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SILICEOUS, HIGH-MAGNESIAN PARENTAL MAGMA COMPOSITIONS OF THE PGE-RICH EARLY PALEO-PROTEROZOIC LAYERED INTRUSION BELT OF NORTHERN FINLAND

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Abstract

The Early Paleoproterozoic (approximately 2.44 Ga) mafic intrusion belt which crosses the Fennoscandian shield has geochemical signatures that resemble those of modern boninites, and of Archean siliceous, high magnesium basalts (SHMB). Major and trace element compositions were determined for chilled margin and preintrusion dike samples of the Penikat, Portimo, and Koillismaa Complexes. Similarities to boninitic magmas include: high MgO contents at intermediate SiO_2 contents, low TiO_2 and HFSE contents (mostly < 0.5 wt.% TiO_2), high Cr contents, and high CaO/TiO_2 and Al_2O_3/TiO_2 ratios combined with low Ti/Zr ratios. Although the presence of a negative normalized Ta anomaly has yet to be proven, a negative Nb anomaly is present. Sc/Y ratios are also close to those of modern boninites. The Nd isotope values, however, show negative ϵ_{Nd} values similar to those of Archean contaminated komatiites and to the Bushveld and Stillwater Complexes, but different from the positive values of modern boninites.

The genesis of the intrusion belt's parental magmas can be explained either by processes that form boninites in incipient rift environments, or by assimilation of crust by komatiitic magma and subsequent fractional crystallization of ultramafic components. Earlier Archean tholeiitic magmatism, and late-Archean arc volcanism and craton assembly may have produced depleted mantle underneath the Fennoscandian shield crust. Rift volcanism due to a rising mantle diapir resulted in the emplacement of the mafic intrusion belt. Geochemical modelling of contamination of idealized komatiite by granite-gneiss basement for Sc, Zr, La and Nb matched the measured Finnish parental magma compositions at values of 20 - 30% contamination and 35 - 45% fractionation. Modelling of Y and Nd indicated much higher values for both parameters. Trace element ratios support the boninite model of genesis, while the contaminated komatiite model is only partially supported by trace element modelling and by Nd isotopic evidence. If contamination occurred, it may have been with crust other than the granite-gneiss basement into which the intrusions were placed.

Keywords: Layered intrusions, Parental magma, Northern Finland, Paleoproterozoic

INTRODUCTION

The last decade has seen the recognition that the parental magmas of the platinum-group element (PGE)-rich critical zone of the Bushveld Complex are of high-silica, high-magnesium, and low-Ti composition [36, 18, 7, 20, 37]. These authors have, however, disagreed on whether the parental magmas are truly boninitic or are of a 'siliceous, high-Mg basalt' (SHMB) nature. Other of the few examples of Precambrian rocks with boninitic affinities are described in Poidevin (1994) [33] and references therein.

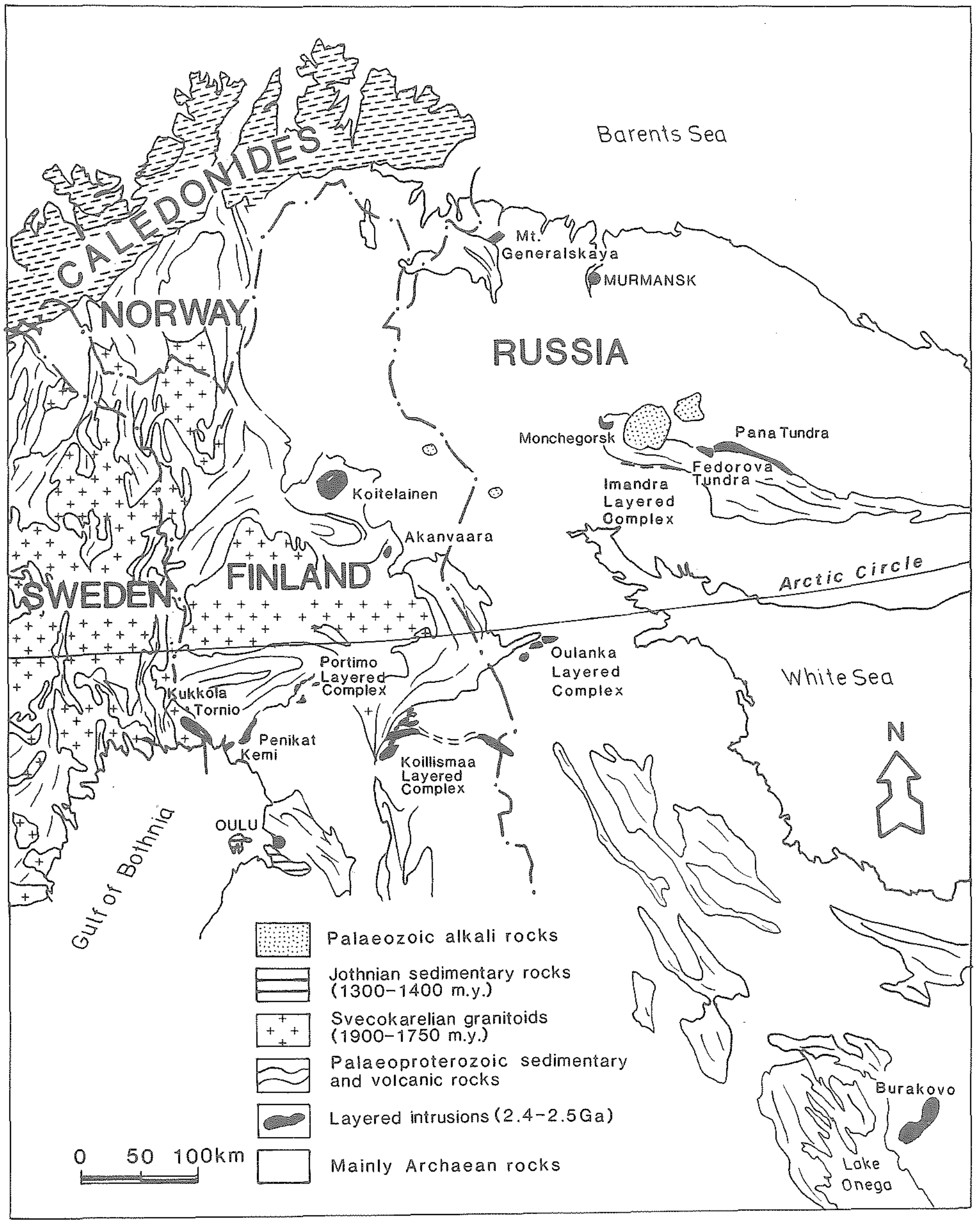

Figure 1. Generalized geologic map of the northeastern part of the Fennoscandian Shield showing the location of early Paleoproterozoic ca. 2.44 Ga layered intrusions. Modified after Alapieti *et al.* [6].

The distinction of whether the parental magmas are of SHMB or of boninitic affinity has major implications for the tectonic reconstruction of an intrusion's emplacement environment. An SHMB parent magma might indicate derivation from a komatiitic melt by assimilation-fractional crystallization processes, connected with the early, high-temperature phase of mantle plume incursion into a stable craton. A boninitic parent magma, on the other hand, points toward derivation from second-stage melting of depleted, refractory peridotite by fluxing with hydrous fluid in a subduction zone environment [18, 12]. In this paper, we demonstrate that parental magmas of the early Proterozoic, PGE-rich layered intrusion belt of the northern Fennoscandian shield have chemical signatures resembling both modern boninites and Archean SHMB, and that a differentiation between the processes which formed the two types remains elusive for Precambrian high-MgO, high silica mafic rocks.

GENERAL GEOLOGY

Approximately two dozen intrusions and intrusion fragments are found scattered across the Fennoscandian shield [1, 6, 24-25, 16-17, 22, 15, 23](Fig. 1). The PGE-rich intrusions are part of a zone which crosses the shield at a latitude of about 66°, extending from Sweden into Russia. Numerous age determinations have been carried out on these intrusions, and many different dating methods have been used, including the U-Pb method for zircon and the Pb-Pb whole rock and Sm-Nd methods. These have together yielded a fairly coherent set of ages, the mean being about 2.44 Ga. The intrusions lie stratigraphically within late Archean granitoids or on the contact between these and the unconformably overlying Proterozoic supracrustal sequence of tholeiitic volcanics, subvolcanic sills, or in places a polymict conglomerate. The overlying supracrustal rocks are younger than the intrusions, indicating that the original roof rocks and the uppermost parts of the intrusions themselves were removed by erosion in those places.

Post-emplacement deformation and metamorphic events variably altered the primary magmatic minerals, although relict textures and pseudomorphs remain recognizable. These events also tilted and broke the intrusions into blocks. The overall stratigraphy of the intrusions is usually one of repeated sequences of ultramafic, gabbroic and anorthositic rocks, referred to as megacyclic units, each of which can be interpreted as a new pulse of magma.

A wide variety of ore types is present in the intrusions, including chromitite layers such as the one at Kemi, basal PGE-bearing sulfide zones, PGE-rich, low sulfide zones in the layered series, PGE mineralization in the Late Archean basement granite-gneisses, and the V-bearing magnetite horizon in the Koillismaa Complex [1, 16-17, 22, 25, 15, 23] and references therein).

In general, the magmatic stratigraphy of the intrusions can be subdivided on the basis of major and trace element geochemistry into a lower and upper series, which may represent two different parental magmas [3, 6]. Fig. 2 [27] correlates the magma types among the intrusions of the belt. As is discussed below in detail, the first magma type has relatively high silica, MgO, and Cr and relatively low Ti, while the second magma type has lower MgO and Cr. Average compositions of the lower three megacyclic units (I-III) of the Penikat and of Narkaus megacyclic units I and II are of the first magma type; and those of the highest two megacyclic units (IV-V) of the Penikat and Narkaus megacyclic unit III are of the second magma type. All of the exposed portions of the Tornio and Kemi intrusions are considered to be of the first magma type, while the Suhanko-Konttijärvi and western Koillismaa Complexes are of the second type.

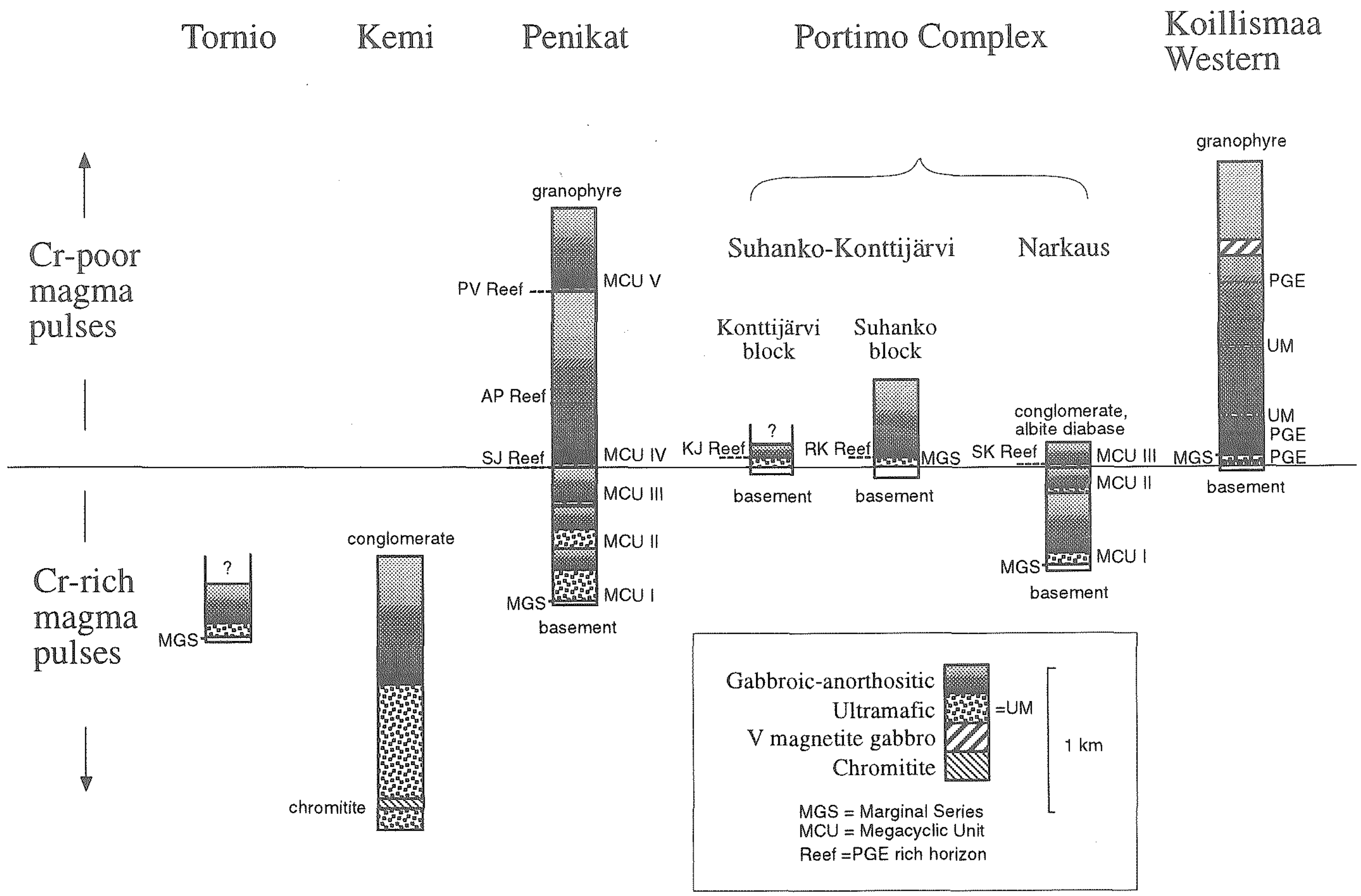

Figure 2. Correlation chart showing Cr-rich and Cr-poor magma types across the layered intrusion belt. Modified from Lahtinen *et al.* [27].

OCCURRENCE OF ROCKS WITH POTENTIAL PARENT MAGMA COMPOSITIONS

Chilled or fine-grained rocks were sampled from the basal margins of the Penikat, Portimo, and Koillismaa intrusions, and from preintrusion dikes beneath the Suhanko-Konttijärvi intrusion. A dike east of the Penikat intrusion and perpendicular to its margin was also investigated, although its geologic relationship to the intrusion is unclear.

Penikat

The footwall rocks of the Penikat intrusion consist of late Archean/early Proterozoic granitoids. These are in sharp contact with the intrusion's thin, fine-grained chilled margin, which in turn contacts the marginal series. The marginal series, which varies in thickness from 10 to 40 meters, is composed of subophitic, non-cumulate textured gabbroids grading into gabbroic and bronzitic cumulates. Very little interaction is evident between the basement rocks and the intrusion's marginal rocks, although siliceous fragments and small rheomorphic veins occur in places. Chilled sample 1 (9383-7003) is from the base of the Yli-Penikka block of the Penikat intrusion, and chilled samples 2-3 from drill core Ki-6 (at 171.82 , 171.49, and 168.27 meters depth) are from the base of the Sampujärvi block. The sample 5 of subophitic rock (73-PtPro) is from above the basal chilled margin in the Kilkka block [21].

Portimo Layered Complex

This complex comprises two intrusions: the Suhanko-Konttijärvi intrusion and the Narkaus intrusion. The Suhanko-Konttijärvi intrusion, due to the current erosional level, is divided into two bodies which are interpreted to have crystallized in the same magma chamber. The intrusion is composed of a marginal series, normally 20-80 meters in thickness, and an overlying layered series. The marginal series usually comprises a sequence grading from plagioclase-augite-bronzite cumulates at the base through bronzite cumulates to olivine cumulate at the top. No chilled margins have been found, while evidence of pronounced contamination is characteristic of the marginal series, as shown by numerous xenoliths of siliceous footwall rocks within the basal gabbroic and pyroxenitic rocks. The layered series and PGE mineralization of the Portimo Layered Complex is described in [4, 24-25, 23].

Three of the four samples in this study are from preintrusion basal dikes which are crosscut by the marginal zone of the Suhanko-Konttijärvi intrusion. As described in [24-25, 23], the dikes are subparallel to the basal contact of the intrusion and merge with it locally, so that in some cases, a dike may actually form the basement of the intrusion. Pieces of preintrusion dikes are also encountered as xenoliths in the basal portions of the Konttijärvi and Ahmavaara marginal series. A few of the thicker dikes show some evidence of cumulus textures. Most of the dikes have a pyroxenitic composition, but some also contain gabbronoritic portions. Xenoliths of country rock also occur in the preintrusion dikes.

Sample 9 [KOJ-10/30.22-31.10 m) is an eight meter thick websteritic dike beneath the Konttijärvi marginal series ([23] Table 3, #1). Its mineralogy comprises clinopyroxene and orthopyroxene (and in some parts plagioclase), plus disseminated chromite. Some portions contain enrichments in Cu-Ni sulfides and PGE's. Although the relict cumulate texture which can be recognized in this dike makes it strictly inappropriate for consideration as a primary liquid, nevertheless its composition corresponds with those samples exhibiting true chilled textures. Below this dike is a second, two meter thick preintrusion dike of plagioclase-bearing websterite (samples 6-7 = 469-PtPro and 454-PtPro).

Sample 8 (470-PtPro) is from a fine-grained autolith from the margin of the Suhanko Body. The major element chemistry of this sample is similar to that of the other MgO- and SiO_2 -rich, TiO_2 poor samples discussed here, but its REE signature make it appear to represent the Cr-poor magma type

[23]. Its low MgO and Cr contents are similar to those of the weighted average of the Suhanko Body itself.

The Loljunmaa dike

The Loljunmaa dike subcrops east of the Penikat intrusion and perpendicular to its margin [5-6]. As is the case with the Portimo dikes, the contact between the Loljunmaa dike and the Penikat intrusion is not exposed. The samples used for this study are from the approximate center of the dike.

The Koillismaa Complex

The Koillismaa Complex [1, 5] and references therein) comprises two intrusions, the western and the eastern, and a large hidden connecting dike. Subsequent tectonic and erosional events have broken the western intrusion into a number of blocks; these are (from south to north): the Pirivaara, Syöte, Porttivaara, Kuusijärvi, Lipeävaara, Kaukua and Murtolampi intrusion blocks. The eastern intrusion, which continues over the border into Russia, is named the Näränkävaara intrusion.

In general, the magmatic stratigraphy of the Koillismaa Complex can be divided into a basal marginal series, a layered series, and a thick granophyre. The Näränkävaara intrusion comprises an ultramafic zone (peridotites, bronzites and websterites) and a gabbroic and dioritic zone. In the western intrusion blocks, the 50 - 200 m thick marginal series separates the mafic layered series proper from the underlying basement rocks, and is composed of variably contaminated, heterogeneous mafic and ultramafic rocks. It is invariably reversely zoned (gabbroic near the contact with the country rock and grading up into ultramafic), a feature which is interpreted as due to basement rock contamination.

Samples of chilled rock were taken from different intrusion blocks. Sample 11 (1Ch = sample U144I of Alapieti [1]) was taken from the Kuusijärvi block of the western intrusion. This sample, a fine-grained gabbronorite with accessory trace sulfide, is composed of plagioclase ($An_{54.5}$), slightly uralitized orthopyroxene, and clinopyroxene. Some features indicating a cumulus texture are evident, and this together with the alteration may have affected the bulk composition of the rock. As described in [1], the liquid equivalent of sample 11 (1Ch) would have been in equilibrium with an olivine of $Fo_{89.5}$, whereas the composition of the stratigraphically lowest olivine encountered in the Näränkävaara intrusion is $Fo_{87.5}$. A similar calculation using Ni contents also shows good agreement, indicating that basement contamination had little effect on this sample. Sample 12 (U172) is also from the margin of the Kuusijärvi block.

Sample 14 (B7/12.80-12.90) is from fine-grained rock intersected in a drill hole in the Syöte intrusion block (Rometölväs area), and sample 15 (PO-33) is from similar rock in the Porttivaara intrusion block (Baabelinälkky area). It is not clear whether these rocks represent autoliths of chilled margin which have rafted up into the cumulus stratigraphy, if they are cross-cutting dikes, or if they are examples of the "microgabbronorites" found in the Lukkulaisvaara intrusion on the eastern end of the intrusion belt in Russia [38]. Their geochemistry, however, is quite similar to that of the chilled margin and preintrusion dike samples and we have included them in this survey. Sample 13 (U264I), which has a slightly different geochemical signature compared to the other samples, is from what has been interpreted as a greenstone which occurs above the cumulus stratigraphy in the Kuusijärvi block, but below the overlying granophyre.

GEOCHEMICAL COMPARISON OF THE PARENTAL MAGMAS WITH SIMILAR ROCK TYPES

Major elements

Analyses of the chilled margin and preintrusion dike samples are shown in Tables 1 and 2. Most samples have MgO contents ranging from approximately 6.5 to over 20 wt.% MgO. The SiO2 contents are high, averaging about 54 wt.% for the basal chills and dikes (excluding the relatively TiO2-rich Loljunmaa dike, with 52 wt.% SiO2). Total alkali contents range from less than 0.5 wt.% (Konttijärvi preintrusion dikes) to very high values (8.5 wt.%; Penikat basal chill). The very highest values of silica and alkali elements may be a result of local salic contamination. On an AFM plot (not shown here), basal dikes, chilled margins, and other fine-textured rocks of the intrusion belt plot in regions comparable to those of the "quench textured B1" micropyroxenitic sills at the base of the Bushveld Complex [36]. Weighted averages of the megacyclic units plot in a region slightly more primitive than the B1 sills.

Fig. 3 shows CaO/TiO_2 and Al_2O_3/TiO_2 vs. TiO_2 for the fine-grained rocks of the intrusion belt, compared with a field of "siliceous, high Mg basalts" which encloses analyses presented in Sun *et al.* [37] and with a field enclosing tholeiites from Cameron (1989). A large proportion of the compositions falls in the boninitic field of high CaO/TiO_2 and Al_2O_3/TiO_2 and low TiO_2. Al_2O_3/TiO_2 ratios vary between approximately 15 and 107, with a mean of 47 (compare SHMB from Sun *et al.*[37], which range from 12-31). Overlap exists with the field of SHMB, but no points fall in the tholeiitic field. CaO/TiO2 ratios range from 8-63 (Finnish intrusion compositions) vs. 7-23 for SHMB. The Loljunmaa dike falls well within the field for SHMB. On the plot FeO vs. TiO2, the analyses of the Finnish dikes and chills plot within the boninite and SHMB fields. The boninite-like average upper pillowed amphibolites of the BogoinðBoali greenstone belt (UPAB of Poidevin [33]) are also plotted for comparison.

Trace elements

Fig. 3 also plots Ti/Zr vs. TiO_2, elements which can be considered as resistant to metamorphic remobilization. The chilled margin and dike samples again plot mostly within the field of boninites, with some overlap with the field of SHMB.

The two magma types mentioned above can be differentiated by their Cr contents. These differences are most apparent in whole rock profiles through the intrusions [1, 15, 23] and references therein), where the stratigraphically lower megacyclic units (MCU) have consistently higher Cr contents than the overlying megacyclic units. This effect is illustrated by Fig. 4, which compares Cr contents for the same rock types in MCU's II and III from the Narkaus intrusion (cf. Table 1 of Alapieti *et al.* [6], and Fig. 26 of Iljina [23]).

On chondrite-normalized REE profiles (Fig. 5), the Cr-rich samples are LREE-enriched, with (La/Yb)N ranging from 4.7 to 19.7 (including the Loljunmaa dike), although the (La/Yb)N ratio is less than 6.5 for Cr-poor samples. Except for one sample of the chilled margin of the Koillismaa with its large positive Eu anomaly, the chills and dikes have small or no negative Eu anomalies. The REE patterns of the Cr-rich Finnish samples are quite similar to those of the Bushveld B1 quench textured micropyroxenites, including an HREE depletion [36]. These samples fall within the range of SHMB of Barnes [7], while the Cr-poor Finnish samples fall in his range of boninites.

Table 1. Whole rock chemical analyses. Major elements analyzed either at the University of Oulu, Department of Electron Optics, or at the labs of Rautaruukki Oy. Trace elements analyzed by Actlabs, Canada.

	1	2	3	4	5	6	7	8
SiO_2	53.50	57.38	53.73	56.67	55.77	54.62	52.36	51.59
TiO_2	0.40	0.40	0.57	0.17	0.40	0.28	0.41	0.15
Al_2O_3	13.69	13.69	14.25	12.31	10.50	4.24	8.16	16.02
FeO	8.11	9.20	9.35	6.68	9.31	9.19	12.27	6.89
MnO	0.15	0.10	0.12	0.14	0.20	0.24	0.32	0.16
MgO	11.35	6.47	8.04	10.88	14.35	18.90	14.08	11.04
CaO	7.56	3.25	5.27	6.68	7.01	12.09	11.25	11.27
Na_2O	2.82	3.91	2.77	3.95	1.58	0.32	0.63	2.60
K_2O	2.26	4.58	5.73	2.37	0.82	0.09	0.46	0.20
P_2O_5	0.071	0.041	0.078	0.039	0.065	0.042	0.069	0.013
S (ppm)	40	180	70	130	20		50	100
mg# (0.9)	0.735	0.582	0.630	0.763	0.753	0.803	0.695	0.760
CaO/Al_2O_3	0.55	0.24	0.37	0.54	0.67	2.85	1.38	0.70
Al_2O_3/TiO_2	34.2	34.2	25.0	72.4	26.4	14.9	19.9	106.8
CaO/TiO_2	18.9	8.1	9.2	39.3	17.7	42.6	27.5	75.1
Ti/Zr	48.0	18.4	85.4	14.6	39.7	56.7	61.3	31.0
Ti/V	16.0	20.0		11.3	15.9	11.3	10.7	6.0
Sc/Y	4.0			4.0	4.7	3.9	5.3	13.2
Ti/Sc	84.9			38.0	85.1		66.2	

	9	10	11	12	13	14	15	16
SiO_2	52.75	52.00	53.96	53.79	55.34	51.29	51.71	55.72
TiO_2	0.16	0.68	0.23	0.23	0.57	0.14	0.22	1.05
Al_2O_3	3.08	12.30	16.54	8.36	11.10	13.60	16.18	19.66
FeO	7.72	10.20	6.75	10.04	9.22	8.89	7.22	6.76
MnO	0.16	0.18	0.12	0.19	0.24	0.18	0.15	0.09
MgO	22.78	13.00	9.72	19.82	12.87	15.65	12.02	4.74
CaO	9.70	9.26	10.05	6.37	7.72	8.81	10.29	7.63
Na_2O	0.11	1.74	2.44	0.59	1.93	1.14	2.05	3.74
K_2O	0.01	0.71	0.10	0.34	0.76	0.12	0.14	0.58
P_2O_5	0.030	0.101	0.024	0.018	0.082	0.015	0.015	0.040
S (ppm)	50	710						
mg# (0.9)	0.854	0.716	0.740	0.796	0.734	0.777	0.767	0.581
CaO/Al_2O_3	3.15	0.75	0.61	0.76	0.70	0.65	0.64	0.39
Al_2O_3/TiO_2	19.9	18.1	71.9	36.3	19.5	97.1	73.0	18.7
CaO/TiO_2	62.5	13.6	43.7	27.7	13.5	62.9	46.4	7.3
Ti/Zr	46.5	58.2	35.4	31.3	46.2	22.7	41.5	84.2
Ti/V	18.6	17.8	14.1	13.7	22.8	5.6	13.2	58.6
Sc/Y		2.3	>12					
Ti/Sc		145.0	59.1					

1-Penikat intrusion/Yli-Penikka chill. Oulu sample 9383-7003 and 471-PTPRO. Analyzed by Rautaruukki.

2-Penikat intrusion /Sompujärvi chill (Ki-6 171.82 m). Analysis 1, Table 1, Alapieti *et al.* [6].
3-Penikat intrusion /Sompujärvi chill (Ki-6 171.49 m). Analysis 2, Table 1, Alapieti *et al.* [6].
4-Penikat intrusion /Sompujärvi chill. Oulu sample 472-PTPRO. Analyzed by Rautaruukki.
5- Gabbronoritic sample, Penikat/ intrusion Kilkka. Oulu 36-THU-87 and 73-PTPRO. Analyzed by Rautaruukki.
6- 3 m thick preintrusion dike below Konttijärvi intrusion. Oulu sample 454-PTPRO and DH KOJ-10/44.20-44.32 m.
7- Pyroxenitic pre-intrusion dike below Suhanko. Oulu sample 469-PTPRO, also see[23] analysis #2. Analysis Rautaruukki.
8- Suhanko fine-grained autolith - chilled margin [6], Oulu sample 470-PTPRO. Trace elements from Oulu sample 476-PTPRO.
9- 8 m thick preintrusion dike below Konttijärvi intrusion block. DH KOJ-10/30.22-31.10 m. See [23] analysis # 1. Analysis by Rautaruukki.
10 - Loljunmaa dike. Oulu sample 474-PTPRO =1/Lo = 1-TOH-92. From Alapieti *et al.* [6]; analysis Oulu.
11 - Chill of Koillismaa intrusion in marginal series. South of Unilampi, Kuusijärvi block. Oulu sample U144I= 473-PTPRO. analysis Rautaruukki.
12 - A basic rock below the Koillismaa intrusion (Kuusijärvi block/Lotanvaara). Oulu sample U172, analysis Rautaruukki.
13 - A greenstone between top of Koillismaa intrusion and granophyre (Kuusijärvi block). Oulu sample U264I.
14 - A fine grained rock in the Koillismaa intrusion, Syöte block /Rometölväs area. DH B7/12.80-12.90.
15 - A fine grained rock in the Koillismaa intrusion, Porttivaara block /Baabelinälky. Sample PO-33; analysis Oulu.
16 - A fine grained rock in the Koillismaa intrusion, Soukelinälkky area. Sample PO-34; analysis Oulu.

When incompatible element abundances for the chilled margin samples and the preintrusion dikes are normalized to chondrite concentrations (Fig. 6), a pronounced negative anomaly is seen in Nb, P and in some cases, Ti. Most samples contained Nb and Ta values of less than the detection limits of 2 and 0.3 ppm, respectively; true measured values would therefore result in even greater negative anomalies than shown. Fig. 6 compares the Finnish samples to an average of nine B1 micropyroxenite sill samples related to the Lower Zone of the Bushveld Complex [19-20] and to a fine-grained marginal rock (B3) related to the Main Zone of the Bushveld Complex [20], (sample CO-045).

Additional trace element ratios which are relevant to the discussion of parental magma genesis are Sc/Y, Pd/S and Pd/Cu as discussed by Sun *et al.* [37]. They state that modern boninites have high Sc/Y (5-8), Pd/S (1×10^{-4}) and Pd/Cu (5×10^{-4}) ratios vs. Sc/Y = 2-3, Pd/S = $2\text{-}4 \times 10^{-5}$, and Pd/Cu = $1.5\text{-}2 \times 10^{-4}$ for Archean SHMB. First considering the Sc/Y ratio (Fig. 7), Finnish samples again fall into two groups coincident with the Cr-rich and Cr-poor types. The Cr-rich samples have Sc/Y ratios ranging from 3.9 to 5.3 (ave. = 4.4, not including Loljunmaa dike), while the Cr-poor samples have very high Sc/Y ratios >12. The Paleoproterozoic UPAB boninite-like rocks of Poidevin [33] also have an intermediate Sc/Y ratio of 4.6. Data for Pd is not available, although Iljina [23] estimated the Pd content of the parental magma of the Portimo intrusion. Based on R-factors calculated on Ni contents of massive sulfide ores, the initial Pd content of the silicate magma was at approximately 10 ppb. This value however, cannot be used to distinguish magma type; on the basis of the other trace element data we predict that the Pd/S ratio would be relatively high for the parental magma.

Isotopic data

A compilation of Nd isotope data for the Fennoscandian ca. 2.44 Ga intrusions in Finland and Russia [23] (Fig. 8) shows ϵ_{Nd} values between 0 and -4, which are less negative than those of the Bushveld Complex $\epsilon_{Nd}^{(2050)}$ = -2 to -14, Sharpe [35] as quoted in Barnes [7]. The Fennoscandian values are similar to those of the Stillwater Complex $\epsilon_{Nd}^{(2701)}$ from +1.7 to -5.6 [28]; $\epsilon_{Nd}^{(2731)} = -1.5 \pm 1.3$ [34]; $\epsilon_{Nd}^{(2701)} = -2.8 \pm 0.2$ [13]. All of these values differ markedly from the positive ϵ_{Nd} of modern boninites and of mid-Tertiary boninites from New Caledonia [10]. Cambrian boninites from Tasmania [9] and Victoria [29], however,do have ϵ_{Nd} values between -2.6 and ca. -8. Sun *et al.* [37] present ϵ_{Nd} values for Archean and Proterozoic SHMB which range between +0.7 and -3.3. The ϵ_{Nd} values for the Fennoscandian 2.44 Ga suite and for the Bushveld and Stillwater Complexes [7] seem to have closer affinities with those of contaminated SHMB than with Nd isotope data for modern boninites.

Table 2. Trace element analyses, sample numbers as in Table 1.

	1	4	5	6	7	8	10	11
Sc	28	28	28	51	37	33	28	24
V	150	90	150	147	230			98
Cr	860	510	1300	1160	2300	290	1100	310
Co	51	39	55		57	42	59	40
Ni	160	140	160	267	250	180	360	160
Cu	50	70	30	40	<10		99	62
Zn	130	200	110	121	160	63	130	80
Rb	95	96	34	4.7	17	<10	28	10
Sr	400	200	300	38	20	500	300	600
Y	7	7	6	13	7	2.5	12	<2
Zr	50	70	60	46	40		70	39
Nb	<2	<2	2		2	2.7	4	0.3
Sb	1.9	8.5	0.2		0.2	<0.1	0.2	0.2
Cs	1.1	2.2	0.7		1.4	0.2	0.5	<0.2
Ba	470	200	150		47	110	210	80
La	8.6	19.8	7.8		10.9	2.5	11.1	4.2
Ce	20	45	17		25	7	24	9
Nd	9	21	8		12	4	12	4
Sm	1.7	3.3	1.6		2.5	0.75	2.6	0.81
Eu	0.49	0.69	0.41		0.61	0.32	0.78	0.43
Tb	0.2	0.3	0.2		0.3	0.2	0.5	0.1
Yb	0.92	0.68	0.89		1.08	0.59	1.61	0.44
Lu	0.14	0.1	0.16		0.16	0.09	0.26	0.08
Hf	1	1.6	1.2		1	0.6	1.9	0.6
Ta	0.4	<0.3	<0.3		0.6	<0.3	0.3	<0.3
W	2	<1	<1		<1	<1	<1	<1
Pb		10		11	16			10.4
Th	1.5	9.6	3.4	7	2	0.3	2.3	0.4
U	0.3	1.7	0.5	2.5	1.2	<0.1	0.4	0.3

DISCUSSION

The question of what type of parental magma the intrusions were derived from has been considered by Alapieti and coworkers since the 1970's. The Cr-rich ultramafic rock types from the lower part of the Konttijärvi marginal series were interpreted in Alapieti *et al.* [2] as magmatic layers and were correlated with MCU I of the Narkaus intrusion. However, when the Konttijärvi deposit was exposed, these rocks were discovered to be xenoliths of a dike with compositions that resembled boninites. Further drilling and analysis of other mafic dikes below the Suhanko-Konttijärvi intrusion have led to the present study.

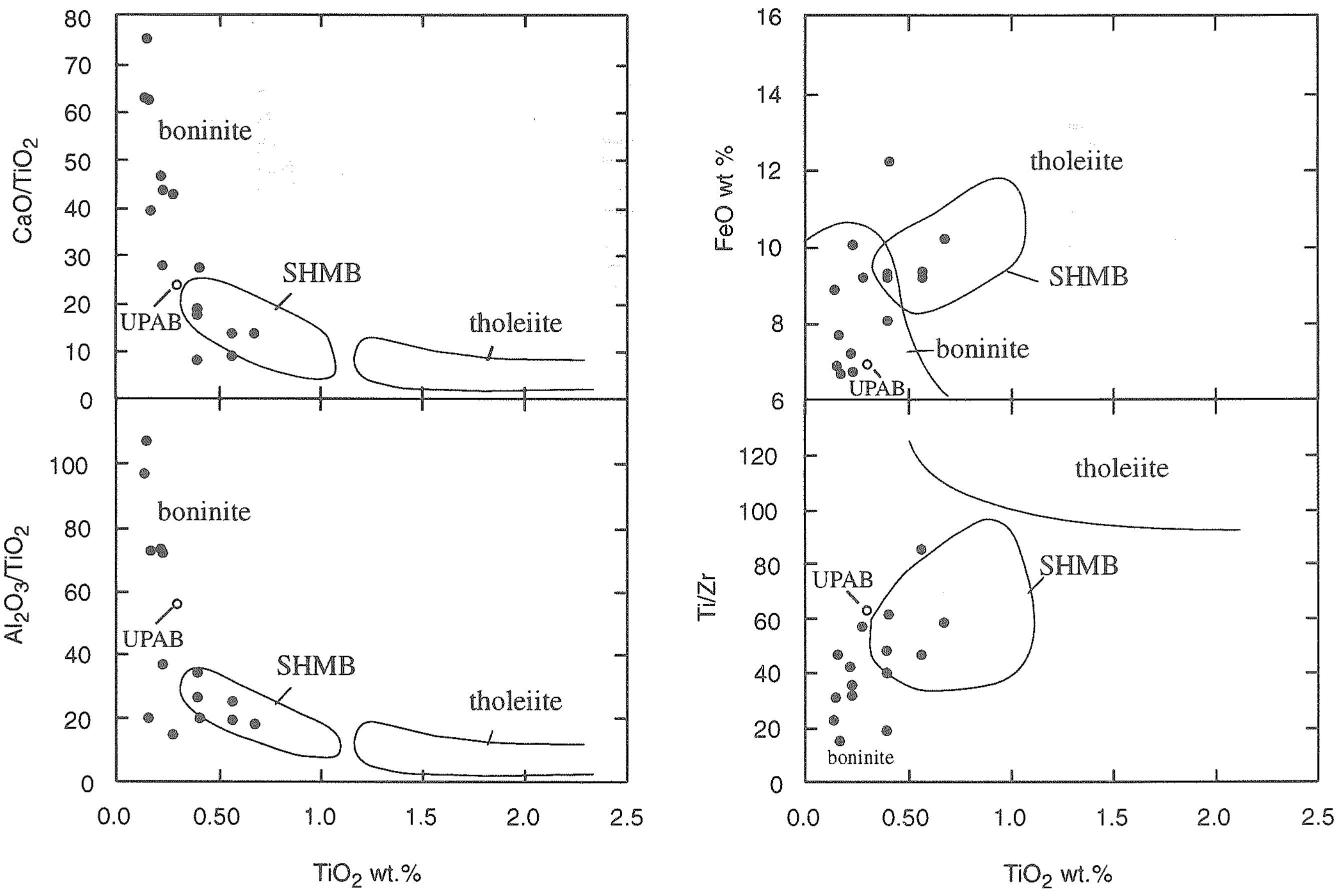

Figure 3. Variation of TiO2 with CaO/TiO2, Al2O3/TiO2, FeO and Ti/Zr. Fields for SHMB enclose data of Sun *et al.* [37], and fields for tholeiites enclose data pillowed amphibolites of the Bogoin-Boali greenstone belt (UPAB of Poidevin [33]) are also plotted for comparison.

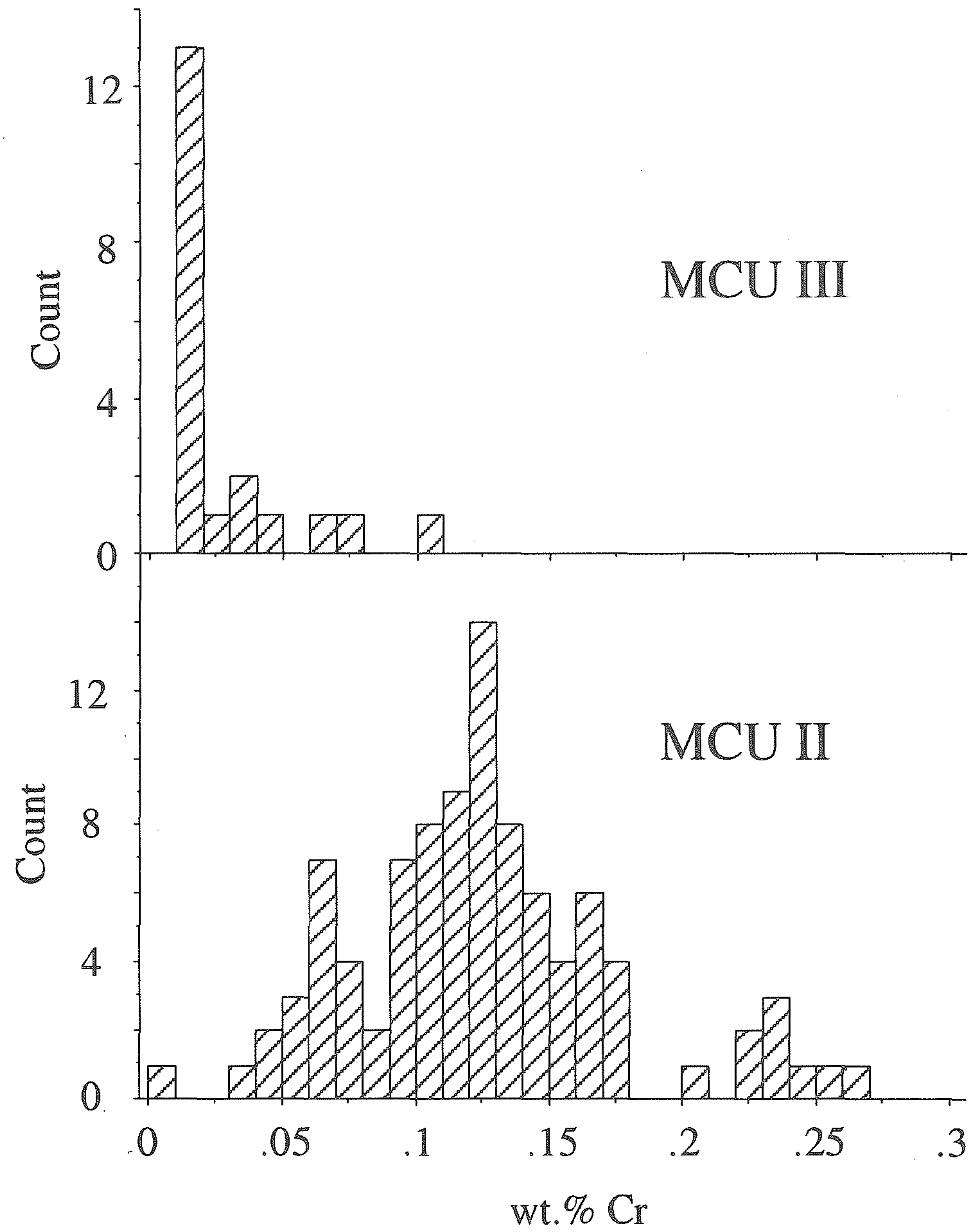

Figure 4. Histograms showing the difference in metagabbro Cr-contents between megacyclic units (MCU) II and III in the Narkaus intrusion.

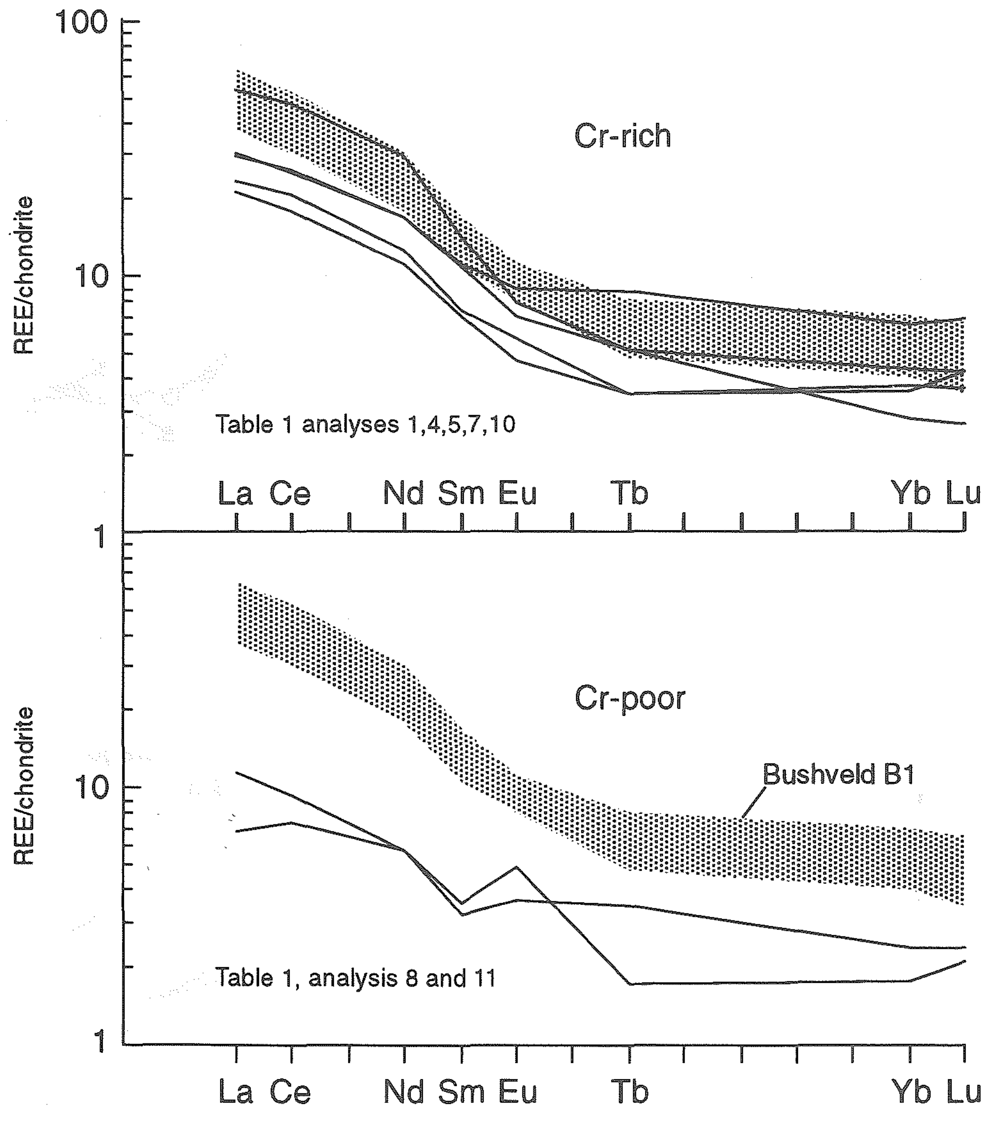

Figure 5. Chondrite-normalized REE patterns for Cr-rich and Cr-poor magma types in the Finnish intrusion belt. The stippled field representing the range for Bushveld B1 magma [36] is shown for reference.

The major and trace element geochemical data for the chilled margin and preintrusion dike samples show that these compositions are generally similar to those of modern boninitic series magmas. Similarities include: high MgO contents at intermediate SiO_2 contents, low TiO2 and HFSE contents (mostly < 0.5 wt.% TiO_2), high Cr contents, and high CaO/TiO_2 and Al_2O_3/TiO_2 ratios combined with low Ti/Zr ratios. Although the presence of a negative normalized Ta anomaly has yet to be proven, a negative Nb anomaly is present. Sc/Y ratios are also close to those of modern boninites. The Nd

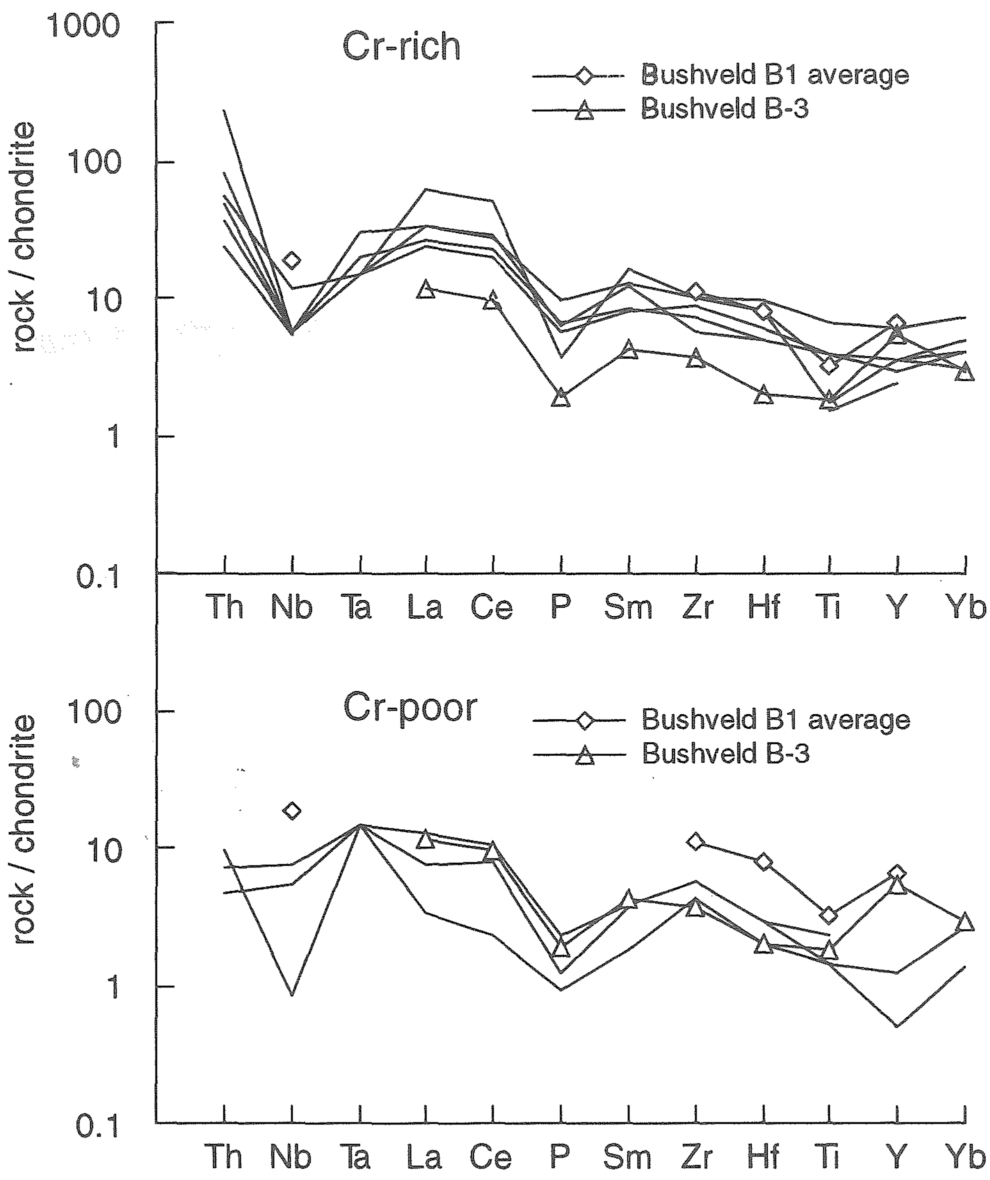

Figure 6. Chondrite-normalized trace element patterns for magma types in the Finnish intrusion belt: Cr-rich (analyses 1, 4, 5, 7, 10) and Cr-poor (analyses 8 and 11, plus one Cr-poor autolith from the Niittylampi block of the Narkaus intrusion, sample PtPro-497). The patterns for average Bushveld B1 and B3 magma types [36, 20] are shown for reference. Normalizing values from Thompson [39].

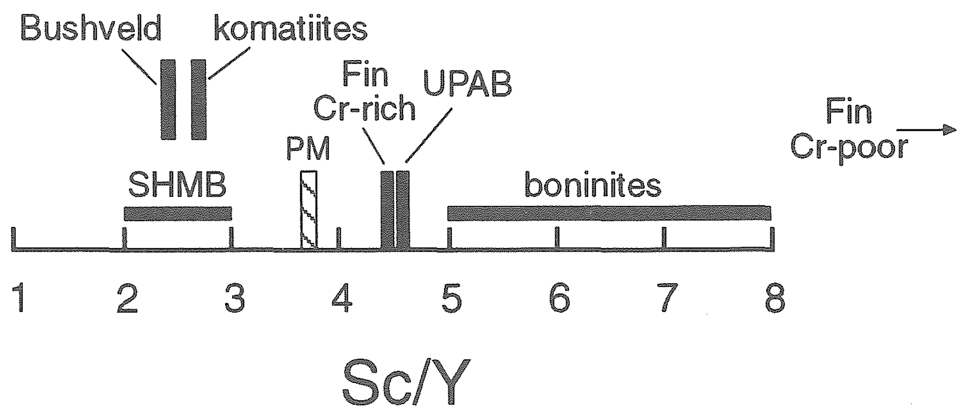

Figure 7. Ratios of Sc/Y for selected rocks. Data from Sun *et al.* [37], Poidevin [33] and from this study. SHMB, siliceous, high-magnesium basalts; PM, primitive mantle; UPAB, upper pillowed amphibolites of Bogoin.

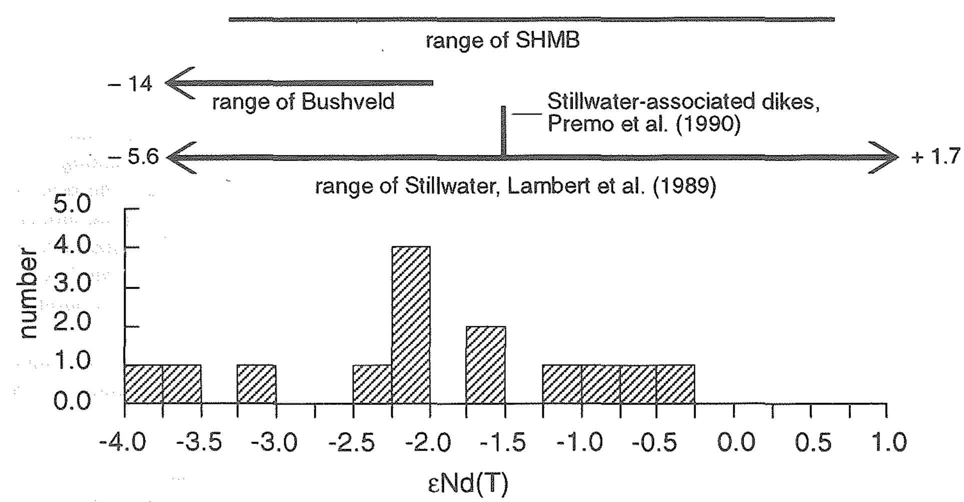

Figure 8. Histogram showing ϵ_{Nd} for rocks of the Fennoscandian intrusion belt, compared with those of the Bushveld and Stillwater Complexes. Data from Iljina [23], Turchenko [40], Premo *et al.* [34] ($\epsilon_{Nd}^{2731} = -1.5 \pm 1.3$ for group 2 high-Mg gabbronorite Stillwater-associated dikes and sills), DePaolo and Wasserburg [13] (-2.8 ± 0.2 for gabbro from the Stillwater intrusion); Bushveld data from Sharpe [35] as quoted from Barnes [7].

isotope values, however, show negative ϵ_{Nd} values similar to those of Archean contaminated komatiites but quite different from the positive values of modern boninites. The geochemistry of the Fennoscandian rocks is also similar to that of the Paleoproterozoic upper pillowed amphibolitesof Bogoin, Central African Republic [33].

Geochemical Modeling

We tested the possibility that the average parental magma compositions could have been produced by contamination of an idealized komatiitic liquid by a granite-gneiss followed by simple ultramafic crystal fractionation, using geochemical modeling. The element concentrations used for the contaminant are from a granite-gneiss sample which outcrops south of the Porttivaara Complex and is its host rock (sample 2 = PO-31, Table 3), and the komatiite used in the calculations is from Nesbitt and Sun [30], analysis 9) which is very close to Sun *et al.'s* [37] "idealized" komatiite.

Three approaches were used in the modeling. First, mass balance calculations of the major elements showed that the average parental magma composition can be derived by combining the basement and komatiitic compositions with approximately 13% olivine (Fo_{92}) fractionation. Second, the behavior of trace elements was modeled following the assimilationðfractional crystallization calculations of Sun *et al.* [37] using the formula

$$Cm = [c_m^o(1-\chi)+C_a\chi]F^{D-1}$$

where C_m, C_m^o, and C_a are the element concentrations in fractionated magma (here, the parental magmas to the Finnish intrusions), komatiite, and the contaminant, respectively; χ is the per cent assimilation, F is the (mass of fractionated magma/mass of initial magma), and D is an element's partition coefficient between the fractionated mineral and the melt.

If we assume that D approaches 0 for elements such as Sc, Nd, and Zr in early fractionating phases such as olivine, then the equation

$$F= [C_m^o(1-\chi)+C_a\chi]/C_m$$

can be plotted as in Fig. 9 for all values of c and F between 0 and 1 for selected elements. Sun *et al.* [37] used these equations to estimate the element concentrations in the contaminant resulting in a convergence near F ~ 0.68 (32% crystallization) and χ= 15% contamination (Fig. 9a). The lack of convergence for the Finnish example (Fig. 9b) indicates that for a contaminated komatiite model, either the trace elements did not behave coherently during assimilation-fractional crystallization, or the contaminant may not have been the granite-gneiss which surrounds the intrusions. One line of evidence that supports the latter scenario is that Y concentrations for this sample and for another granite-gneiss basement sample from nearby (PO-32) are rather low (analyses ranged from <1 to 3.9 ppm). Contamination with a rock of a different trace element composition, although similar major element composition, could have taken place deeper in the crust before the magma ascended to its level of emplacement.

The third approach confirmed the above modelling. The same major and trace element compositions were entered into Mixnfrac, a phase equilibria differentiation program derived from the model described in Nielsen [31-32]. The program parameters were set to simulate assimilation and fractional crystallization with no magma chamber recharge or eruption. Modeled concentrations of Sc and Zr matched those of the average Finnish parental magma at approximately 35% fractionation, while those of La and Nb indicated approximately 45% fractionation. Again, the behaviors of Y and Nd did not fit those of many other trace elements. The results for the Mixnfrac modeling of Sc, Zr and La broadly match the boxed area on Fig. 9b.

Implications

The observed geochemical similarities of the mafic intrusions' parental magmas to boninitic magmas have two areas of significance. The first involves understanding of the tectonic regime in which the intrusion belt was emplaced and the tectonic processes active during early Proterozoic times in the

Table 3. Values used for the geochemical modeling. Trace element concentrations (ppm) for Fig. 9a from Sun *et al.* [37]; for Fig. 9b from this study and from Nesbitt and Sun [30]. C_m^o = concentration of element in the parent magma, C_a = concentration of element in contaminant and C_m = concentration in the fractionated magma.

	1	2	3
SiO_2	53.89	71.93	45.85
TiO_2	0.31	0.19	0.35
Al_2O_3	11.55	14.72	8.35
FeO	8.63	1.34	10.95
MnO	0.18	0.02	0.22
MgO	13.43	0.55	23.45
CaO	8.38	2.85	8.74
Na_2O	1.92	4.68	0.83
K_2O	1.28	2.29	0.15
P_2O_5	0.043	0.053	0.020

1 - Average composition of Table 1
2 - granite-gneiss basement near the Porttivaara block of the Koillismaa intrusion, sample PO-31
3 - komatiite from Munro Township locality, Canada. Analysis 9, Table 1 of Nesbitt and Sun [30], Univ. Adelaide No. 422/95.

Fig. 9a.	C_m^o	C_a	C_m
Sc	35	≤10	35
Zr	20	172	63
La	0.82	30	7.86
Y	10	20	17

Fig. 9b.	C_m^o	C_a	C_m
Sc	27	1.3	31.5
Zr	2.0	6.0	9.6
La	0.8	15.5	7.8
Y	10	2	7

Fennoscandian shield. The second involves the implications to genesis of platinum-group element (PGE) ore concentrations.

Although heat flow may have been higher during early Proterozoic times resulting in a different scale of processes, abundant evidence exists in this region for the occurrence during the Archean of tectonic processes resembling those of modern plate tectonics. Brewer and Pharoah [8] describe the subduction of early tholeiitic oceanic crust during Archean time, which resulted in formation of garnet amphibolites. When these rocks underwent partial melting, they produced the 3.1 Ga tonalitic, trondhjemitic and granodioritic gneisses of the Archean basement in the Karelian province. The assembly of the Archean Fennoscandian shield may have occurred during the 2.9-2.6 Ga Lopian orogeny. These events, especially Archean tholeiitic magmatism, may have produced depleted mantle which, when partially melted at 2.4 Ga, resulted in the second-stage melts parental to the intrusion

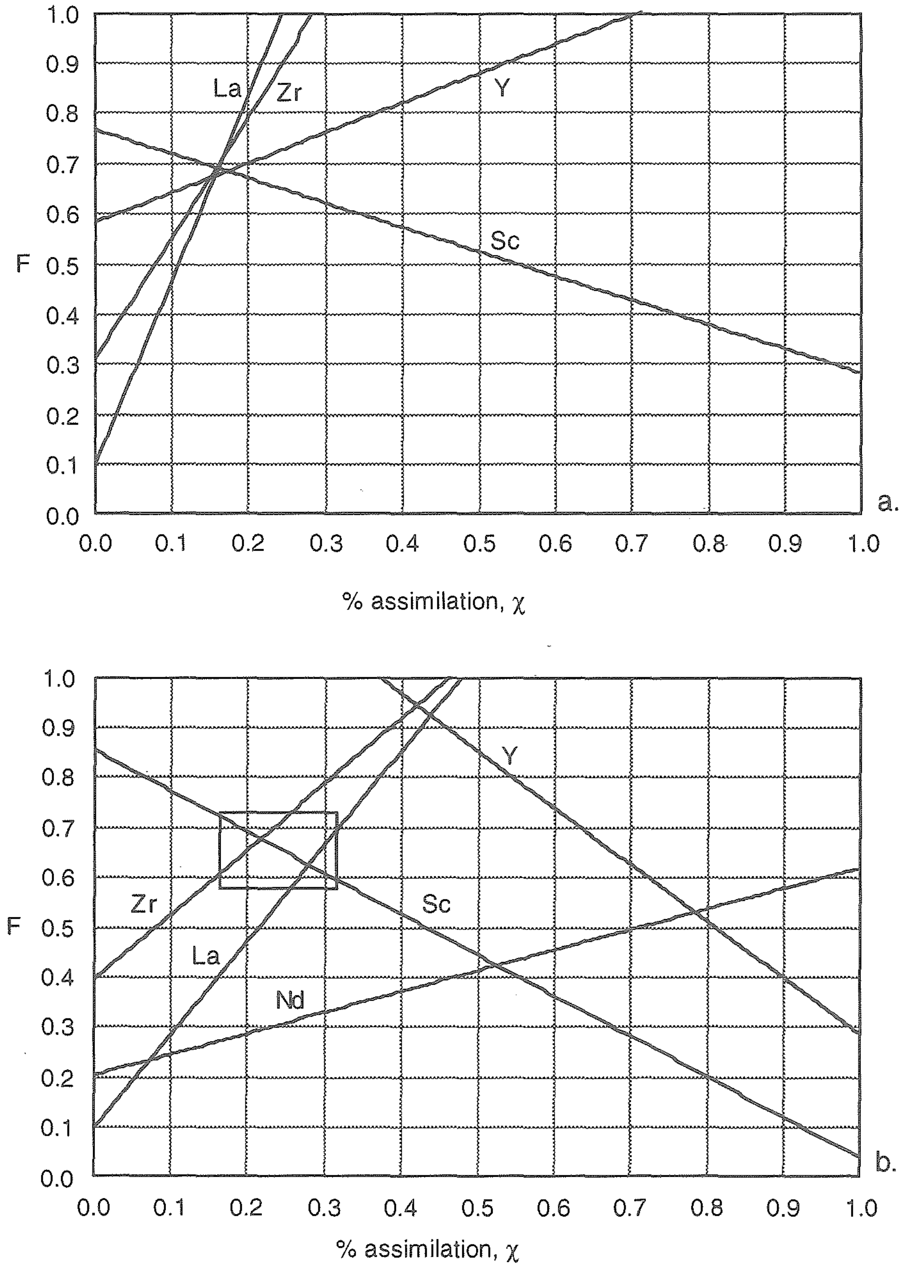

Figure 9. Plots of the equation $F= [C_m^o(1-\chi)+C_a\chi]/C_m$ for selected trace elements assuming a contaminated komatiite model for data from a) Sun *et al.* [37], and b) this study. See text for discussion. belt complexes. Nd isotopic evidence presented in Iljina [23] indicates that (assuming no contamination during magma ascent) the mantle that produced magmas at 2.44 Ga had experienced a previous Nd isotopic 'reset' between 3.0 and 2.8 Ga.

While some authors take negative Nb and Ta anomalies to reflect clear evidence of a supra-subduction zone environment of formation (e.g. [14, 12]) propose that processes active in other types of tectonic settings can generate rocks with boninitic affinities. Specifically, continental rifting and ocean-floor spreading can produce the necessary conditions for boninitic magma genesis under anhydrous conditions (T>1100 °C, P<5 kbar). The Fennoscandian intrusion belt seem to have been emplaced within an extensional tectonic environment.

The Finnish intrusion belt contains numerous high-grade PGE-bearing horizons [4, 6] and references therein, and [16-17, 22]. Their parental magmas are similar to assumed Bushveld Complex parental magmas in two ways: first, the overall magmatic stratigraphy of both areas can be subdivided into distinct magma types, and second, parental magma compositions are similar to boninites [12, 20], although Barnes [7] claims that these are actually SHMB magmas. These resemblances suggest that, regardless of the exact tectonic processes which produced them, magmatic intrusions resulting from second-stage melts have high potential for PGE ore bodies. Of course, in order for an ore body to be formed, this potential must be realized by some mechanism of PGE concentration.

CONCLUSIONS

The geochemical data above can be combined into a model for the genesis of the intrusion belt (Brewer and Pharoah [8] and references therein). Archean tholeiitic magmatism, Lopian (late-Archean) arc volcanism and craton assembly produced depleted mantle underneath the Fennoscandian shield crust. Late Lapponian-Jatulian rift volcanism (2.45-2.0 Ga) due to a rising mantle diapir resulted in the emplacement of the mafic intrusion belt, and later to eruption of tholeiitic basalts within rifted Archean crust. Many of the parental magmas of the intrusion belt have compositions that could be explained either by processes that form boninites in incipient rift environments [12], or by a komatiitic magma which assimilated granite-gneiss and subsequent fractional crystallization of ultramafic components [37]. Geochemical modelling of contamination of idealized komatiite by granite-gneiss basement for Sc, Zr, La and Nb matched the measured Finnish parental magma compositions at values of 20 - 30% contamination and 35 - 45% fractionation. Modelling of Y and Nd indicated much higher values for both parameters. Trace element ratios support the boninite model of genesis, while the contaminated komatiite model is only partially supported by trace element modelling and by Nd isotopic evidence. If contamination occurred, it may have been with crust other than the granite-gneiss basement into which the intrusions were placed.

Acknowledgments

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