Originally published as:

Lindh, A., Andersson, U. B., Lundqvist, T., Claesson, S. (2001): Evidence of crustal contamination of mafic rocks associated with rapakivi rocks: an example from the Nordingrå complex, Central Sweden. - Geological Magazine, 138, 4, 371-386.

DOI: 10.1017/S0016756801005672

Evidence of crustal contamination of mafic rocks associated with rapakivi rocks: an example from the Nordingrå complex, Central Sweden

ANDERS LINDH*, ULF BERTIL ANDERSSON†, THOMAS LUNDQVIST‡
& STEFAN CLAEISSON§

*Geological Department, Sölvegatan 13, SE-223 62 Lund, Sweden

†Department of Earth Sciences, Villavägen 16, SE-752 36 Uppsala, Sweden

‡Geological Survey of Sweden, Box 670, SE-751 28 Uppsala, Sweden

§Laboratory for Isotope Geology, Swedish Museum of Natural History, Box 50007, SE-104 05 Stockholm, Sweden

(Received 4 August 2000; accepted 27 April 2001)

Abstract – Gabbro and leucogabbro are volumetrically important rocks in the Nordingrå rapakivi complex, East Central Sweden. Plagioclase, ortho- and clinopyroxenes, and olivine dominate the gabbro. Perthitic orthoclase and quartz are interstitial in relation to the major minerals. The present work is based on 232 major-element and a large number of trace element analyses together with 15 whole rock Sm–Nd isotope analyses of the Nordingrå gabbroic rocks. $\epsilon_{\text{Nd}(T)}$ values are negative, -1.1 to -3.2 ; the most negative values come from the gabbro. Most rocks are enriched in iron, some extremely enriched; none represent primitive mantle melts. The range of Mg-numbers is the same in the gabbro and the leucogabbro. Plots of the Ni-content vs. the Mg-number are scattered, but there is a positive correlation between these two parameters. The primary mantle-normalized ratios between similar trace elements are normally strongly different from one. Values larger as well as smaller than one are found for the same ratio in different rocks. The rare earth elements are only weakly fractionated with small Eu anomalies, negative for the gabbros and positive for the leucogabbros. The primary magma of the Nordingrå gabbro-anorthosite is thought to have been derived from a mildly depleted mantle source. Variations in the degree of partial melting of a reasonably homogeneous enriched mantle do not explain the observed chemical evolution. Crystal differentiation can account for some geochemical features, especially the Fe-enrichment. Crustal contamination is required by other characteristics as, for example, the negative $\epsilon_{\text{Nd}(T)}$ values and the irregular and sometimes high primary-mantle normalized incompatible trace-element ratios. Al-rich relic material from the formation of the rapakivi granite melt is another source of assimilation. Most probably contaminants are heterogeneous, including undepleted crust (represented, for example, by early Svecofennian and Archaean granitoids), depleted crust (restitic after rapakivi magma extraction), and to some degree the associated rapakivi magma itself. Significant parts of this crust should be Archaean in age.

1. Introduction

Rapakivi granites and associated mafic rocks occur on all continents. In the Baltic Shield, they form an important rock group. Most of them have intruded into the Palaeoproterozoic Svecofennian rocks; the most easterly massifs, however, were emplaced on the border between the Archaean craton and the Svecofennian Orogen. Figure 1 shows the major massifs of the Shield. In addition, numerous smaller massifs occur scattered in the same general area as the major ones. The massifs show a distinct younging westwards (cf. Fig. 1) from the oldest in southeastern Finland and northern Estonia (*c.* 1.65–1.61 Ga) to central Sweden (*c.* 1.53–1.50 Ga). This belt-like appearance of rapakivi rocks seems to have developed stepwise,

where an intermediate (*c.* 1.59–1.56 Ga) belt from the Riga Batholith in the south to the Nordingrå Massif in the north separates the oldest and the youngest rapakivis (cf. Andersson, 1997a). However, the easternmost massifs in Russian Karelia break this simple pattern, since they are 0.1 Ga younger than their nearest neighbours to the west.

The Nordingrå rapakivi massif occurs in East Central Sweden. Lundbohm (1899) and Högbom (1909) first mapped the massif. The most detailed mapping was, however, published a few years later, accompanied by an elaborate description of the rocks (Sobral, 1913). The latest published map is part of the mapping programme of the Geological Survey of Sweden (Lundqvist *et al.* 1990). These maps are all in good agreement because of good exposure and distinct lithologies in the area. Figure 2 is a simplified compilation of these maps. Granite, gabbro and leucogabbro with associated anorthosite make up the massif together with minor monzonite. Mafic rocks play an

* Author for correspondence: anders.lindh@geol.lu.se

† Present address: GeoForschungsZentrum, P.B. 4.1, Telegrafenberg, D-14473 Potsdam, Germany

Figure 1. Location map showing the rapakivi massifs of the Baltic Shield and neighbouring parts of the East European Platform. Age provinces are indicated with numbers (in Ga) and heavy lines (after Andersson, 1997a). Some small Swedish and Finnish rapakivi massifs are excluded from the map. The Suomenniemi massif is a satellite to the Wiborg massif. KB – Kristiansand–Bang Zone; MZ – Mylonite Zone.

important part. Specific to the Nordingrå massif is its high percentage of outcropping leucogabbro and anorthosite.

According to an age determination on zircons, the intrusion age of the Nordingrå rapakivi granite is 1578 ± 19 Ma (Welin & Lundqvist, 1984). This is an upper intercept age obtained from slightly discordant zircon fractions. The same authors also reported a two-point discordia suggesting an identical age for the leucogabbro. More recently, T. Mårtensson (unpub. Masters thesis, Univ. Lund, 1997) reported ages

obtained by the single zircon evaporation technique on the Nordingrå granite (1577 ± 6 Ma) and enclaves in the granite. His results confirm the older data. Efforts to date the granite with the Rb–Sr whole rock and separated mineral–whole-rock isochron methods were not successful (Welin & Lundqvist, 1984). Rocks from the approximate time interval 1.78–1.58 Ga, that is, between the late Svecofennian granites and the Nordingrå rapakivi rocks, are unknown in the Nordingrå area. Although some shear zones and faults probably were active during this time, the rapakivi plu-

Figure 2. Map of the southern and central parts of the Nordingrå rapakivi massif, simplified after Sobral (1913) and Lundqvist *et al.* (1990). Sample numbers refer to set 1 of the chemical analyses and the new Sm–Nd analyses of rapakivi granites.

tonic rocks are in all evidence anorogenic, emplaced into a cratonized crust. The present paper is devoted to the mafic rocks, especially their chemical composition and the reasons for their chemical variation.

2. Geological setting and field relations of the Nordingrå rocks

2.a. Country rocks

All Swedish rapakivi complexes occur in the Svecofennian Bothnian Basin (Hietanen, 1975) dominated by metagreywacke and minor argillite. These have depositional ages between > 1.95 and 1.87 Ga old (see, e.g. Lundqvist *et al.* 1990; Claesson *et al.* 1993; Wasström, 1993; Welin, Christiansson & Kähr, 1993;

Lundqvist, Vaasjoki & Persson, 1998). An early generation of calc-alkaline granitoids (intrusion ages, mainly 1.89 – 1.85 Ga; early Svecofennian), dominated by granodiorite and tonalite and two younger generations (1.83 – 1.78 Ga) of granites intrude the metasediments; the first (1.82 – 1.80 Ga) comprises typically S-granites, and the second (1.80 – 1.77 Ga) dominantly I-type (see, e.g. Skiöld, 1988; Skiöld *et al.* 1993; Romer & Smeds, 1994; Claesson & Lundqvist, 1995; Öhlander & Romer, 1996).

The metamorphic grade in the Bothnian Basin varies. Typically, rocks are characterized by low-pressure upper greenschist to upper amphibolite facies. Abundant migmatites occur in the high-grade areas (Lundqvist *et al.* 1990). The Nordingrå massif is

emplaced into a low-grade area. Thermal effects related to the Nordingrå rapakivi rocks have been observed in a narrow zone along the western contact of the massif and in wall-rock xenoliths. Cordierite and hypersthene are formed in xenoliths of meta-greywacke, and hypersthene is most prominent in metabasalt xenoliths. A younger dolerite sill is intruded into the Nordingrå rocks (cf. Fig. 2)

2.b. The Nordingrå rocks

Three rock types form the major constituents of the Nordingrå massif: granite, gabbro and leucogabbro (cf. Fig. 2). The granite occupies the northern parts, whereas in the south the massif is composed of gabbro in the west and leucogabbro in the east. Results from gravimetric surveys along NW–SE and E–W profiles have revealed a positive gravity anomaly in the granite area. This has led H. Henkel to suggest that the granite forms a 1 km thick sheet on top of the gabbro (see Lundqvist *et al.* 1990 for details). The gravimetric data further indicate that the leucogabbro forms an approximately equally thick sheet on top of *c.* 5 km of gabbro. In the west, the contact between gabbro and country rocks dips westwards below the metasediments.

The Nordingrå granite dominates the exposed surface of the massif. Xenoliths of leucogabbro in the granite and dykes of granite in the leucogabbro indicate that the granite is the younger. Mingled contacts and monzonitic hybrids in contact zones suggest that at least locally the granite and the gabbro were liquid simultaneously. Generally, the granite seems to have remained above its solidus longer than the gabbro.

The Nordingrå granite is red or greyish red, rarely grey and typically contains tabular, 0.5–2 cm long K-feldspar megacrysts embedded in a fine-grained or finely medium-grained, partly granophyric matrix. Lundqvist *et al.* (1990) and Lindh & Johansson (1996) give more petrographic data. It is an A-type granite with the extremely low Mg-numbers typical of rapakivi granites. No evolved varieties occur; Rb/Ba ratios are low, rare earth element (REE) patterns are gently negatively sloping with pronounced but not very deep negative Eu-anomalies. An origin by melting of early Svecofennian granitoids is consistent with both the chemical and the Sm–Nd isotope composition (Lindh & Johansson, 1996).

Gabbro and leucogabbro are spatially intimately related. In outcrop, the gabbro sometimes forms dykes in, or brecciates, the leucogabbro. Enclaves of true anorthosite and of rare gabbro-like rocks occur in the normal, grey leucogabbro. These facts, together with abundant evidence of contacts between different gabbro types (coarse-, medium- and fine-grained), indicate a close co-magmatic relation among gabbro, leucogabbro and anorthosite, and suggest a multiple intrusion mechanism. The leucogabbro with minor anorthosite occupies an easterly position within the Nordingrå

massif. Gravimetric investigations suggest that the leucogabbro overlies the gabbro. The contacts between gabbro and leucogabbro are mostly irregular. At a number of localities, the gabbro displays rhythmical layering and lamination. G. Lundqvist (unpub. FL-thesis, Univ. Gothenburg, 1976) could not demonstrate any consistency in the orientation of this layering.

3. Petrographic description of the gabbro and leucogabbro

The gabbro is dark grey, usually medium- or fine-grained but sometimes coarse-grained, the latter with a tendency to weather to gravel. A fine-grained quartz-albite rock occurs as dykes. The leucogabbro is a coarse-grained rock with a plagioclase content between approximately 70 and 90%. Rocks with higher plagioclase contents are referred to as anorthosite; such rocks make up about 20% of the total anorthosite + leucogabbro volume. Extremely feldspar-rich, white anorthosite varieties occur as enclaves with diameters of up to some tens of metres in 'normal' leucogabbro or gabbro.

Modal and mineral chemical data are partly taken from G. Lundqvist (unpub. FL-thesis, Univ. Gothenburg, 1976) and Lundqvist *et al.* (1990). The modal composition of the gabbro is dominated by normally zoned plagioclase (An_{30-60}). In porphyritic varieties, this mineral occurs as crystals several centimetres in size in addition to matrix plagioclase. It should be noted that some 'porphyritic' gabbros evidently formed by disintegration from enclaves of leucogabbro. In such cases, scattered plagioclase crystals occur in the gabbro close to the enclaves. Olivine (Fo_{10-50}) is a normal constituent of the gabbro, but the abundance varies greatly. Reaction rims of orthopyroxene on olivine occur. Iddingsite, serpentine and magnetite are secondary minerals after olivine. Orthopyroxene (En_{25-60}) and clinopyroxene (Di_{30-70}) occur in the gabbro; Ca-poor pyroxene dominates. The two pyroxenes form discrete crystals as well as lamellar, drop-like or more irregular intergrowths with each other. When clinopyroxene is the host, the intergrowth tends to be finely lamellar.

Small amounts of reddish brown biotite, ilmenite and magnetite occur in the gabbro. Magnetite is usually subordinate to ilmenite and only rarely contains ilmenite lamellae. Scattered grains of pyrrhotite, chalcopyrite, pyrite and cubanite also occur.

Perthitic orthoclase and quartz are interstitial minerals. Their contents may be raised in schlieren in the gabbro. This leads to monzogabbroic and monzodioritic compositions. A high content of K-feldspar and quartz, at times accompanied by hornblende, calcite, epidote and prehnite, is typical for some reddish, pegmatoid or granitoid dykes and schlieren in the gabbro.

The leucogabbro is coarser-grained than the gabbro. Plagioclase crystals are normally 1–4 cm in length.

Occasionally larger crystals exist, attaining diameters up to several decimetres. Very coarse-grained (crystals up to a decimetre in size) pegmatoid bodies occur within the leucogabbro. In the leucogabbro, the compositional range of the plagioclase is An_{48-67} , although typically An_{60-65} and thus slightly more calcic than in the gabbro. A weak zoning is sometimes observed. Bluish or greenish, labradorizing cores of the crystals are found at some localities. Needle-shaped microlites of ilmenite and probably also of magnetite occur as inclusions. Secondary alteration to sericite, prehnite, epidote and calcite is rather common in the plagioclase. This type of alteration affects particularly some varieties with a high content of interstitial K-feldspar. These rocks have a characteristic pinkish-greenish colour.

The mafic minerals of the leucogabbro are mainly a uraltic hornblende, which more or less completely replaces former pyroxenes, clinopyroxene (Di_{60}), olivine, reddish brown biotite and opaque minerals. In the uraltite, orthopyroxene may occur among the pyroxene relics. Olivine forms small rounded crystals, which are often partially altered to serpentine or amphibole. Ilmenite is the dominant opaque mineral. The magnetite content is higher in the leucogabbro adjacent to the dolerite, possibly due to oxidation caused by the dolerite intrusion (Magnusson, 1983). Pyrrhotite is the most common sulphide. Small amounts of prismatic apatite are noted. Other, secondary minerals are cummingtonite-grunerite and chlorite.

4. Sm–Nd isotope systematics

Results from new Sm–Nd isotopic analyses including four analyses of the rapakivi granite are reported in Table 1. One set of analyses was performed at the Mineralogical-Geological Museum, University of Oslo, Norway. This batch of samples was also analysed chemically as part of this investigation (cf. Fig. 2). The analytical procedures are described by Johansson & Kullerød (1993), among others. An analysis of the international Johnson & Matthew 321 Nd-standard during this period yielded $^{143}Nd/^{144}Nd = 0.511117 \pm 12$ and $^{145}Nd/^{144}Nd = 0.348425 \pm 5$. Errors are given as 2σ .

A second batch of analyses was performed at the Laboratory for Isotope Geology, Swedish Museum of Natural History, Stockholm. The analytical procedures followed that described by Claesson (1987), except that the $^{143}Nd/^{144}Nd$ ratios were determined on totally spiked samples (see also Andersson, 1997b). During the period when these rocks were analysed, 22 measured $^{143}Nd/^{144}Nd$ isotope ratios for the La Jolla Nd standard gave an average of 0.511754 ± 16 , that is, 0.000100 less than the reference value (0.511854). The sample analyses were corrected accordingly. Four measurements of the La Jolla Nd standard interspersed with the samples in this study gave a corrected

mean $^{143}Nd/^{144}Nd$ ratio of 0.511860 ± 8 . All data are normalized to $^{146}Nd/^{144}Nd = 0.7219$. This second set was collected independently of sampling for whole-rock chemical analyses, and consequently there is no exact correspondence with the chemical data.

All $\epsilon_{Nd(1.58)}$ values are negative, varying between -1.1 and -3.3 for the gabbro, between -1.1 and -2.7 for the leucogabbro and between -2.7 and -3.1 for the new analyses of the granite. These granite data completely overlap with those reported by Lindh & Johansson (1996). All ϵ_{Nd} data are displayed in Figure 3 together with data for some other Fennoscandian rapakivi complexes and early Svecofennian granitoids and metasediments. Table 1 displays depleted-mantle model ages for the Nordingrå complex. They vary between 2.13 and 2.42 Ga for the gabbro, between 2.07 and 2.28 Ga for the leucogabbro and between 2.25 and 2.34 Ga for the granites. The depleted mantle is modelled according to DePaolo's (1981a) equation.

5. Chemical composition of gabbro and leucogabbro

The chemical data come from two data sets. Twenty-one gabbro and seventeen leucogabbro analyses are from samples directly collected for this investigation

Figure 3. Time-evolution of the $^{143}Nd/^{144}Nd$ isotope ratio (whole rocks). Note that the $\epsilon_{Nd(1.58)}$ values of the basic rapakivi rocks are totally encompassed in the time-integrated development of the early Svecofennian granitoids. Also, note the small range of Nordingrå rapakivi granites and the much larger range of felsic enclaves in the granite, partly overlapping the younger westerly massifs. The composition of the Archaean crust used for modelling is indicated with a solid circle. DM = Depleted mantle. References for the different fields and data, in addition to those reported here, may be found in Andersson (1997b), Andersson, Neymark & Billström (in press), Claesson (1987), Welin, Christiansson & Kähr (1993) and Claesson & Lundqvist (1995).

Table 1. Results from the Sm-Nd isotope analyses

Sample	Rock	Sm (ppm)	Nd (ppm)	$\frac{^{147}\text{Sm}}{^{144}\text{Nd}}$	$\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \pm 2\sigma$	T_{DM} $\epsilon_{\text{Nd}}(1.58\text{Ga})$	(Ga)	Sample locations (Swedish National Grid)
125**	Gabbro	4.472	20.00	0.1352	0.511946 ± 5	-1.1	2.13	698250/162225
311**	Gabbro	12.149	53.81	0.1365	0.511456 ± 7	-2.1	2.24	699290/162675
312**	Gabbro	4.116	18.31	0.1359	0.511929 ± 7	-1.6	2.18	698470/162695
031*	Gabbro	9.904	42.63	0.1405	0.511914 ± 6	-2.8	2.36	698325/162470
032*	Gabbro	5.983	25.16	0.1438	0.511939 ± 9	-3.0	2.42	698295/162490
033*	Gabbro	3.417	14.60	0.1415	0.511927 ± 4	-2.7	2.36	698490/162700
034*	Gabbro	9.807	43.30	0.1369	0.511853 ± 8	-3.3	2.37	698140/162670
036*	Gabbro	7.967	34.04	0.1415	0.511930 ± 8	-2.7	2.36	698110/162280
038*	Gabbro	7.413	31.33	0.1430	0.511947 ± 7	-2.6	2.37	697585/163400
119**	Leucogabbro	2.662	11.92	0.1350	0.511927 ± 11	-1.4	2.16	697690/163385
123**	Leucogabbro	1.870	9.32	0.1213	0.511720 ± 5	-2.7	2.18	697870/162855
320**	Leucogabbro	0.969	4.69	0.1257	0.511848 ± 9	-1.1	2.07	697750/162895
035*	Leucogabbro	3.290	13.82	0.1439	0.511999 ± 8	-1.8	2.28	698145/162670
86037*	Leucogabbro	3.887	16.97	0.1384	0.511955 ± 8	-1.6	2.20	697700/163370
040*	Granite	15.80	72.63	0.1315	0.511804 ± 5	-3.1	2.30	698690/163200
041*	Granite	15.05	71.17	0.1278	0.511779 ± 8	-2.8	2.25	698890/163410
042*	Granite	15.80	70.32	0.1359	0.511851 ± 13	-3.1	2.34	699665/163285
037*	Granite	15.07	68.54	0.1333	0.511844 ± 6	-2.7	2.28	701315/165100
BCR-1	Basalt std.	6.561	28.87	0.1374	0.512629 ± 9			

* Determined at the Laboratory for Isotope Geology, Museum of Natural History, Stockholm, Sweden.

** Determined at the Mineralogisk-Geologisk Museum, University of Oslo, Norway.

All $\epsilon_{\text{Nd}}(T)$ values refer the intrusion age of the Nordingr granite, 1.58 Ga. $^{147}\text{Sm}/^{144}\text{Nd} = 0.1966$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ are used for the present-day chondrite.

and have not been published earlier. The analytical results are reported in Tables 2 (major elements) and 3 (trace elements). These analyses were performed at the Geolaboratory of the Geological Department, Lund University, employing XRF, AAS, photospectrometry and INAA. The analytical procedures are described in more detail by Solyom, Lindqvist & Johansson (1992). Additional data (113 gabbros and 81 leucogabbros) have been presented by G. Lundqvist (unpub. FL-thesis, Univ. Gothenburg, 1976).

Selected Harker diagrams (Fig. 4) demonstrate the distinct chemical separation between gabbro and leucogabbro. However, scattering is considerable, especially for the leucogabbro. SiO_2 contents are largely above 52%, thus, many of the 'gabbros' are in fact intermediate rocks. The K_2O content of the leucogabbro is lower than that of the gabbro within most of the variation field (Fig. 5) despite significant overlap. The gabbro has a high K_2O content and especially a very high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio, which already at $\text{SiO}_2 = 58\%$ is typical of granites. A regression analysis indicates that about half of the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ variation is tied to the SiO_2 variation (coefficient of determination = 0.47; cf. Fig. 5). No covariance between $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and the Mg-number or any other single element can be found. The residuals seem to be equally distributed over the entire variation range.

All leucogabbros have SiO_2 contents above 49%. However, this does not imply that the leucogabbros are more differentiated than the gabbros. In Figure 6, the data are plotted against the Mg-number (based on the molecular content of magnesium, ferrous and ferric iron) as the independent parameter. The spread in

Mg-number is essentially identical for leucogabbro and gabbro, indicating similar differentiation ranges for both. In addition, to display the conspicuous chemical separation of gabbro and leucogabbro, Figure 6 suggests Ti first to behave incompatibly but later to become compatible reaching its maximum at about the Mg-number 0.25. The rock sequence is iron-enriched; the maximum Mg-number (0.52) is almost identical to the mean Mg-number of basalt (0.53) found by Le Maitre (1976), which is significantly different from primitive values.

Plagioclase, orthopyroxene and clinopyroxene dominate the normative mineralogy. Most samples lack normative olivine; others have minor amounts and only a few have major amounts. The preponderance of Ca-poor pyroxene over Ca-rich pyroxene is very evident from the normative plag-opx-cpx diagram (Fig. 7). In terms of normative mineralogy, the rocks could be described as norite, gabbro-norite (of which only two samples are orthopyroxene gabbro), leuconorite and anorthosite. There is a small overlap between noritic and leuco-noritic rocks. The two outliers, a gabbro (GL46) and the orthopyroxene gabbro (318), do not have much in common. The leucogabbro has a low Mg-number (0.28), is low in Al and is fairly high in Ca. The orthopyroxene gabbro has a high Mg-number (0.51); it is also high in Ca and rather low in Al. High Mg-numbers are found in a few leucogabbros, but only in those with low Mg- and Fe-contents.

The ratios between incompatible trace elements show no consistent trends. The ratio Ce/La is almost constant in the gabbro, mean = 1.9, $1\sigma = 0.1$. This is a little less than the primordial mantle value, 2.6, suggested by

Table 2. Results of major element analyses, set 1; for sample locations, see Figure 2

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI
<i>Leucogabbro and anorthosite</i>												
119	50.9	0.90	23.6	0.7	5.4	0.09	1.35	10.4	3.8	0.91	0.25	1.8
120	52.2	0.85	24.0	0.8	4.2	0.08	1.61	9.8	3.83	1.01	0.05	1.6
121	51.9	0.61	24.2	0.7	4.6	0.08	1.71	10.4	3.79	0.80	0.11	1.0
122	51.6	0.38	23.9	0.6	4.1	0.09	2.52	10.3	3.47	1.13	0.05	1.9
123A	56.6	0.27	24.1	0.5	1.4	0.03	0.30	8.5	4.13	1.99	0.02	1.9
123B	53.8	1.04	22.2	0.9	4.5	0.09	1.00	9.2	3.79	1.63	0.13	1.8
123W	57.1	0.24	24.0	0.7	1.4	0.03	0.23	8.4	4.31	1.89	0.04	1.9
124	52.8	1.15	22.9	1.1	4.2	0.08	1.03	9.5	3.76	1.12	0.23	1.4
127C	54.5	0.42	24.1	0.6	2.5	0.05	0.41	9.1	4.46	1.51	0.11	2.1
127D	55.5	0.42	23.8	0.7	3.2	0.06	0.40	9.1	4.19	1.34	0.09	1.3
320	52.8	0.31	27.8	0.5	1.2	0.02	0.45	11.3	4.35	0.60	0.05	0.7
504	53.1	1.15	22.7	0.9	5.3	0.09	1.12	9.9	3.67	1.01	0.26	1.3
505	52.2	0.40	26.6	0.4	1.7	0.04	0.49	11.0	3.86	1.58	0.06	1.9
506	52.4	0.11	28.6	0.3	0.8	0.02	0.52	12.4	3.76	0.59	0.02	0.6
507	52.3	1.54	21.9	1.3	6.0	0.13	1.36	9.4	3.63	0.90	0.26	1.7
508	53.5	0.99	22.4	1.2	5.2	0.09	0.94	9.9	3.59	1.12	0.27	1.2
511	52.7	0.26	26.3	0.6	2.1	0.04	1.21	9.8	4.31	1.14	0.04	2.0
<i>Gabbro</i>												
125	49.3	1.71	16.4	1.2	12.7	0.18	5.52	7.5	2.64	1.26	0.25	1.3
126	49.4	2.32	14.8	1.3	14.1	0.21	4.78	7.2	2.65	1.40	0.33	1.0
127	50.8	1.54	16.6	2.4	12.7	0.23	1.52	6.2	3.47	1.40	0.45	2.4
135	49.6	3.60	14.6	1.0	13.1	0.22	4.38	7.8	2.62	1.29	0.29	1.0
140	50.3	1.75	15.9	1.1	12.7	0.19	4.96	6.9	2.78	1.50	0.26	1.3
141	50.6	2.60	14.2	1.1	13.9	0.21	3.89	6.9	2.72	1.86	0.42	1.1
127B	47.0	1.89	17.6	2.1	15.1	0.27	1.74	7.0	3.52	0.67	0.42	2.4
311	49.9	3.64	13.3	1.5	14.1	0.22	3.36	6.7	2.62	2.40	0.90	1.4
312	47.8	1.60	16.5	1.5	12.4	0.18	6.90	7.6	2.73	1.07	0.32	1.3
313	48.4	1.20	17.3	0.8	12.7	0.18	6.50	7.9	2.78	0.95	0.24	1.0
315	50.3	2.41	14.3	1.4	13.5	0.22	4.63	7.0	2.69	1.65	0.43	1.6
318	48.4	1.39	14.4	0.2	13.0	0.24	7.49	9.6	2.84	0.32	0.12	2.0
408	47.1	3.31	13.3	1.8	16.9	0.26	3.12	7.9	2.75	1.21	1.00	1.0
501	54.3	2.30	14.1	1.2	12.3	0.20	2.11	6.2	2.88	2.41	0.71	1.1
502	46.4	1.52	17.6	2.4	10.3	0.16	6.06	7.8	2.39	0.85	0.13	4.7
503	51.5	2.53	14.0	1.0	14.4	0.22	2.73	7.2	2.95	1.77	0.63	1.2
509	51.8	2.90	13.3	1.3	14.6	0.22	3.33	6.7	2.59	2.08	0.50	1.1
510	51.6	3.93	13.2	1.3	14.1	0.22	3.19	6.5	2.63	2.06	0.42	1.2
512	59.7	1.60	13.6	1.5	10.1	0.16	1.86	4.7	2.87	2.44	0.49	1.5
516	51.4	2.77	13.6	1.0	14.7	0.33	3.58	6.8	2.85	1.87	0.48	1.0
518	51.9	2.73	13.6	0.9	14.4	0.21	3.50	6.7	2.59	1.93	0.47	1.3

LOI – Loss on ignition

Wood (1979), and the chondrite value, 2.64, reported by Nakamura (1974). Other pairs vary more, e.g. La/Lu with a factor of approximately 15 between minimum (4) and maximum (64) values (cf. the REE-diagram, Fig. 10). The ratio between the two ‘continental’ elements Ba and Rb shows a large variation.

The Cr/Ni ratio in the gabbro varies strongly, between 0.4 and 42, but few values are above 15. Cr/Ni ratios show a poorly defined peak between Mg-numbers 0.3 and 0.4 (Fig. 8). Contamination from continental crust does not affect the Cr/Ni ratio, so this variation must have originated early in the development, possibly due to fractionation. To the best of our knowledge, chromite has never been reported from the Nordingrå gabbro. In spite of this, it cannot be ruled out that sporadic high Cr-concentration is due to the accidental presence of chromite in a few samples. We do not believe that a systematic removal or accumulation of chromite has influenced the Cr/Ni ratio.

Figure 9 shows concentrations of various elements

normalized to the primordial mantle (Wood, 1979). The fractionation between large-ion lithophile elements (LILE) and high field strength elements (HFSE) is limited in the gabbros and only slightly more pronounced in the leucogabbros. Conspicuous is a negative Sr-anomaly in most of the gabbros and a complementary positive anomaly in most of the leucogabbros. The (Rb/Ba)_N ratios (subscripted N stands for a normalized ratio) are scattered in both gabbro and leucogabbro (gabbro mean 1.0; $\sigma = 0.4$; one extreme value, 24 from sample 318, is omitted, leucogabbro mean 1.1 and $\sigma = 0.6$). Likewise, (K/Rb)_N ratios scatter. No significant correlation between the Mg-number and the K/Rb ratio is found.

The primary mantle-normalized concentrations of Ta and Nb are lower than their neighbouring elements in Figure 9. This applies to the gabbro as well as the leucogabbro. However, the primordial mantle-normalized Nb/Ta ratios are close to but mostly slightly below 1.

Figure 4. Selected Harker diagrams for gabbros (crosses) and leucogabbros (open rings).

Figure 5. Plot of the ratio K_2O/Na_2O against SiO_2 for the Nordingrå complex gabbro.

Figure 6. Major elements plotted vs. the Mg-number. The elements plotted are selected to show the differences between gabbro (crosses) and leucogabbro (open rings) in the Nordingrå complex.

Figure 10 shows chondrite-normalized REE analyses. A weak negative slope is typical, with chondrite-normalized La/Lu ratios varying between 3.8 and 6.6 for the gabbros. The leucogabbros with one exception show a similar slope (3.7 to 7.9).

The gabbros have small negative Eu anomalies. The minimum Eu/Eu^* ratio is 0.74. Three rocks classified as gabbro have positive Eu-anomalies. Their major element chemistry is intermediate between gabbro and leucogabbro. All leucogabbros except the anomalous rock mentioned above have a pronounced positive Eu-anomaly. The small positive Ho-anomaly might be an artefact of the chondrite analysis used for normalizing.

Table 3. Results of trace element determinations, set 1; for sample locations, see Figure 2

Sample	Ba	Cr	Nb	Rb	Sc	Sr	Y	Zr	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Ta	Hf	Ga	Cs	Th	U
<i>Leucogabbro/anorthosite</i>																						
119	214	13	6	27	14	380	16	46	10.5	21	14	2.8	1.74	0.53	1.26	0.21	0.36	1.4	23	0.9	1.7	1.0
120	230		5	36		378	12	57											24			
121	223	12	*	19	9.5	383	13	41	10.2	18	11	2.3	1.62	0.42	1.08	0.22	0.27	1.5	22	0.8	1.6	0.8
122	182	37	*	42	10.5	366	9	24	5	10	8	1.1	1.39	0.2	0.65	0.14	0.22	0.9	21	0.7	1.1	0.9
123A	483	7	5	65	6.3	362	10	77	10.8	21	11	2.1	2.13	0.3	0.98	0.18	0.36	2.2	26	4.5	5.5	1.3
124	311		8	34		370	21	74											25			
123B	361		7	61		353	27	91											25			
127C	431		7	43		477	13	52											27			
127D	439		7	45		410	18	97											26			
320	193			18		513		31											19			
504	345		9	24		396	24	95														
505	216	16	*	50	4.6	454	7	45	6.4	11	9	1.3	1.54	0.22	0.61	*	*	1.1		1.6	1.1	1.0
506	192	20	*	*	1.6	586	*	18	2.7	4	*	0.3	1.09	*	*	*	*	1.1		0.8	*	1.0
507	327	26	14	22	21	377	26	94	17	36	21	5.0	1.99	1.01	2.49	0.42	1.05	2.6		1.6	2.7	1.3
508	346		7	33		374	23	82														
511	425		*	26		536	5	26														
123W	483	15	*	53	6.7	375	14	108	15	28	15	2.9	2.19	0.48	1.31	0.26	0.41	3.2		4.6	4.9	0.8
<i>Gabbro</i>																						
125	348	27	10	48	24	277	30	120	19	35	23	4.8	1.57	0.85	2.66	0.43	0.52	3.5	20	2.7	4.1	2.2
126	423	34	9	41	32	237	37	148	23	44	30	6.3	1.72	1.06	3.46	0.57	0.71	4.1	18	1.4	4.4	1.4
127	686	26	25	45	35	389	46	91	41	79	49	11	3.95	1.52	3.92	0.64	1.36	2.3	29	1.7	4.1	2.2
135	360		12	45		234	30	127											20			
140	428		8	59		250	28	126											19			
141	536	32	10	60	35	211	49	208	31	60	35	8.3	1.93	1.44	4.39	0.7	0.84	5.5	20	1.5	6.0	2.5
127B	423		16	14		426	23	34											32			
311	662		19	103		190	66	309											25			
312	297		7	39		288	25	117											18			
313	273		7	30		291	22	94											18			
315	476		12	56		234	44	184											22			
318	27		6	59		133	16	90											16			
408	466		21	45		251	60	152											20			
405	674		19	129		166	53	218											21			
501	609		23	106		224	56	192														
502	200	80	7	24	13.5	314	15	87	12	24	12	2.5	1.34	0.55	1.27	0.23	0.56	2.5		0.6	2.1	1.6
503	726		17	63		225	59	129														
509	625	40	13	63	38	187	63	224	34	70	38	8.7	2.05	1.56	4.78	0.75	0.95	6.8		1.4	5.1	2.8
510	533		14	61		196	42	234														
516	608		12	46		200	44	206														
518	606		11	47		201	53	193														
512	719	36	18	86	31	245	55	250	44	95	51	10.5	2.25	1.78	4.96	0.77	1.37	7.6		3.3	9.0	3.7

* Below detection limit

6. Interpretations and discussion

Previously described field data suggest a co-magmatic relation among gabbro, leucogabbro and anorthosite and that rocks occur as multiple intrusive bodies. The chemical trends shown in Figures 4 and 6 suggest that plagioclase separation occurred at all stages of the evolution, as was also demonstrated by G. Lundqvist (unpub. FL-thesis, Univ. Gothenburg, 1976). These two figures also show the clear distinction between gabbro and leucogabbro and, specifically in Figure 6, that all rocks are iron-enriched.

Figures 3 to 8 display the chemical and isotopic evolution of the mafic Nordingr magmas. The possible major causes for this evolution are various degrees of partial melting, crystal differentiation and assimilation of crustal rocks. All three processes drive the evolution in a similar direction, which makes it difficult to estimate the contribution from each one separately.

The strong iron-enrichment causes an increased

magma density, which helps plagioclase to float and separate. Approximate magma densities for the gabbros are estimated for a magma temperature of 1200C using the method designed by Bottinga & Weill (1970) and modified by McBirney (1993). The results vary between 2.7×10^3 and 3.1×10^3 kg/m³ with a mean of 2.8×10^3 kg/m³. All plagioclases are negatively buoyant in magmas of a composition corresponding to this mean value, whereas a magma of a composition corresponding to the minimum value only allows plagioclase more albite-rich than approximately An₅₅Ab₄₅ to float. This means that in the Nordingr gabbro, plagioclase will float in all but the most Mg-rich magmas. However, the degree of separation depends on kinetic factors governed by viscosity, size of crystals and density contrast.

The Mg-number monitors the chemical evolution. The K/Rb ratio and the Ni-content show only weak correlations and the Ba/Rb ratio and Cr-content no correlations to the Mg-number; this does not suggest

Figure 10. Chondrite-normalized REE diagrams. The upper diagram shows results from the gabbros and the lower from the leucogabbros. Interrupted lines are due to contents below the detection limit. Lines are differently ornamented to allow tracing of slopes.

Billström, in press), that is, not much different from that of the most negative Nordingrå gabbro (-3.3). Mixing calculations using this mean and a mildly depleted mantle magma (Claesson & Lundqvist, 1995) with $\epsilon_{\text{Nd}(1.58)} = +2.9$ and 5–15 ppm Nd, yields reasonably low ($< c. 25\%$) values of bulk assimilation only for the least negative gabbros and less than 10 ppm Nd in the primary mantle magma. Only when assuming that the contaminant to a primary mantle magma with only 5 ppm Nd has an $\epsilon_{\text{Nd}(1.58)}$ less than -6 , the proportion of crustal rocks becomes $< 25\%$ for the more negative gabbros. Since early Svecofennian meta-igneous reservoirs are not, in general, expected to show such negative $\epsilon_{\text{Nd}(1.58)}$ values, partly Archaean contaminants are likely. Using an average Archaean component compiled from literature data (Martin *et al.* 1983; Jahn, Vidal & Kröner, 1984; Huhma, 1986; Öhlander *et al.* 1987; Mellqvist, 1996, 1999, in press) on Archaean rocks in the northeastern part of the Shield, with an average Nd content of 25–30 ppm and $\epsilon_{\text{Nd}(1.58)} = -17.4$, yields reasonable crustal contributions to all the mafic Nordingrå magmas varying between 5 and 20%. Mixed Archaean–early Svecofennian contributions are accordingly also plausible, where, at least for the most negative rocks, Archaean components should dominate.

The high Nd content of several gabbros requires either:

- (1) that the Archaean and/or Svecofennian conta-

Figure 11. The ratio normative opx/(opx + cpx) plotted against ϵ_{Nd} for nine gabbros (crosses) and five leucogabbros (open rings) in the Nordingrå complex.

minant were partly much higher in Nd than the average, which is possible as both groups range up to at least 70 ppm, or

- (2) that the coeval rapakivi magma (*c.* 70 ppm Nd; Table 1) was in part an additional component, or

- (3) that crystal fractionation raised the LREE content.

All three processes are likely to have contributed; their relative importance is impossible to determine. In contrast, the low Nd content of a few gabbros may implicate participation of the low-Nd depleted crustal residue (pyroxene+plagioclase dominated) left after rapakivi melt extraction (*cf.* Emslie & Hegner, 1993; Emslie, Hamilton & Thériault, 1994).

Additional support for an Archaean influence in the Nordingrå Complex comes from Nd-isotope data obtained from quartz-syenite enclaves in the Nordingrå granite (T. Mårtensson, unpub. Masters thesis, Univ. Lund, 1997). These enclaves represent an early felsic magmatic phase, which yields scattered but partly lower $\epsilon_{\text{Nd}(1.58)}$ than in the host granite.

6.b. Constraints from the major element compositions

Major element data are ambiguous when trying to discriminate among crystal differentiation, varying degrees of partial melting or contamination as cause for chemical diversification. However, no mantle gives a primary liquid as iron- and silica-rich as found among the Nordingrå gabbros. Thus, we exclude variable degrees of partial melting as the prime cause for chemical variation.

The Nordingrå gabbro is not a gabbro in the strict sense. Besides partly being too siliceous to be termed a basic rock, it is more precisely described as a K-rich,

Figure 12. Results from tests of crustal bulk-rock assimilation. The horizontal scale gives percentage of assimilation and the vertical scale numbers of rocks in each class. Assimilated rocks: (a) local early Svecofennian granitoids with $\text{SiO}_2 > 65\%$; (b) 'all' local early Svecofennian granitoids; (c) average tonalite according to Le Maitre (1976); (d) local metagreywackes.

olivine-clinopyroxene norite (cf. Fig. 7). Already Bowen (1928) suggested that norites resulted from contamination of mafic magmas with continental crust. More recently the norite problem has been discussed by Macera *et al.* (1994), among others, who consider mixing of crustally derived acid magmas and mantle derived basic magmas to explain the formation of the Cima D'Asta norite. Chai & Eckstrand (1994) suggested that strong contamination (up to 60%) with Archaean lower crustal material was instrumental in the formation of the Sudbury norite.

Figure 13. Results of the AFC test for trace elements. Bars give the obtained F -value $\pm 1\sigma$. (F = fraction of remaining magma). The sample number is given below each bar. An asterisk indicates that at least one $F > 1$. Above the bar are indicated the number of elements included in the mean for each sample, the element giving the highest and the element giving the lowest F -value. Ba, Rb, Sr, Nb, Y and Zr are included in the means for six elements. In addition to these elements, Ce, Nd, Sm, Eu, Tb, Yb and Lu are included in the means for thirteen elements.

In order to form norite, crustal rocks provide the components alumina and silica from reacting phases to the magma leading to reactions of the types:

$[\text{Ca}(\text{Mg}, \text{Fe})\text{Si}_2\text{O}_6]_{\text{MELT}}$ and $[(\text{Mg}, \text{Fe})_2\text{SiO}_4]_{\text{MELT}}$ correspond to components in the primary magma. Corona formations on olivine suggest that already crystallized olivine also takes part in the reaction. These or similar reactions explain not only the noritic character of the rock but also an increased content of plagioclase leading to the formation of leucogabbro and anorthosite. Emslie & Hegner (1993), Emslie, Hamilton & Thériault (1994) and Dempster, Preston & Bell (1999) among others have suggested continental crust as a contaminant in anorthosite genesis. Dempster, Preston & Bell (1999) concluded that 'underplating basalts and juvenile undifferentiated lower crustal rocks are the key to the anorthosite problem'. In some investigations (e.g. Emslie & Hegner, 1993), authors have stressed that the contaminant should have a restitic character. We also note that strongly plagioclase-depleted rocks like ferrodiorites, which often accompany anorthosite massifs (see, e.g. Bhattacharya *et al.* 1998; Markl, Frost & Bucher, 1998), representing the liquid after removal of fractionating plagioclase, have not been identified in the Nordingr massif. The lack of restitic liquid after plagioclase removal is, together with constraints from the isotope analyses, consistent with the suggestion

Figure 14. Results of the AFC test for Nd isotopes. $\epsilon_{\text{Nd}(1.58)}$ refers to the value of the assimilated rock; the corresponding value for the primary magma is assumed to be 2.9. Unfilled columns correspond to the least negative and filled columns to the most negative $\epsilon_{\text{Nd}(1.58)}$.

that continental crust contributes much of the material necessary for anorthosite formation.

If the noritic character of these rocks is due to crustal contamination of a 'normal mantle melt', we should find a negative correlation between this character and the $\epsilon_{\text{Nd}(1.58)}$. However, crustal rocks are always heterogeneous and various amounts of crystal differentiation give a variable parent magma. Thus we cannot expect a straight-line behaviour between two defined endmembers but scattering between two components, which both show some chemical variability. The second set of chemical analyses was not performed on the same rock powder used for Sm–Nd analyses, which introduces additional scatter. Nevertheless, the correlation between $\epsilon_{\text{Nd}(1.58)}$ and the ratio normative $\text{opx}/(\text{opx}+\text{cpx})$ is high (-0.7 ; Fig. 11).

A test as to whether merely bulk assimilation of crustal rocks explains the noritic character of the gabbro involves successive subtraction of the tested assimilated rock from the gabbro analysis until no normative orthopyroxene remains. We tested one greywacke and three igneous compositions as contaminants. Figure 12 displays the results, suggesting high degrees of bulk contamination. The model also suggests a mantle-derived magma of an 'impossible' composition. Alternatively, the assimilated rocks would be

rich in Fe-extreme mafic minerals, rich in SiO_2 and simultaneously very poor in alkalis. These considerations lead to a suggestion involving not only bulk assimilation but also selective contributions from the crust. Extensive, initial crystal fractionation explains much of the Fe-enrichment. The dominating fractionating phases must be olivine, which is effective in reducing the Mg-number, and to a lesser and variable extent clinopyroxene, to explain the lack of a correlation between Ni and Mg and between Ni and Cr. The noritic character of the final rock excludes large amounts of late orthopyroxene fractionation after crustal assimilation.

6.c. Constraints from the trace element composition

In the Nordingr gabbro, incompatible trace-element ratios, e.g. K/Rb, Rb/Ba, Nb/Ta and Rb/Nb, vary considerably. This strongly suggests more than one source for the magmas. One of these sources must be in the mantle and the other(s) in the continental crust. This is consistent with conclusions from Sm–Nd isotopes and major element analyses.

Extensive crystal differentiation explains the Fe-enrichment and assimilation the noritic character of the rock. Varying Ni/Cr ratios point to various degrees of olivine separation before crustal assimilation processes. The low normalized Nb and Ta contents (Fig. 9) are consistent with suggestion of assimilation of crustal material. Intraplate mafic magmatic rocks are not supposed to be depleted in these two elements compared to the neighbouring elements in Figure 9. Bulk assimilation may be part of the process but is incapable of reproducing the entire range of rock compositions. The scattered Rb/Ba ratios point to inhomogeneous source regions, in this case a reasonably constant mafic source and varying degrees of assimilation of a non-homogeneous continental component. Assimilation–Fractionation–Crystallization (AFC) processes contribute to explaining both the Fe-rich and the noritic character. Testing follows the procedure suggested by DePaolo (1981b), applying the simplifying border conditions of a constant assimilation to fractionation ratio (r in DePaolo's equation) and a constant total distribution coefficient (weighted average, D in DePaolo's equation) between magma and the crystallizing phases. We use a small value of r (0.4), since much heat is lost due to the simultaneous formation of the rapakivi granite magma. This test is, however, rather insensitive to the exact value of r . We assume the fractionating phases plagioclase (60%) > olivine (30%) >> clinopyroxene (10%, cf. Irvine, 1976). A high content of plagioclase among the fractionating phases explains the formation of leucogabbro and anorthosite and a high content of olivine the Fe-enrichment and the increased orthopyroxene content in the rock. The degree of clinopyroxene fractionation is probably variable. We use the

Figure 15. $\epsilon_{\text{Nd}(1.58)}$ of assimilated rock satisfying DePaolo's (1981b) equation as a function of the Mg-number. Boundary conditions as described in the text.

composition of average silicic (>65% SiO_2) early Svecofennian granitoids (as in the major element test) and two primary mantle magma compositions.

Using an enriched magma corresponding to an Ocean Island Basalt (see compilation by Sun & McDonough, 1989) results in failed tests for almost all elements. The outcome of the test is appraised from the similarity of the fractions of remaining liquid (F in DePaolo's equation) for all tested elements. Thus, isotope and trace element evidence confirms that the primary magma was not enriched.

Testing a more depleted primary magma corresponding to an E-MORB (see compilation by Sun & McDonough, 1989) meets with more success (cf. results in Fig. 13). Normally, F is less than one, even if there are exceptions. Analytical errors alone do not explain all of the scattering, indicating that the model does not account for all of the variation. Strontium is strongly overrepresented among the elements with high F -values and Ba among those with low F -values (Fig. 13). The most probable explanations for high F -values for Sr is an overestimate of the Sr-content in the model's original magma. The low F -values for Ba may be due either to underestimates of Ba in the original magma or overestimates in the contaminant. Further, the absorbed continental crust was not homogeneous and different batches of the mafic melt had probably experienced different degrees of fractional crystallization before the onset of the AFC process. A combination of bulk assimilation, AFC and early crystal fractionation might explain most of the variation of the rock suite.

An additional AFC test uses the Nd isotopes (DePaolo, 1981b). Border conditions are: the same D -values used in the first AFC-test, $\epsilon_{\text{Nd}(1.58)}$ of the subcontinental mantle = 2.9 (estimated from the suggestion of Claesson & Lundqvist, 1995), primary Nd content equal to 9 ppm (E-MORB suggested by Sun & McDonough, 1989), r varying between 0.3 and 0.9 and

F between 0.6 and 0.8. The results of the calculation are estimates of the $\epsilon_{\text{Nd}(1.58)}$ of the assimilated crust (assuming 30 ppm Nd). Figure 14 displays the results. The least negative ϵ_{Nd} (unfilled columns) is obtained for the largest r and the smallest F . Samples 033 and 312 require an unreasonably low $\epsilon_{\text{Nd}(1.58)}$ of the assimilated crust to satisfy the model. The low Nd contents of these two samples (cf. Table 1) make the modelling extremely sensitive to small errors in the Nd-content of the chosen original magma. The results for the other seven samples are accepted as a positive outcome of the test, where differences in obtained ϵ_{Nd} values can be explained with non-constant D -values (that is, they must vary during the process) and F -values that differ among the samples. There is a tendency among the data that samples with high Mg-numbers require a more negative $\epsilon_{\text{Nd}(1.58)}$ to satisfy the model (cf. Fig. 15). This is a hint that the primary magma might be less depleted than tentatively suggested by Claesson & Lundqvist (1995). The results from the two samples 033 and 312 suggest the presence of a low-Nd contaminant, e.g. the depleted restite from the rapakivi magma extraction.

In addition to the types of contamination that have been tested, the coexisting rapakivi granite magma may contribute to the chemical composition of the mafic rocks (cf. Emslie, Hamilton & Thériault, 1994; Andersson, 1997b). Lindh & Johansson (1996) noted that the rapakivi granite is low in alumina leading to the formation of clinopyroxene and hornblende instead of biotite as mafic phases. They suggested the possibility that excess aluminium from crustal melting forming the rapakivi granite magma could enter into the coexisting mafic magma, thereby contributing to the increased Al-content manifest in an increased plagioclase production. The complete model for the mafic Nordingrån rocks must consider the assimilated rocks as well as the two magmas: the mantle-derived gabbroic magma and the crustal-derived granitic magma. It is also not fully understood how the physical intrusion of the separate mafic and felsic magmas occurred. Contrary to many other rapakivi complexes, the mafic rocks are concentrated at one end and the felsic rocks at the other end of the Nordingrån complex. The amount of mafic rocks underlying the northern part of the Nordingrån rapakivi granites and the extent of the Nordingrån rapakivi complex eastwards under the sea are incompletely known.

7. Conclusions

(1) Varying degrees of partial melting of the mantle do not explain the observed chemical variation of the Nordingrån mafic magma; even the most Mg-rich rock can hardly be a primary mantle melt. The noritic character of the rocks and the Nd isotope composition suggest other processes to be of prime importance for the formation of the rock sequence.

(2) Major and trace element chemistry suggests that only part of the observed chemical evolution can

be explained by crystal differentiation from a reasonably homogeneous mantle melt, for example, some trace-element ratios are inconsistent with such a suggestion.

(3) The overlap of Mg-numbers from leucogabbros and gabbros suggests that plagioclase separation has occurred at all stages in the evolution of the Nordingrå gabbro norite.

(4) The Nd-isotope composition of the gabbroic rocks of the Nordingrå rapakivi complex requires, and its trace- and major-element chemistry strongly suggests, that crustal rocks were incorporated into the magma. In the absence of any strong evidence for an enriched sub-lithospheric mantle, the negative $\epsilon_{\text{Nd}(1.58)}$ values suggest an Archaean crustal component. Combined trace element and isotope studies suggest that AFC processes are of prime importance for explaining the chemical composition of the gabbros and leucogabbros. The associated granites can be explained by partial melting of early Svecofennian granitoids even if an involvement of older rocks is not excluded.

(5) The exact nature of the contaminants is difficult to quantify. Most probably contaminants are heterogeneous, including undepleted crust (e.g. represented by Archaean and the early Svecofennian granitoids), depleted crust (restitic after rapakivi magma extraction), and to some degree the rapakivi magma itself. A significant part of this crust should be Archaean in age.

Acknowledgements. Anders Lindh acknowledges financial support from the Swedish Counsel for Natural Science. The chemical analyses in set 1 were performed by Ingrid Johansson, at the Geolaboratory, Lund University. Hans Schöberg, Marina Fischerström and Ann-Marie Kähr at the Laboratory for Isotope Geology are thanked for technical assistance with isotope analyses. Lina Pudas and Rikard Anehus at the Geological Department, Lund University made the thin sections. Comments from T. Dempster and an anonymous referee have improved the manuscript.

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