental magmas Table 3 gives some analyses of the Portimo Dykes and the fine-grained marginal rocks, Konttijärvi Mixing Zone gabbros and weighted averages of the Suhanko Intrusion and MCU I of the Narkaus Intrusion. For comparison, the same table shows the composition of the Loljunmaa dyke (thought to be coeval with the lower Penikat Intrusion) as well as sills from the Bushveld and Stillwater Complexes.

Figure 15 depicts chondrite-normalized REE patterns of the Konttijärvi gabbroic cumulates, Mixing Zone gabbros and Ahmavaara and Niittylampi auloliths. These are compared with the Bushveld sills. The figure also shows the patterns in some dykes depicted in Fig. 8 and the Archean quartz diorite gneiss below the Konttijärvi Intrusion.

Two groups can be distinguished on the basis of whole-rock Cr and MgO content: an earlier magma type richer in Cr and MgO and subsequently intruded magma type poorer in Cr in MgO. The whole-rock main and trace element (except REE) of the Portimo Dykes and Ahmavaara auloliths resemble each other and the MCU I of the Narkaus Intrusion. Conversely, the composition of the Niittylampi auloliths corresponds closely to

the weighted average of the Suhanko Intrusion (Cr-MgO poorer type).

The normalized REE pattern in the Portimo Dykes almost equals that of the Bushveld B1 sill and correspondingly the patterns of the Niittylampi auloliths resemble Bushveld sills adjacent to the Main Zone (~B3 magma). The Ahmavaara auloliths differ slightly from the Niittylampi ones in that they have slightly higher LREE. The Konttijärvi Mixing Zone gabbros seem to plot between the Portimo Dykes and Ahmavaara auloliths.

The conclusion is made that the Portimo Dykes give close approximation to the chemical composition of the MCU I and II of the Narkaus Intrusion while the Niittylampi auloliths are the best representatives of the magma which gave rise to the Narkaus MCU III and the Suhanko and Konttijärvi Intrusions. The main chemical features of the Portimo Dykes are high magnesium and chromium concentrations and a high SiO<sub>2</sub> content. Magmas of this type have been described either as an ancient counterpart to modern boninites or as 'siliceous, high-Mg basalt' formed from a komatiitic melt by assimilation-fractional crystallization processes. The subsequently intruded magma type was poorer in Cr and MgO and had more tholeiitic affinity.

## CONCLUDING REMARKS ON THE MARGINAL SERIES HOSTED MINERALIZATION

The following west-to-east trends can be observed in the Konttijärvi and Suhanko Intrusion areas (Fig. 7):

- The spatial frequency of massive sulphide accumulations increases from west to east.
- The lower contact of the Suhanko Intrusion is 'transgressive' with the base of the southeastern tip, which was much higher than that of the western limb. Drilling evidences show that the Rytikangas Reef is located physically below the Suhanko proper massive sulphide deposit.

- The most extensive interaction (Mixing Zone) between mafic magma and footwall rocks is found in the west (Konttijärvi).
- The Cu, Ni and precious metal concentrations in the whole-rock and the sulphide fraction are highest in the west (Konttijärvi and Ahmavaara areas).
- The relative proportion of ultramafic cumulates of the entire stratigraphic section through the marginal series and overlying layered series is highest in the west (Konttijärvi section).

Table 3. Chemical compositions for the evaluation of the parental magmas.

wt.%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SiO <sub>2</sub>	52.2	51.3	51.7	52.7	53.5	53.4	53.4	54.0	51.4	52.0	56.1	50.7	49.9	50.4	52.6	45.1	53.5	54.5	55.7	57.0	57.4
TiO <sub>2</sub>	0.15	0.12	0.19	0.33	0.21	0.24	0.30	0.16	0.40	0.68	0.34	0.22	0.53	0.23	0.19	0.25	0.44	0.44	0.63	0.29	0.47
Al <sub>2</sub> O <sub>3</sub>	16.1	17.1	16.8	16.9	13.4	12.2	9.8	3.2	8.0	12.3	11.5	14.2	13.6	16.9	11.5	20.1	15.4	13.0	15.6	6.0	19.4
FeO <sub>tot</sub>	7.4	5.9	7.1	7.3	9.7	9.9	10.5	7.9	12.0	10.2	9.5	7.1	11.6	6.1	8.7	9.1	8.0	8.5	7.8	10.0	6.3
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.1	0.2	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.1
MgO	9.8	10.6	7.9	9.0	12.6	13.7	15.1	23.3	13.8	13.0	13.0	14.7	11.3	11.7	18.5	13.9	8.4	9.7	8.2	17.3	6.2
CaO	10.9	12.2	11.8	10.7	8.0	8.0	9.2	9.9	11.0	9.3	6.7	11.6	10.1	13.0	7.1	9.5	10.6	10.4	5.4	8.3	2.1
Na <sub>2</sub> O	2.84	2.26	2.31	2.38	2.14	2.05	1.29	0.11	0.62	1.74	1.68	1.22	1.34	1.26	0.71	0.48	2.89	2.42	4.41	0.07	6.50
K <sub>2</sub> O	0.42	0.18	0.24	0.57	0.10	0.19	0.11	0.01	0.45	0.71	0.80	0.22	0.27	0.18	0.34	1.23	0.55	0.64	1.92	0.65	1.36
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.02	0.04	0.01	0.01	0.02	0.03	0.07	0.10	0.07	0.02	0.15	0.02	0.02	0.02	0.04	0.13	0.14	0.02	0.24
<b>ppm</b>																					
V	150	150	130		127	126	157	50	230		167			108	98	96	185	171	147	102	121
Cr	290	380	550	280	1137	951	1000	1800	2300	1100	1240	3330	640	583	754	355	264	477	354	1030	81
Ni	160	190	130	280	375	440	318	610	250	360	295	270		255	399	1038	162	456	703	893	80
Zn	60	58	56		83	81	79	85	160	130	78		86	48	63	113	75	106	101	177	86
Sc	33	35	31		28	29	30	23	37	28		32		26	27	25	32	39	31	37	12
Sr	340	500	330	210	382	308	157	10	20	200	160	150		249	71	319	907	681	316	10	263
Y	2.5	1.0	1.1		4.1	4.9	6.2	4.8	7.0	2.0	13			4.7	3.6	4.6	6.3	11	13	10	10
Zr	30	1.0	26	47	10	10	15	20	40	70	77	25		13	10	10	10	10	81	27	76
Nb	2.7	1.9			<0.2	0.34	0.22	1.9	2.0	<2.0	3.6			<10	<10	<10	<10	<10	<10	<10	<10
Ba	110	52	180		68	108	63	53	47	210		75	60	54	82	70	160	190	491	146	224
La	2.50	1.10	3.80		1.83	3.81	2.51		10.9	11.1	14.8		3.28	3.04	2.06	3.78	3.79	7.43	10.9	5.58	25.1
Ce	7.00	2.00	8.30		3.37	7.44	5.83		25.0	24.0	29.5		8.00	6.11	4.12	6.56	8.04	17.3	21.6	12.6	45.2
Nd	4.00	1.00			1.76	3.95	4.04		12.0	12.0	12.1		8.90	3.03	2.24	3.51	5.85	12.1	12.3	7.09	17.2
Sm	0.75	0.37	0.86		0.26	0.53	0.77		2.50	2.60	2.70		1.29	0.70	0.41	0.72	1.30	2.64	2.83	1.73	2.56
Eu	0.32	0.26	0.52		0.37	0.52	0.38		0.61	0.78	0.72		0.58	0.30	0.22		0.69	0.88	0.98	0.36	1.20
Tb	0.20	<0.10			<0.1	0.13	0.19		0.30	0.50	0.30		0.29	0.14	0.10	0.12	0.20	0.36	0.40	0.30	0.34
Yb	0.59	0.30	0.64		0.58	0.55	0.48		1.08	1.61	1.16		1.29	0.48	0.34	0.38	0.58	1.06	1.20	0.91	0.83
Lu	0.09	0.04	0.07		0.10	0.1	<0.10		0.16	0.26	0.15		0.20	<0.10	<0.10	<0.10	0.10	0.16	0.17	0.14	0.12
U	<0.10	<0.10			<0.2	<0.2	<0.2	0.80	1.20	0.40				0.20	0.20	0.20	0.20	0.20	0.83	0.59	0.66

1. Niittylampi autolith. Iijina, 1994.
2. Niittylampi autolith. Iijina, 1994.
3. Fine-grained marginal rock adjacent to the Main Zone/Bushveld Complex. Hatton and Sharpe, 1989).
4. Weighted average of the Suhanko Intrusion. Alapieti *et al.*, 1990.
5. Ahmavaara autolith. yp-517/109.9m.
6. Ahmavaara autolith. yp-517/115.5m.
7. Ahmavaara autolith. yp-517/126.4m.
8. Websterite Portimo Dyke. Konttijärvi. Iijina, 1994.
9. Websterite Portimo Dyke. Ahmavaara. Iijina, 1994.
10. Lojunmaa Dyke. Alapieti *et al.*, 1990.
11. Bushveld B1 Sill. Sharpe and Hulbert, 1985.
12. Weighted average of Narkaus MCUI. Alapieti *et al.*, 1990.
13. High-Mg gabbro. Konttijärvi sill. Stillwater Complex. Heltz, 1985.
14. Gabbro. Konttijärvi layered series. koj-386/6.1m.
15. Gabbro. Konttijärvi layered series. koj-386/23.3m.
16. Homogenous gabbro. Konttijärvi marginal series. koj-386/98.9m.
17. Hybrid gabbro. Konttijärvi koj-386/145.9m.
18. Hybrid gabbro. Konttijärvi koj-386/147.0m.
19. Hybrid gabbro. Konttijärvi koj-386/170.6m.
20. Ultramafic dyke. koj-386/119.5m.
21. High alkali dyke. koj-386/203.7m.

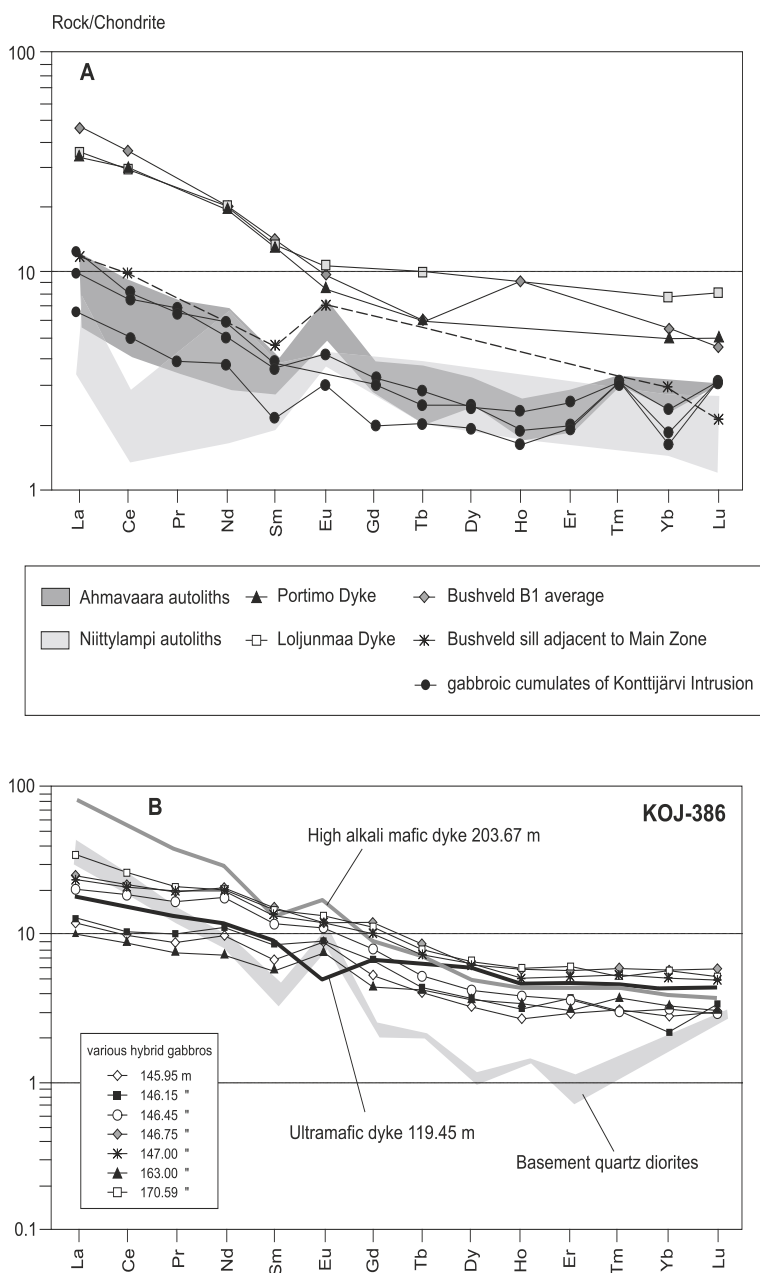


Fig. 15. Chondrite-normalized REE patterns, for discussion, see text.

- Observations of the Portimo Dykes, suggested to represent the earlier more Cr-MgO enriched parental magma, are restricted to the Konttijärvi and Ahmavaara areas.
- Chill margin rocks (autoliths) become less Cr and MgO bearing to the east. The ‘west to east’ change in whole-rock main and trace element concentrations of the autoliths (including REE) resembles the change from B1 to ~B3 type parental magma in the Bushveld Complex.
- Iljina and Lee (2005) demonstrated that the whole-rock Se/S ratio drops from west to east.

This is in line with the observation of Hattori *et al.* (2002), who concluded that high Se/S ratios are characteristic features of boninitic high-MgO second stage melts.

The last three of the above features support the conclusion that the westernmost part of the Suhanko-Konttijärvi area had an influx of the earlier Cr-MgO richer magma type (‘more boninitic’) and the metal enrichments are related to that influx and the mineralization of the eastern areas are related to the subsequently intruded magma type.



## DESCRIPTION OF EXCURSION SITES: KONTTIJÄRVI AND AHMAVAARA DEPOSITS

The locations of Konttijärvi and Ahmavaara PGE deposits in relation to the regional geology are shown in Fig. 16. Ahmavaara occurs at the western edge of the Suhanko Intrusion within a large regional embayment. Konttijärvi is separated from Ahmavaara by 3.5 km of barren Archaean basement rocks. Konttijärvi is regarded as a faulted offset and subsequent erosion of the Suhanko intrusion, because of the similar stratigraphic succession and style of mineralization as Ahmavaara.

The stratigraphy of the Konttijärvi – Suhanko intrusion consists of a thick layered series sequence dominated by gabbroic rocks, and of a relatively thin, contaminated and/or reverse fractionated marginal series. At Konttijärvi the marginal series below the marker peridotite and underlying pyroxenite comprises a single gabbroic to pyroxenitic unit with an average thickness of 2-10 metres. At Ahmavaara the corresponding zone has been divided into three stratigraphic units which typically have a combined thickness of approximately 30-60 metres. The Cu-Ni-PGE mineralization is hosted within the marginal series and extends in to the basement. The typical sulphide assemblage is pyrrhotite-chalcopyrite-pentlandite, and accessory sulphides include pyrite, sphalerite, galena and molybdenite. The main oxides are magnetite and ilmenite, with chromite in trace amounts. The grades of PGE mineralization roughly correspond with the abundance of sulphides, particularly chalcopyrite, and are generally higher at Konttijärvi than at Ahmavaara. The results of recent exploration demonstrate that primary magmatic mineralization within these deposits has been remobilized by hydrothermal processes.

The Konttijärvi deposit has a strike length of 1,000 metres. The thickness of open pit mineralization varies from 30 to 100 metres. The orebody dips north at between 30 and 40 in the central and western parts, to

between 10 and 20 in the eastern part. Down dip continuity of the main orebody (“Main Block”) is terminated by a normal fault which displaces the mineralized zone back to surface north of the fault. The northern fault block is known as Konttijärvi North. The northern extent of Konttijärvi North is terminated against a second normal fault. A reverse fault in the west of Konttijärvi results in Fault Block 1, which hosts the deepest known mineralization present, at approximately 250 m below surface.

The stratigraphic domains present at Konttijärvi deposit are summarised in Fig. 17. A plan view of exposed mineralization is shown in Fig. 18.

The Ahmavaara deposit has a total strike length of 2,700 metres of which the eastern 1000 metres is called Ahmavaara East. The deposit comprises two slab-shaped mineralized units with a combined total thickness varying from 20 to 60 metres. These well mineralized zones are usually separated from each other by a poorly mineralised gabbroic unit some 5-30 metres in thickness. The western part of Ahmavaara deposit dips northeast at between 70° along the southwestern margin to 5° at the northeastern side of the deposit. Ahmavaara East dips north at fairly constant 10-25°. The western and southern limits of the deposit are defined by fault-disrupted lithological contacts with Archaean basement rocks. The northern extent is limited by a normal fault and the northeastern part of the resource is currently terminated against a relatively small reverse fault. The deepest known marginal series mineralization at Ahmavaara is approximately 500 m below surface.

The stratigraphic domains present at Ahmavaara deposit are summarised in Fig. 19.

Mineral resource estimates based on July

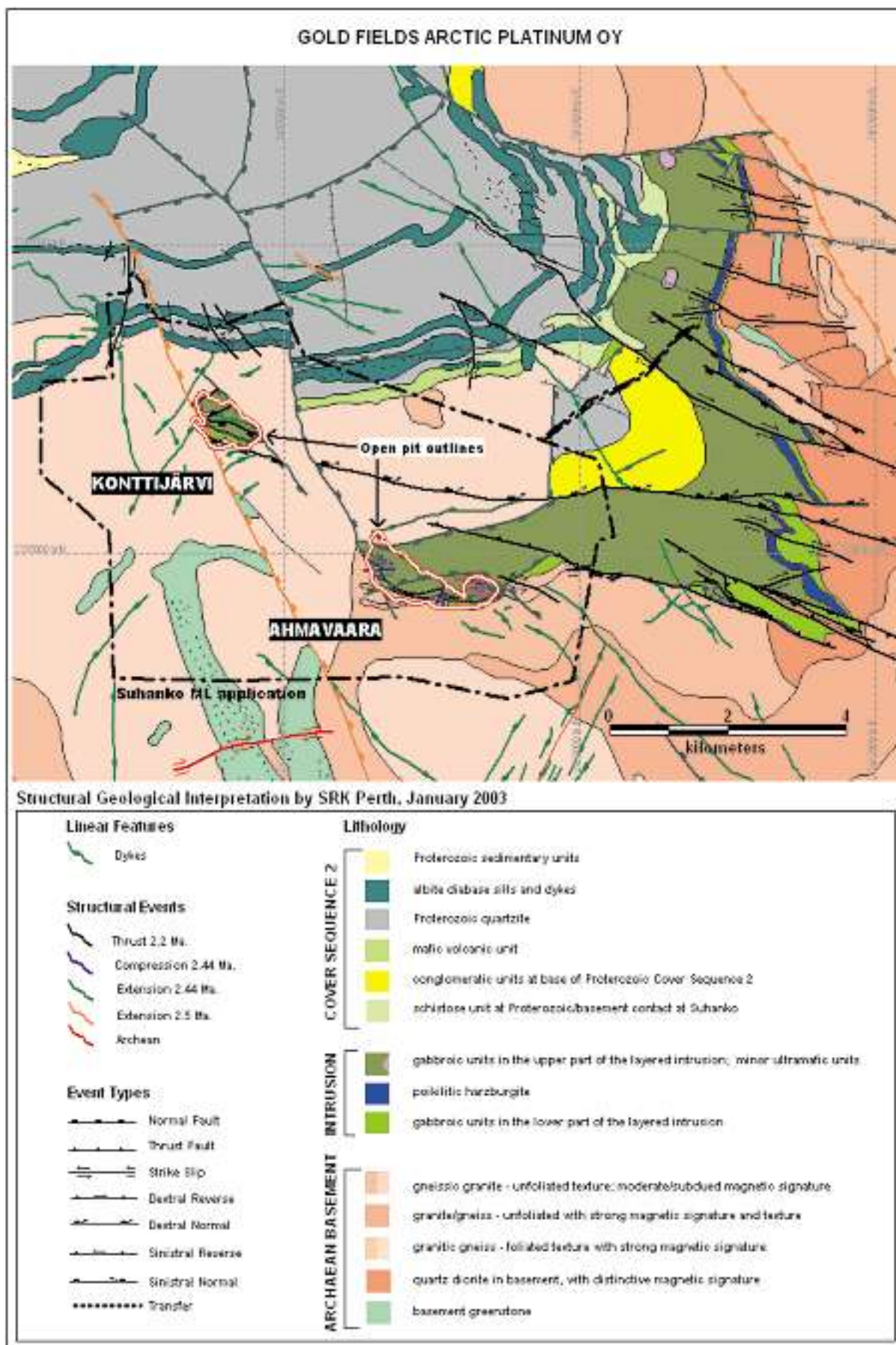


Fig. 16. General Geology of the Suhanko Area (Gold Fields Arctic Platinum Oy).

Stratigraphic Unit		Average Thickness	Description
Hangingwall		Up to 70 m	Gabbroic rocks, ranging from melanocratic to leucocratic varieties, with thinner or minor units of pyroxenites and olivine pyroxenites, dominate the Konttijärvi hangingwall rocks. Not mineralised.
Peridotite Marker		15 – 50 m, avg. 25 m	Pyroxenites and olivine Pyroxenites at the top, through peridotite in the middle to olivine pyroxenites at the bottom. Highly magnetic. Sulphide content (mainly pyrrhotite and chalcopyrite) increases towards the base
Konttijärvi Pyroxenite		2 – 7 m, avg. 5 m	Olivine pyroxenite at the top and pyroxenite at the base. Shows a decrease in magnetic susceptibility compared to PM. Fine disseminated sulphides (mainly chalcopyrite and pyrrhotite). A narrow, irregular and anastomosing chloritic shear zone is commonly present at lower parts of the unit.
Marginal Series Gabbro		0 – 20 m, avg. 10 m	Gabbronorites, feldspathic pyroxenites, pyroxenites and assimilated hybrid gabbros. Assimilation features very common. Well mineralized with disseminated chalcopyrite and pyrrhotite, strong hydrothermal overprint.
Transitional Zone		0 – 60 m, avg. 10 m	Comprises assimilated Marginal Series rocks, mainly hybrid gabbros, and contaminated and mineralized basement rocks. The unit is well mineralized with chalcopyrite and disseminated pyrrhotite.
Basement			Variable Archaean rocks, i.e. diorites, banded gneisses and amphibolites, interlayered with hybrid gabbros and mafic dykes/sills (Portimo dykes). Massive hydrothermal and structural alteration evident. The basement rocks host approximately 45% of the mineralization at Konttijärvi.

Fig. 17. Konttijärvi Stratigraphic Column (Gold Fields Arctic Platinum Oy).

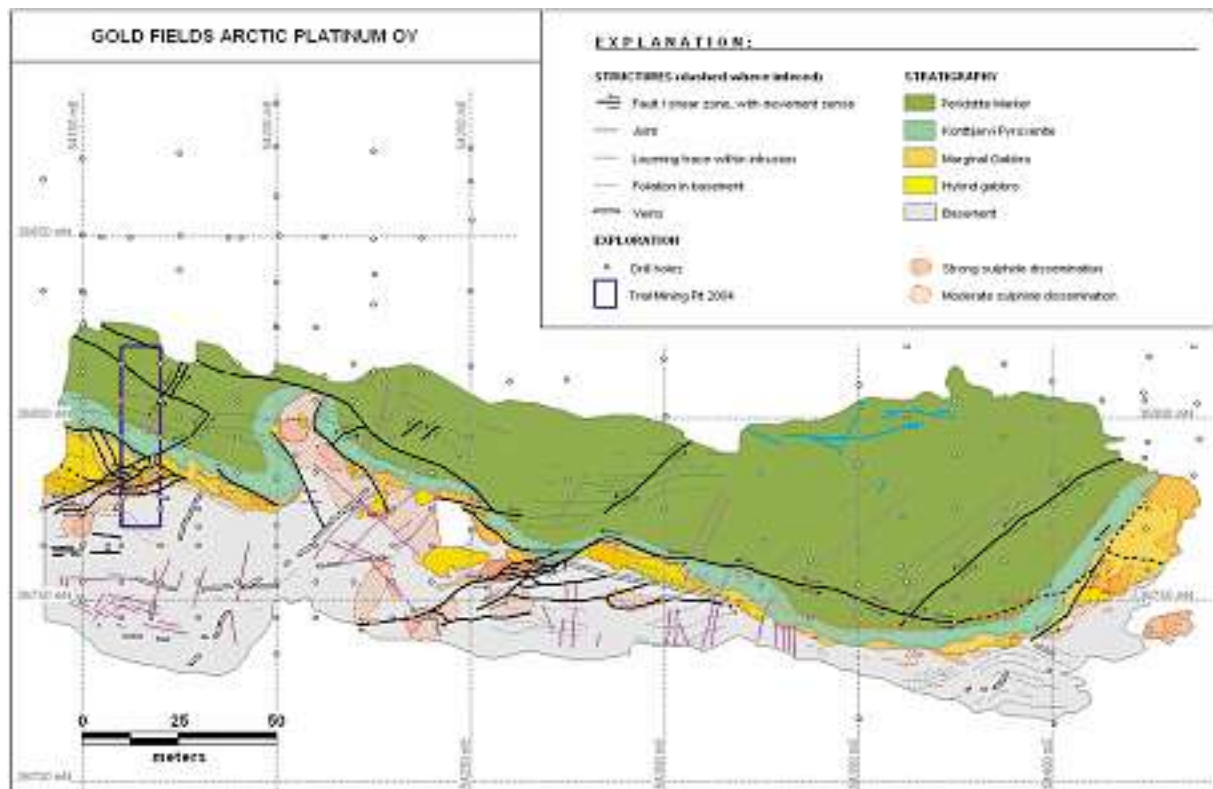


Fig. 18. Plan View of the Geology of the Konttijärvi Trial Mining Area (Gold Fields Arctic Platinum Oy).



Table 4. July 2004 Classified Resources at Suhanko.

Project	Tonnes (Mt)	Grade (g/t)	Metal (000's oz)	Pd (g/t)	Pt (g/t)	Au (g/t)	Cu (%)	Ni (%)
Konttijärvi	38.8	2.32	2,903	1.72	0.48	0.12	0.17	0.07
Ahmavaara	60.0	1.86	3,592	1.40	0.30	0.16	0.27	0.10
Ahmavaara East	20.1	1.61	1,043	1.20	0.28	0.14	0.23	0.08
<b>Total Suhanko</b>	<b>118.9</b>	<b>1.97</b>	<b>7,538</b>	<b>1.47</b>	<b>0.35</b>	<b>0.15</b>	<b>0.23</b>	<b>0.09</b>

Resources reported at 1.0g/t 2PGE+Au cut-off grade

Stratigraphic Unit	Average Thickness	Description
Hangingwall 2	>50 m	Gabbroic rocks, varying between melanocratic to leucocratic varieties with narrower units of pyroxenites and olivine pyroxenites. Not mineralised.
Upper Peridotite	10 m	
Hangingwall 1	10 – 20 m, avg. 15 m	Gabbroic rocks, varying between melanocratic to leucocratic varieties with narrower units of pyroxenites and olivine pyroxenites. Not mineralised.
Peridotite Maker	15 – 50 m, avg. 25 m	Pyroxenites and olivine Pyroxenites at the top, through peridotite in the middle to olivine pyroxenites at the bottom. Highly magnetic. Sulphide content, mainly pyrrhotite and chalcopyrite, increases towards the base
Ahmavaara Pyroxenite	2 – 7 m, avg. 5 m	Olivine pyroxenite at the top and pyroxenite at the base. Lower magnetic susceptibility than PM. Fine disseminated sulphides (mainly chalcopyrite and pyrrhotite). A narrow, irregular and anastomosing chloritic shear zone is commonly present at lower parts of the unit.
Marginal Upper Gabbro	0 – 30 m, avg. 15 m	Gabbros and gabbronorites. Feldspathic pyroxenites are also present at the top contact. The unit is well-mineralized with disseminated chalcopyrite and pyrrhotite and rare massive sulphide veins. Common xenoliths of Marginal central in lower parts.
Marginal Central Microgabbro	0 – 50 m, avg. 25 m	Fine-grained, micro-gabbronorites ranging to feldspathic pyroxenites, with thin veins of coarser-grained marginal lower and/or upper, near the top and bottom contacts. The marginal central zone is poorly mineralized although hosts occasional massive sulphide veins. Interpreted as a precursor to the main intrusive.
Marginal Lower Gabbro	0 – 30 m, avg. 20 m	Skeletal gabbronorites, evidence of assimilation near basement. The contact with the basement may be gradational. Common xenoliths of Marginal central in upper parts. The unit is well-mineralized, with matrix-disseminated and blotchy chalcopyrite and pyrrhotite, occasional massive sulphide veins.
Basement		Archaean gneisses, diorites, banded gneisses, amphibolites and, in the western part of Ahmavaara, quartz-sericite schists. Mineralised near the base of intrusion with occasional massive sulphide veins.

Fig. 19. Ahmavaara Stratigraphic Column (Gold Fields Arctic Platinum Oy).

2004 resource models for Konttijärvi and Ahmavaara are tabulated in Table 4. The total resources at Suhanko above a 1 g/t 2PGE+Au cut-off total 118.0 million tonnes at 1.97 g/t 2PGE+Au for 7.5 million contained 2PGE+Au Oz. In addition the deposits contain significant concentrations of copper and nickel.

## REFERENCES

- Alapieti, T., Filen, B., Lahtinen, J., Lavrov, M., Smolkin, V. & Voitsekhovskiy, S., (1990). Early Proterozoic layered intrusions in the north-eastern part of the Fennoscandian Shield. *Miner. Petrol.* 42: 1-22.
- Hatton, C. & Sharpe, M., (1989). Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: Crawford, A. (ed) *Boninites*. University Press, Cambridge, pp 174-207.
- Hattori, K.H., Arai, S. & Clarke, D.B., (2002). Selenium, tellurium, arsenic and antimony contents of primary mantle sulfides. *The Canadian Mineralogist*, vol.40, pp. 637-650.
- Heltz, R., (1985). Compositions of fine-grained mafic rocks from sills and dikes associated with the Stillwater Complex. In: Czamanske, G. & Zientek, M. (eds) *The Stillwater Complex, Montana: Geology and Guide*. Montana Bureau of mines and geology, special publication 92, pp 97-117.
- Huhtelin, T., Lahtinen, J., Alapieti, T., Korvuo, E. & Sotka, P., (1989). The Narkaus intrusion and related PGE and sulphide mineralization. In: Alapieti, T. (ed) *5<sup>th</sup> International Platinum Symposium. Guide to the post-symposium field trip*, Geol. Surv. Finland, Guide 29: 145-161.
- Iljina, M., (1994). The Portimo Layered Igneous Complex with emphasis on diverge sulphide and platinum-group element deposits. *Acta Univ. Ouluensis. Ser. A, Sci. Rer. Natur.* 258.
- Iljina, M. & Hanski, E., (2002). Multimillion-ounce PGE deposits of the Portimo Layered Igneous Complex, Finland. *9<sup>th</sup> Platinum Symposium, 22-25. 7. 2002*, Billings, Montana, 4p.
- Iljina, M.J. & Lee, C.A., (2005). PGE deposits in the marginal series of layered intrusions. *in* Mungall (ed.). *Exploration for Platinum-group Element Deposits*. Mineralogical Association of Canada Short Course 35, p. xx-xx.
- Iljina, M., Alapieti, T., Lahtinen, J. & Lerssi, J., (1989). The Suhanko-Konttijärvi intrusion and related sulphide and PGE mineralizations. In: Alapieti, T.T. (ed) *5<sup>th</sup> International Platinum Symposium. Guide to the post-symposium field trip*, Geol. Surv. Finland, Guide 29, 163-187.
- Iljina, M., Alapieti, T., & McElduff, B., (1992). Platinum-group element mineralization in the Suhanko-Konttijärvi intrusion, Finland. *Australian J. Earth Sci.* 39: 303-313.
- Mutanen, T., (1997). Geology and ore petrology of the Akanvaara and Koitelainen mafic layered intrusion and the Keivitsa-Satovaara layered complex, northern Finland. *Geological Survey of Finland, Bull.* 395, 233 p.
- Naldrett, A., (1989) *Magmatic Sulfide Deposits*. Oxford University Press, New York – Oxford, 186 pp.
- Naldrett, A., Lightfoot, P., Fedorenko, V., Doherty, W. & Gorbachev, N.S., (1992). Geology and geochemistry of intrusions and flood basalts of the Noril'sk region, USSR, with implications for the origin of the Ni-Cu ores. *Econ. Geol.* 87: 975-1004.

## Acknowledgement

Author is grateful to the Gold Fields Arctic Platinum Oy for the permission to publish this paper. The whole personnel of the Company are also thanked for their help in the various phases of this work.

Pernu, T., Keränen, T., Lerssi, J. & Hjelt, S.-E., (1986). Suhangon kerrosintruusion geofy-sikaalinen rakenneselvitys. Geophysical Research Project of the Suhanko Layered Intrusion, Report of investigations, Department of Geophysics, University of Oulu, Finland, 44 pp. (in Finnish).

Sharpe, M. & Hulbert, L., (1985). Ultramafic sills beneath the eastern Bushveld Complex: Mobilized suspensions of early Lower Zone cumulates in a parental magma with boninitic affinities. *Econ. Geol.* 80: 849-871.



## Chapter 5

# KOILLISMAA LAYERED COMPLEX AND RELATED COPPER-NICKEL AND PGE MINERALIZATIONS

Tuomo T. Alapieti

Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland

### GENERAL GEOLOGY OF THE KOILLISMAA COMPLEX

The Koillismaa Layered Complex (KLC) comprises the layered mafic-ultramafic igneous rocks  $2436 \pm 5$  Ma in age located in the Koillismaa district of northeastern Finland, beginning with the hill of Syöte in the west and continuing to that of Näränkäväära in the east and across the border into Russia (Fig. 1). The KLC consists of two intrusions - the eastern, Näränkäväära Intrusion and the western intrusion, together with a hidden 'dyke' that connects them, which is not exposed but can be identified as a strong gravity high and may itself be a layered intrusion. These two intrusions and the connecting 'dyke' represent three original magma chambers that were initially linked and were located partly within the Archaean (~2700 Ma) basement complex and partly between this basement and the early Palaeoproterozoic supracrustal rocks. The hanging wall rocks comprise mafic volcanics and a polymictic conglomerate, which are younger than the intrusions (Alapieti 1982, Alapieti *et al.* 1990).

The western intrusion originally formed a more or less sheet-like body 1-3 km thick, but tectonic movements have broken it into a number of tilted blocks. The four southernmost blocks dip towards the north and the northern ones towards the south or southwest, thereby forming a broad, interrupted synformal feature. The blocks, from south to north, are those of Pirivaara, Syöte, Porttivaara, Kuusijärvi, Lipeäväära, Kaukua and Murto-lampi (Fig. 1).

The eastern, Näränkäväära Intrusion seems to have retained its original form of an elongated layered intrusion of roughly funnel-shaped cross-section and a depth of the order of about six kilometres. The data on the connecting 'dyke', based mainly on geophysical investigations, suggest that its upper surface lies at an average depth of about 1.4 km below the ground surface, and that the anomalous mass is about 3 km wide and very deep, descending almost vertically and becoming narrower. The feeder channel which supplied the

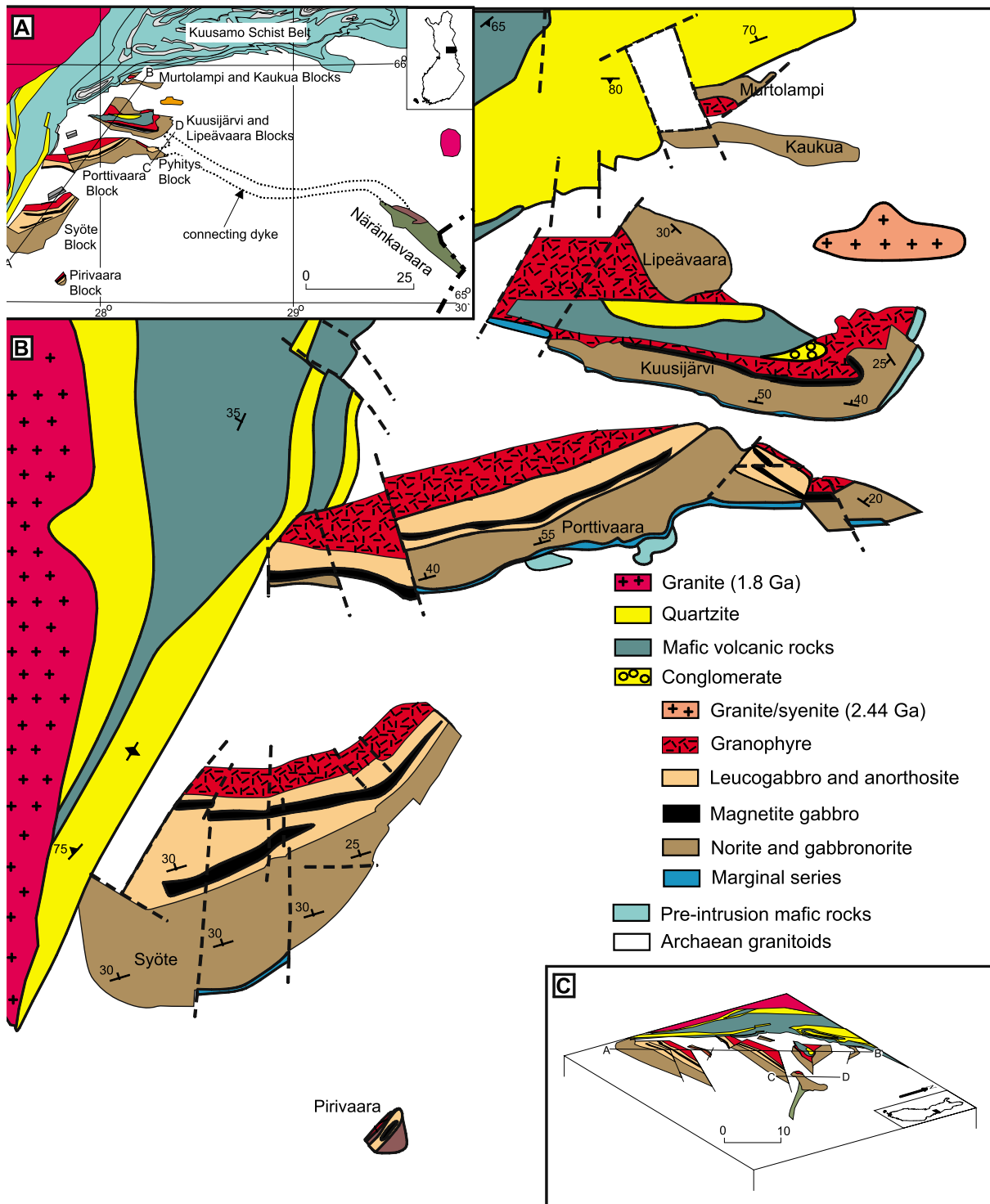


Fig. 1. A. Generalized geological map of the Koillismaa Layered Complex, B. Geological map of the western part of the Koillismaa Complex (slightly modified after Alapieti and Piirainen, 1984), and C. Block diagram of the western part of the Koillismaa Complex (Karinén pers. Comm., 2001). Profile lines A-B and C-D are marked on map A.

entire KLC was situated mainly just below the Näränkävåara Intrusion and the connecting 'dyke', which together form a dyke-like layered complex resembling the Great Dyke in Zimbabwe (Wilson and Prendergast, 1989, Oberthür 2002). PGE exploration in the areas of the Näränkävåara Intrusion and the connecting 'dyke' is still in its infancy, and therefore they will not be described in detail here.

The western intrusion blocks of the KLC are separated from the underlying basement by the marginal series, some 50 to 150 m thick, the rock types in which are heterogeneous, containing diffuse streaks and veinlets of granitic basement. The sequence is usually base-metal sulphide bearing and shows reversed fractionation, grading inwards from gabbroic to ultramafic rocks, followed by the rocks of the layered series. On the other hand, chilled margins are not encountered anywhere at the contact with the basement, probably as a consequence of erosion caused by the continuous injection of magma into the chamber, although remnants of it are found in the form of mafic autoliths further away from the contact.

The layered series of the western intrusion is most complete in the Porttivaara Block (Fig. 1), where it consists of three mineralogically distinct zones: the lower, middle and upper zones, which may further be divided into subzones (Fig. 2). Geophysical investigations have suggested, however, that the lower zone may be underlain in the eastern part of the block by further hidden layers which may also contain ultramafic rocks that are not exposed at the surface. Olivine is a significant cumulus phase in the lowermost

(a) and uppermost (c) subzones of the Lower Zone, occurring together with plagioclase and bronzite, whereas subzone *b* is almost olivine-free. In the Middle Zone olivine is absent and is replaced by augite as a cumulus mineral, together with plagioclase and inverted pigeonite. In the Upper Zone, which is divided into three subzones, the lower and upper parts are plagioclase-rich cumulates, grading in places to anorthosites, whereas the middle subzone is composed of a plagioclase-augite-magnetite adcumulate. This vanadium-bearing rock type was exploited as a vanadium ore at the Mustavaara Mine in the 1970-80's. The upper zone is overlain by an unusually thick, relatively homogeneous granophyre that caps the layered series in a conformable manner (Alapieti 1982, Alapieti and Piirainen 1984).

The chemical compositions of the chilled margin rocks and the average chemical composition of the Porttivaara Block are presented in Table 1. The calculated means of the chemical compounds and elements are weighted by the thicknesses of the layers represented by the given samples. The compositions of the chilled rocks and the average composition resemble each other, being titanium-poor and aluminum-rich, with a MgO content around 10 wt. %, and thus provide an impression of a titanium-poor, aluminum-rich basalt. The above chemical compositions also distinctly resemble the average composition of the Suhanko Block and those of MCU III in the Narkaus Intrusion and MCU IV in the Penikat Intrusion (cf. Alapieti and Lahtinen 2002).

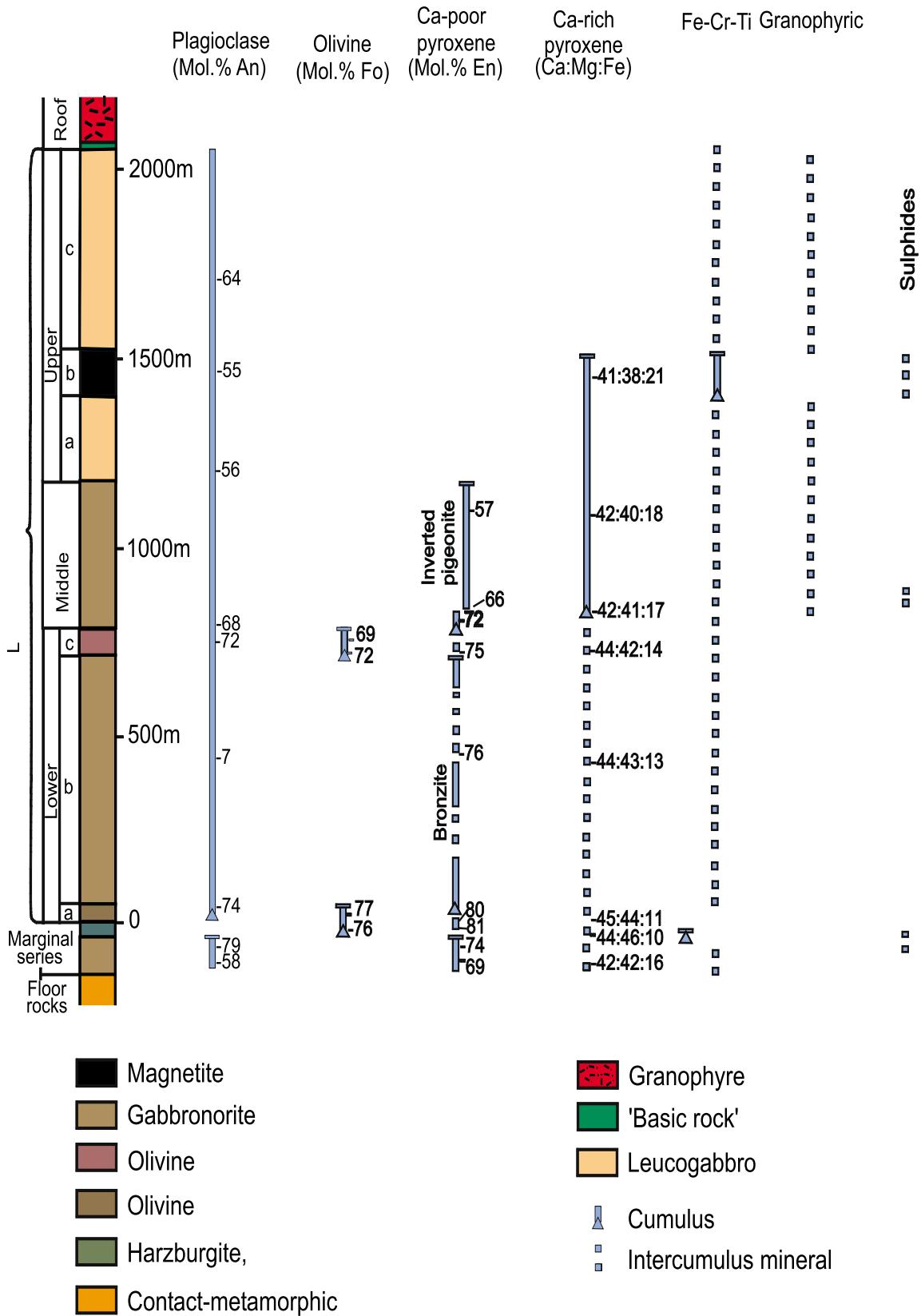


Fig. 2. Stratigraphic sequence and cryptic variation in minerals of the Porttivaara Block of the Koillismaa Complex. Cumulus minerals are indicated by thick solid lines and intercumulus minerals by broken lines. Slightly modified after Alapieti and Piirainen (1984).

## CU-NI-PGE MINERALIZATION IN THE WESTERN PART OF THE KOILLISMAA COMPLEX

### *Disseminated base metal sulphide - PGE deposits in the marginal series*

The low-grade PGE-bearing copper-nickel occurrences in the KLC are mainly concentrated in the marginal series of the western blocks (Alapieti and Piirainen, 1984), and can be followed altogether for some 25 km in the Pirivaara, Syöte, Porttivaara, Kuusijärvi and Lipeävaara Blocks. The thicknesses of these irregular mineralised zones vary from a few metres up to 30 m. The Geological Survey of Finland became interested in exploration of these occurrences in the 1950's, but subsequently lost interest, whereupon Outokumpu Oy initiated an extensive exploration programme in the area in the early 1960's, which included geological mapping, geophysical surveys and diamond drilling. Pilot-plant tests were discouraging, however, and the work was terminated in 1968. The University of Oulu continued investigations in the 1970's, and recently the Geological Survey of Finland and exploration companies have resumed investigations in the Koillismaa area.

The marginal series of the western blocks is in contact with the underlying late Archaean granitoids, in which the original gneissic texture is usually preserved, even in the immediate vicinity of the contact itself. Chilled margins are generally missing at the contact with the basement, as mentioned above. The marginal series itself is a gradational sequence, which parallels the margins of the complex and is generally discordant with respect to the igneous layering in the layered series. The unit shows 'reversed' frac-

tionation of approximately the same kind as in many other layered intrusions, e.g. Jimberlana in Australia (McClay and Campbell, 1976).

The lowest part of the marginal series consists of heterogeneous gabbronorite with diffuse inclusions of partly melted granitoid fragments indicative of pronounced local contamination (Fig. 3). The proportion of these fragments diminishes upwards from the contact, and the rock grades to a homogeneous gabbronorite, and in turn to bronzitite, olivine-bronzitite and harzburgite, which is then followed discordantly by the layered series. The primary minerals in the marginal series are plagioclase, pyroxenes and olivine, and to a lesser extent Fe-Cr oxides. The last mentioned oxides are mostly represented by magnetite, while chromite is found only in the marginal series below an embayment where the subzone *a* of the Lower Zone is exposed (Figs. 1 and 2). The change in the abundance of minerals is accompanied by a change in their composition, the ferromagnesian silicates becoming more magnesian and the plagioclase more calcic in an upward direction, until the trends are reversed in the overlying layered series.

Weak sulphide disseminations and associated PGM are generally encountered throughout the marginal series, but the highest concentrations are found mainly in the homogeneous gabbronorite at the top of the gabbroic sequence (Fig. 3). Sulphides generally occur as disseminated rounded blebs of various sizes interstitial to the silicates, and are also present in the ultramafic rocks, especially in the pyroxenites, where they occur in



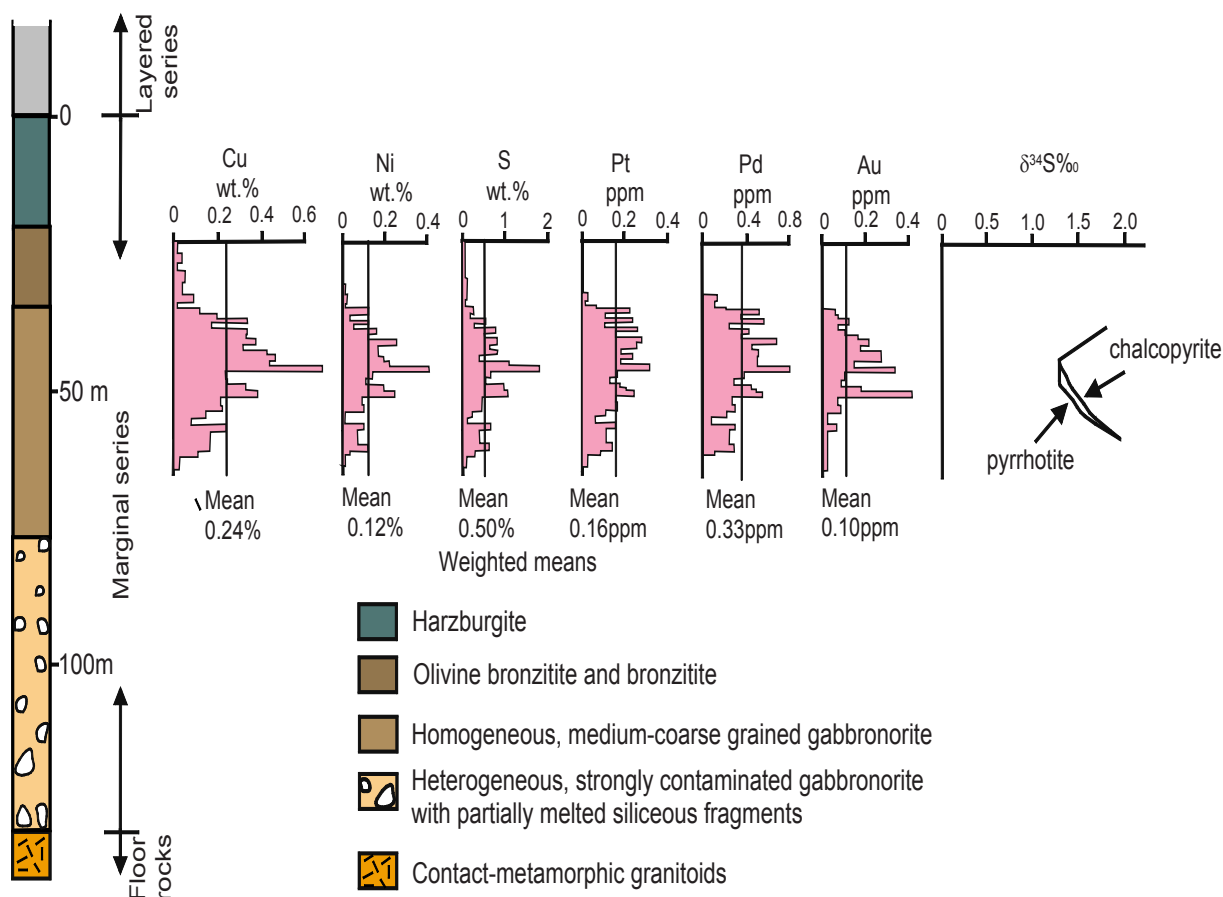


Fig. 3. Vertical variation in Cu, Ni (determined by selective leaching), S, Pt, Pd and Au, and sulphur isotope composition in drill-hole section Pso-7 in the Kuusijärvi Marginal Series. Cu, Ni and S in wt. % and precious metals in ppm. Slightly modified after Alapieti and Piirainen (1984) and Lahtinen (1985).

particular as fine-grained chalcopyrite-dominated disseminations. Sulphides are also encountered locally in the heterogeneous, highly contaminated gabbronorite, but their occurrences have never been found to continue into the granitoids below the contact as in the case of Konttijärvi and Ahmavaara in the Portimo Complex (cf. Alapieti and Lahtinen 2002).

The base metal sulphides are mainly chalcopyrite, pentlandite, pyrrhotite, and in places pyrite, which is characterized by a high Co content of 1-2.5 wt. % (Alapieti and Piirainen, 1984, Lahtinen, 1985). The average concentrations in the sulphide fraction are about 8-10 wt. % Ni, 15-20 wt.% Cu, and around 10 ppm Pt, 20-25 ppm Pd and 5-10 ppm Au. As a whole, the mineralization is characterized by  $\text{Cu} > \text{Ni}$  and  $\text{Pd} > \text{Pt}$ , the ratios for both pairs

exceeding 2:1. The values for the sulphur isotope composition vary between +1.3 and +2.0 ‰ (Fig. 3), and are therefore similar to those for mantle-derived sulphides. The PGM occur mainly as tiny inclusions in sulphides, particularly in chalcopyrite, and are represented by sperrylite, merenskyite, michenerite and froodite (Alapieti and Piirainen, 1984).

#### ***Disseminated base metal sulphide - PGE deposits associated with the layered series***

#### **Disseminated base metal sulphide - PGE occurrences associated with microgabbronorites within the layered series**

A peculiar mafic rock called microgabbronorite is encountered in the middle zones of the Porttivaara and Syöte Blocks. This

rock type occurs as ‘veinlets’ or inclusions that range from a few decimetres to almost thirty metres in diameter, being concentrated in a zone, which is traceable throughout the above blocks. Similar microgabbro-norites and associated PGE-bearing sulphide disseminations are also encountered in some other Fennoscandian layered intrusions, especially the Lukkulaivaara Intrusion in the Oulanka Complex, Russian Karelia (e.g. Grokhovskaya *et al.*, 1992, Glebovitsky *et al.*, 2001, Latypov *et al.*, 2002) and in the Monchegorsk Intrusion on the Kola Peninsula (Dedeev *et al.* 2002). These fine-grained rocks have been interpreted as interrupted dykes or veinlets emplaced into a partly consolidated cumulus pile, xenoliths crystallized from earlier magma pulses, or as having been formed under chilling conditions accompanied by a rapid loss of volatiles (decompression effect). The rocks enclosing these microgabbro-norites are usually mottled gabbro-norites or gabbros, the mottled appearance being due to late crystallizing minerals, concentrated in discrete, light-coloured clusters in which the base metal sulphides and associated PGM have also aggregated. The

minerals that are usually encountered in these light patches include quartz, epidote, scapolite, chlorite, amphibole and ilmenomagnetite. The base metal sulphides and PGM associated with the microgabbro-norites are usually identical to those in the marginal series, and their concentrations are also roughly similar.

#### Reef type occurrences in the layered series

Little work has been done on exploration for PGE reefs in the western Koillismaa area. All that is known so far is that PGE-bearing base metal sulphides exist in a pipe or reef like ultramafic rock (1-2 ppm PGE in whole rock) in the lower part of the Porttivaara Block (Halkoaho 2005, pers. comm.) and base metal sulphide-bearing zones enriched in PGE are encountered in the Kaukua Block in the northern part of the KLC, in which the highest PGE values exceed 2 ppm. This zone is hosted by a rhythmic unit which possesses well-developed inch-scale – decimetre-scale rhythmic layering. An analogous rhythmic unit is encountered in the Middle Zone of the Porttivaara Block, but this area has not so far been subject to intensive exploration.

## EXCURSION SITES IN THE KOILLISMAA AREA

### **Site 1.**

#### **Rhythmic layering in the Kaukua Intrusion Block**

Well-developed rhythmic layering is not common in the Koillismaa area. One of the best outcrops is seen at this site. The Kaukua Intrusion Block is quite poorly exposed, and the outcrops are mainly concentrated on relatively steep slopes. These outcrops represent the middle zone of the intrusion, and the layering is caused by variation in

the amounts of cumulus plagioclase, augite and inverted pigeonite. Augite occurs as the intercumulus phase in some layers.

### **Site 2.**

#### **Granophyre at Sirniö, Kuusijärvi Block**

Granophyre forms a grey-coloured, relatively homogeneous layer about one kilometre thick which constitutes a conformable cap to the layered series of the western intrusion of the Koillismaa complex. The granophyre

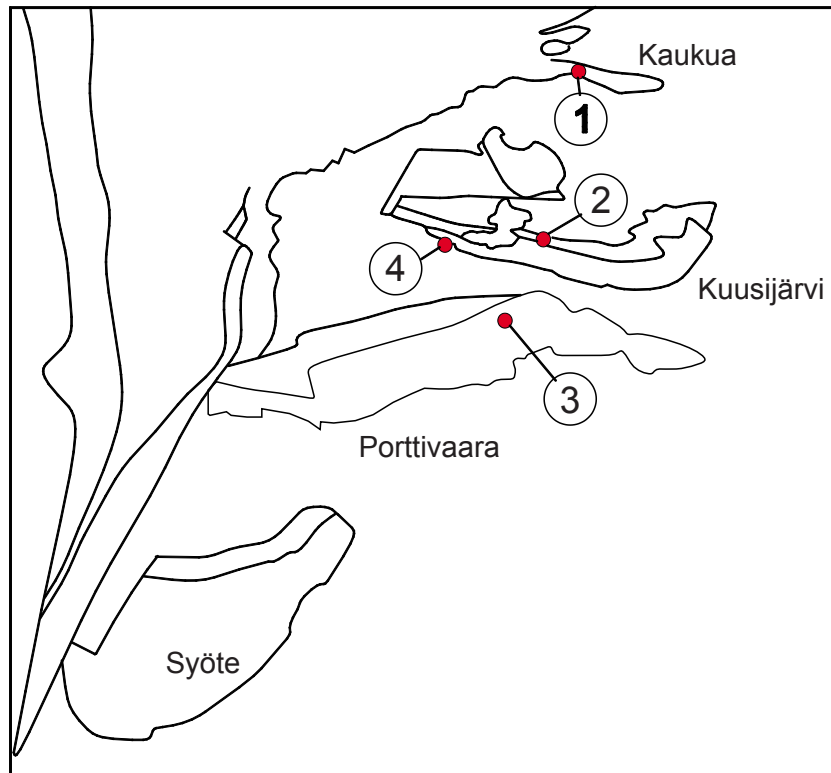


Fig. 4. Excursion sites in the Western Koillismaa area.

corresponds in composition to alkali-feldspar granites and has no layered structures or lamination. The rocks are commonly porphyritic or microphyric in texture, showing subhedral phenocrysts of albite with granophyric intergrowths of quartz and alkali feldspar in the matrix. Biotite and hornblende, probably of metamorphic origin, occur as mafic minerals (Fig. 5). The scattered grains of albite on the weathered surface give the rock the appearance of having been sprinkled with semolina.

### Site 3.

#### Mustavaara Vanadium Mine

The Mustavaara vanadium mine, which was owned by Rautaruukki Oy, is located at the western end of the Porttivaara intrusion block. The main rock type here is a plagioclase-ilmenomagnetite adcumulate (Fig. 6), which contains around 0.9 wt. % V in its magnetic

concentrate.

The existence of a coherent magnetite gabbro layer in the Porttivaara intrusion block was discovered from aeromagnetic measurements performed by Otanmäki Oy in 1959, in connection with prospecting prompted by vanadium-bearing magnetite gabbro samples sent in by members of the public during the years 1957 and 1958. Drillings were commenced at Mustavaara only in the early 1970's, however. The decision to establish a mine was taken in 1973 and production began in

1976. A decline in the world price of vanadium led to its closure in 1985. The buildings of the ore dressing plant were later on occupied by a factory building railway wagons in conjunction with the corresponding Otanmäki works of Rautaruukki Oy. This magnetite gabbro has been described in detail by Juopperi (1977).



Fig. 5. Photomicrograph showing the texture of the granophyre, with albite phenocrysts and intergrowths of quartz and alkali feldspar.



Fig. 6. Photomicrograph showing the texture of the plagioclase-ilmenomagnetite-augite adcumulate.

#### Site 4.

#### **PGE-bearing sulphide deposit in the Kuusijärvi Marginal Series at Haukiaho**

This site shows from south to north, Archaean mafic and ultramafic rocks, Archaean granitoids and the lower part of the marginal series. The last-mentioned rock-type is

contaminated, and granitoid

xenoliths are clearly visible. Disseminated sulphides are also encountered, and variation in Cu, Ni, S, Pt and Pd is depicted in one of the drill-hole section in Fig. 3.



## REFERENCES

- ALAPIETI, T.T., 1982. The Koillismaa layered igneous complex, Finland - its structure, mineralogy and geochemistry, with emphasis on the distribution of chromium. Geological Survey of Finland, Bulletin, 319, p.1-116.
- ALAPIETI, T.T., FILEN B.A., LAHTINEN, J.J., LAVROV, M.M., SMOLKIN, V.F. and VOITSEKHOVSKY, S.N., 1990. Early Proterozoic layered intrusions in the northeastern part of the Fennoscandian Shield. *Mineralogy and Petrology*, 42, p.1-22.
- ALAPIETI, T.T. and PIIRAINEN, T.A., 1984. Cu-Ni-PGE mineralization in the marginal series of the early Proterozoic Koillismaa layered igneous complex, northeast Finland. In *Sulphide deposits in mafic and ultramafic rocks*. Edited by D.L. Buchanan and M.J. Jones. The Institution of Mining and Metallurgy, London, p.123-131.
- DEDEEV, A.V., KHASCHKOVSKAYA, T.N. and GALGIN, A.S., 2002. The PGE Mineralization of the Monchegorsk Layered Intrusion of the Kola Peninsula. In *The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements*. Edited by L.J. Cabri. The Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume, 54, p.569-577.
- GLEBOVITSKY, V.A., SEMENOV, V.S., BELYATSKY, B.V., KOPTER-DVORNIKOV, E.V., PCHELINTSEVA, N.F., KIREEV, B.S. and KOLTSOV, A.B., 2001. The structure of the Lukkulaisvaara Intrusion, Oulanka Group, Northern Karelia: Petrological implications. *Canadian Mineralogist*, 39, p.607-637.
- GROKHOVSKAYA, T.L., DISTLER, V.V., KLYUNIN, S.F., ZAKHAROV, A.A. and LAPUTINA, I.P., 1992. Low-sulfide platinum group mineralization of the Lukkulaisvaara Pluton, Northern Karelia. *International Geology Review*, 34, p.503-520.
- JUOPPERI, A., 1977. The magnetite gabbro and related Mustavaara vanadium ore deposit in Porttivaara layered intrusion, northeastern Finland. *Finland Geol. Surv. Bull.* 288, 68 p.
- LAHTINEN, J., 1985. PGE-bearing copper-nickel occurrences in the marginal series of the early Proterozoic Koillismaa Layered Intrusion, northern Finland. In *Nickel-Copper Deposits of the Baltic Shield and Scandinavian Caledonides*. Edited by H. Papunen and G.I. Gorbunov. Geological Survey of Finland, Bulletin, 333, p.161-178.
- LATYPOV, R.M., ALAPIETI, T.T. and CHISTYAKOVA, S.Y., 2005. PGE reefs as an in situ crystallization phenomenon: case study of the Nadezhda gabbro-norite body, Lukkulaisvaara intrusion, Baltic Shield, Russia. In *Abstract volume of the 10th International Platinum Symposium*. Edited by T.T. Alapieti and T. Törmänen.
- MCCLAY K.R. and CAMPBELL, I.H., 1976. The structure and shape of the Jimberlana Intrusion, Western Australia, as indicated by an investigation of the Bronzite Complex. *Geological Magazine*, 113, p.129-139.
- OBERTHÜR, T., 2002. Platinum-group element mineralization of the Great Dyke, Zimbabwe. In *The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements*. Edited by L.J. Cabri. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, p. 483-506.
- WILSON, A.H. and PRENDERGAST, M.D., 1989. The Great Dyke of Zimbabwe - I: tectonic setting, stratigraphy, petrology, structure, emplacement and crystallization. In *Magmatic sulphides - Zimbabwe volume*. Edited by M.D. Prendergast and M.J. Jones. Institution of Mining and Metallurgy, London, p.1-20.