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EXCURSION
July 16–23 1996

**IGCP PROJECT 315
CORRELATION OF RAPAKIVI GRANITES AND RELATED ROCKS
ON A GLOBAL SCALE**

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Cover: Section of the c. 175 m long roadcut ”Prästberget” in the Ragunda rapakivi complex. This locality shows a diversity of magma mingling structures and textures (see chapter 2.2 and excursion route 4:2). The large gabbro pillow in the right part measures 7 m in height. Photo Anders I. Persson.

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FOREWORD

This guide book is contribution no. 47 to IGCP project number 315 “Correlation of Rapakivi Granites and Related Rocks on Global Scale”. The excursion formed part of the activities arranged within the frames of the 7th and final IGCP 315 symposium, organized at Helsinki University in July 1996. The guide book was originally printed in a very limited number of copies which ran out of stock already during the symposium. Thanks to a generous offer by the Geological Survey of Sweden it has now been possible to reproduce this guide book in a much larger edition. We hope that this edition will be of use both as general background information and for those who want to make visits to any part of the route of this excursion.

The aim of this field tour is to focus attention on the highly variable post- to anorogenic granitoid systems that have been recognized within the Svecofennian Domain in Sweden. In this context, the main part of the field tour will concern the classical rapakivi complexes at Ragunda, Nordingrå, Rödön and Strömsbro, which are anorogenic in relation to the Svecofennian orogeny and have consequently been correlated with the Finnish rapakivi complexes. In addition, some selected Swedish granitoid systems in the Svecofennian Domain, which traditionally have been distinguished as “late-orogenic” and “post-orogenic”, will also be examined during the field tour for comparative purposes because several of them share many of the characteristics of the anorogenic rapakivi complexes. Furthermore, several of the “late-orogenic” and “post-orogenic” granites, particularly those displaying A-type characteristics, have been of large economic interest for their ore potential.

The information presented in this guide book is a result of a joint effort of all researchers who have participated in the Swedish IGCP 315 activities. Agneta Ek at the Geological Survey of Sweden has been technical editor of this edition. To all these contributors, I want to express my sincere thanks.

On behalf of the Swedish IGCP 315 group

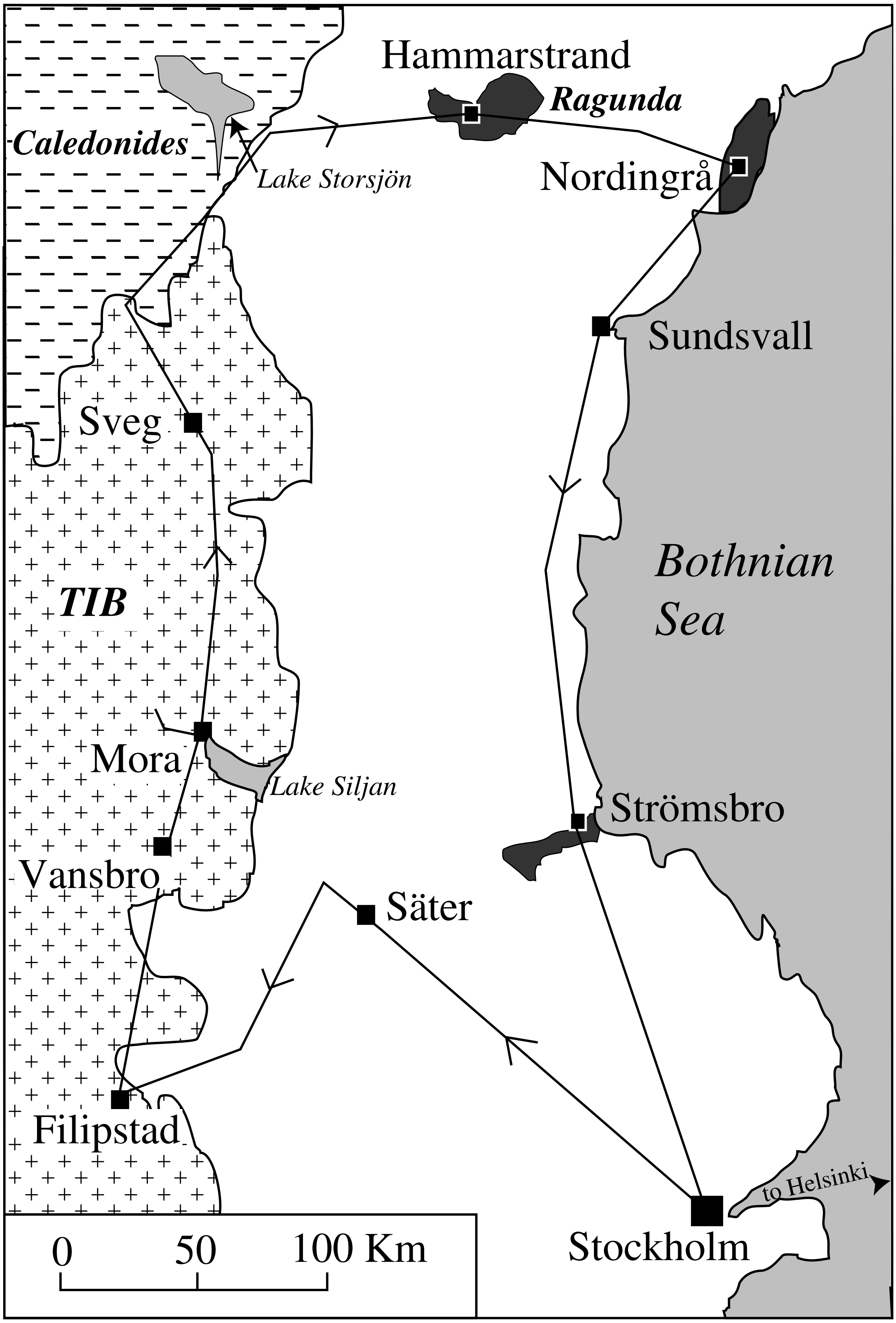
Krister Sundblad
July 1997

gruppfoto

Field trip participants of IGCP Project 315 standing in front of the large road cut ”Prästberget” in the Ragunda complex.

From left: Rickard Ask (S), Jenny Andersson (S), Gary Lowell (USA), Anders I. Persson (S), Martin Ahl (S), Eberhard Wernick (B), Viorica Morogan (S), Ulf B. Andersson (S), Grazina Skridlaite (L), Krister Sundblad (S), Thomas Mårtensson (S), Roberto Dall’Agnoll (B), Claes Mellqvist (S), Magnus Ripa (S), Anatoly M. Larin (R), Alexev Shebanov (R), Agnes Rodhe (S), Anders Lindh (S) and Stefan Claesson (S). Missing on this picture, but participating in the field trip: Brian Upton (UK), Thomas Lundqvist (S), Tapani Rämö (F), and Leif Johansson (S).
S = Sweden, L = Lithuania, B = Brazil, UK = United Kingdom, R = Russia, F = Finland.

Route map


Hammarstrand
Ragunda
Caledonides
Lake Storsjön
Nordingrå
Sundsvall
Sveg
Bothnian Sea
TIB
Mora
Lake Siljan
Strömsbro
Vansbro
Säter
Filipstad
to Helsinki
Stockholm
0
50
100 Km

CONTENTS

1. EARLY TO POST-OROGENIC GRANITOIDS IN THE SVECOFENNIAN DOMAIN

1.1 Regional setting

K. Sundblad

The Fennoscandian (Baltic) Shield is a Precambrian shield complex which is commonly subdivided into three major domains; the Archaean, Svecofennian and Southwest Scandinavian Domains (Fig. 1). The Svecofennian Domain was formed as a result of crustal growth during the time span 1.96–1.87 Ga, followed by accretion onto the Archaean Domain in conjunction with metamorphism and deformation at about 1.83 Ga (Gaál & Gorbatschev, 1987). This crust-forming and diastrophic period is commonly referred to as the Svecofennian or Svecokarelian Orogeny. Significant igneous activity preceded cratonization in the entire Svecofennian Domain. This igneous activity included major reworking of the early Svecofennian crust, forming the potassium-rich late- and postorogenic granitoid suites. Cratonization was essentially completed by 1.75 Ga. Extension-related anorogenic magmatism was active within the craton 1.70–1.50 Ga.

The late-, post- and anorogenic granitoids in the north-easternmost parts of the Svecofennian Domain incorporated significant proportions of pre-Svecofennian (Archaean) crustal components, compared to the corresponding granitoids in the central and southwestern parts of the Svecofennian Domain (Huhma 1986, Patchett et al. 1987, Sundblad 1991, Öhlander et al. 1993). Recently, however, substantial amounts of Archaean material have also been found incorporated in rapakivi complexes of central Sweden (Andersson & Neymark 1994a, Andersson 1997a, b). The most significant rock forming processes in the central and southwestern parts of the Svecofennian Domain can be summarized in the following way.

1.2 Early Svecofennian granitoids

K. Sundblad

The 1.95–1.87 Ga Early Svecofennian granitoids are the oldest of the Svecofennian Domain (e.g. Åberg et al. 1983, Huhma & Vaasjoki 1989, Skiöld et al 1993, Wasström 1993, 1996), which intruded into a sequence of volcanic and sedimentary rocks. The Early Svecofennian plutonic rocks have a wide range of compositions (gabbro-diorite-tonalite-granodiorite-granite), a calcic to calcalkaline chemistry and I-type characteristics (Wilson 1982, Nurmi & Haapala 1986). The granitoids, which often occur in big batholith complexes, are especially abundant in south-central Sweden (Bergslagen) and in south-central Finland.

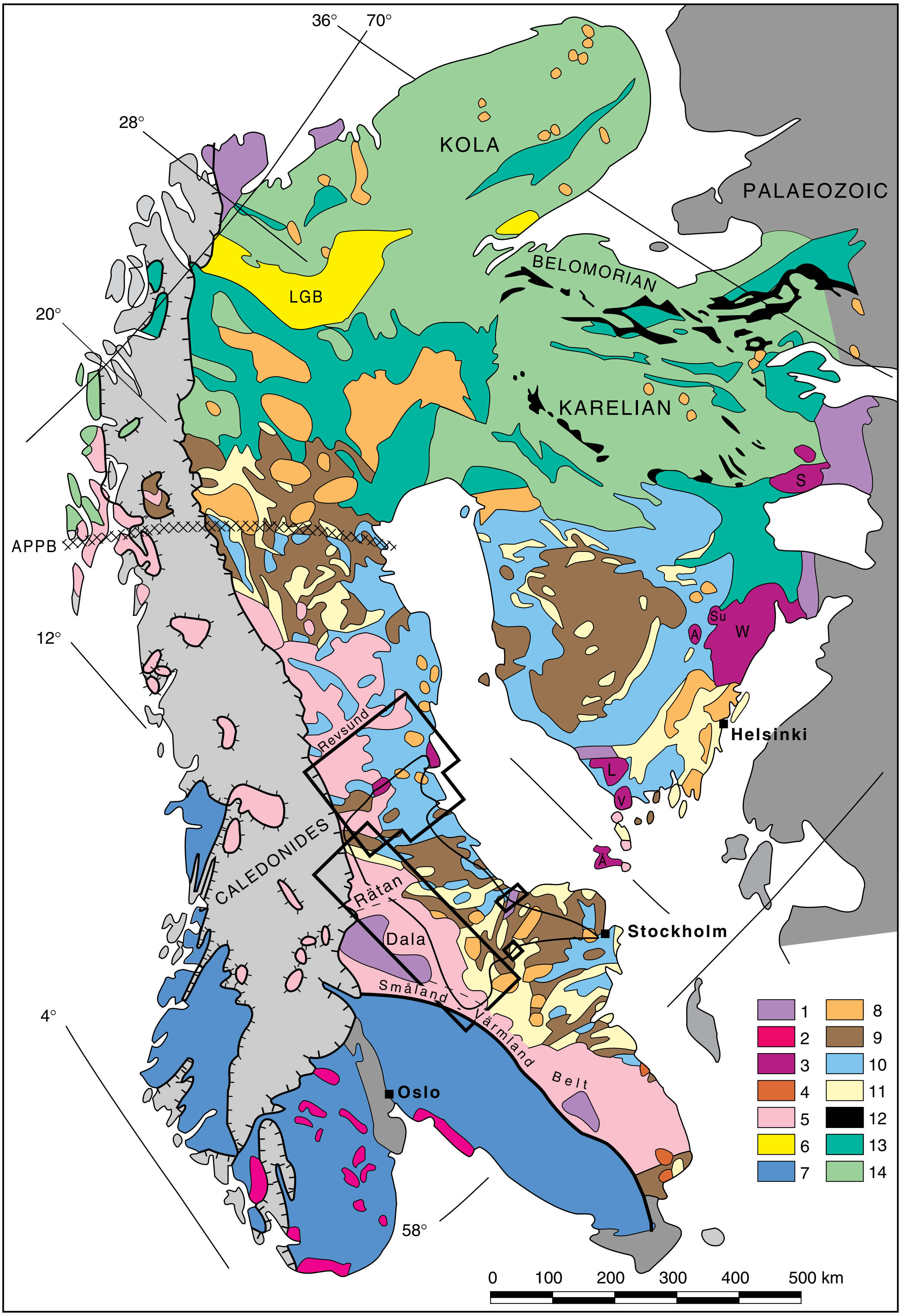
1.3 “Late Svecofennian” granitoids

K. Sundblad & T. Bergman

1.3.1 GENERAL FEATURES

“Late Svecofennian” (or late orogenic) granites are common in several regions within the Svecofennian Domain. Some of these granites, e.g. the 1.82 Ga old anatectic Härnö granites, east-central Sweden, have S-type characteristics, and were formed in close connection with the Svecofennian regional metamorphic and deformational event (Claesson & Lundqvist 1995). Another significant concentration of late Svecofennian plutons is found in Bergslagen and around Stockholm, south-central Sweden (e.g. the Pingstaberg, Skålhöjden, Fellingsbro and Stockholm granites), with ages in the interval 1.80–1.75 Ga (Åberg & Bjurstedt 1986, Patchett et al. 1987, Billström et al. 1988, Sundblad et al. 1993, Bergman et al. 1995, Ivarsson & Johansson 1995, Öhlander & Romer 1996). These granites show less evident links to the Svecofennian regional metamorphic and deformational event. The chemical composition of these granites is significantly more silica- and potassium-rich compared with the Early Svecofennian granitoids and shows locally geochemical characteristics of A-type granites (Öhlander & Zuber 1988, Billström et al. 1988, Sundblad et al. 1993, Bergman et al. 1995).

Three small granite plutons, which traditionally have been designated “Late Svecofennian”, will be highlighted on this field tour; Bispbergs Klack, Högberget and Skålhöjden, all located in the classical mining district of Bergslagen. A common feature for these three granite plutons is that they constitute small (1–2 kilometres in diameter) rounded plutons that cut the regional foliation in the surrounding metamorphosed Svecofennian crust. Xenoliths are rare in these granites and very few pegmatites are associated with them, suggesting relatively dry magmas. A direct link to migmatization of the Svecofennian crust is thus not evident for any of these small plutons. A further common feature for the Bispbergs Klack, Högberget and Skålhöjden granites is the high metallogenetic potential; the Bispbergs Klack pluton forms the host rock to one of the most significant Mo mineralizations in Sweden, the Högberget pluton is associated with a significant W-Mo skarn deposit and the Skålhöjden pluton is associated with a small Mo mineralization.


36°
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28°
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12°
4°
58°
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PALAEOZOIC
LGB
BELOMORIAN
KARELIAN
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Helsinki
Revsund
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CALEDONIDES
Rätan
Dala
Stockholm
Småland - Värmland Belt
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1.3.2 THE BISPBERGS KLACK GRANITE

Geographical and historical background

The Bispbergs Klack intrusion is located some five kilometres to the northeast of Säter, which is a small town in the Bergslagen mining district along the road between Stockholm and Borlänge. The Bispberg area has been of mining interest since several hundreds of years (Lindroth 1944, 1945). The earliest mining interest was focused on stratiform iron ores, which occur in a c. 1.9 Ga old Svecofennian sequence of volcano-sedimentary rocks, which can be traced for 35 kilometres from Bispberg towards Ludvika in the south. The iron mine at Bispberg was operated until the 1960's.

The area is also of historical interest for the presence of molybdenite and scheelite. Ore material collected at Bispbergs Klack played a significant role in the discovery of these minerals and in the discovery of molybdenum and tungsten. Small scale mining of molybdenum took place during World War II. The discovery of tungsten at Bispbergs Klack goes back to 1751 when Axel Fredrik Cronstedt reported the occurrence of a white mineral, which later was handed over to Carl Wilhelm Scheele for chemical investigations. Scheele reported in 1781 that this white mineral contained a previously unknown component which he called "tungsten", meaning heavy stone in Swedish language. Scheele made however a mistake in assuming that his "tungsten" was a mineral and not an element. A few years later (1786) these problems were solved by two brothers (d'Elhyuar) who were able to separate real tungsten from a German wolframite sample. In the end, the name for "heavy stone" in Swedish (i.e. "tungsten") was given to the element in English, while the German name "wolfram" was used for the abbreviation (W). Furthermore, in honor to the work carried out by Scheele, the white mineral was given the name scheelite. The discovery of molybdenum goes back to the same time (1754), when Bengt Qvist reported the occurrence of a "lead mineral" at Bispbergs Klack. It is highly probable (although not completely certain) that this "lead mineral" later was investigated by Scheele when he was able to distinguish a new chemical component (i.e. molybdenum) in 1778.

Geology

The landscape in the Säter area is strongly dominated by Bispbergs Klack, which constitutes a small (2.5 km in diameter) hill with almost circular shape (Fig. 2a). Almost the entire hill is composed of a red granite which belongs to the Late to post-Svecofennian granites in Bergslagen. Later fractures and faults have emphasized these topographic features even more. The last magmatic event is represented by the intrusion of dolerites that belong to the Neoproterozoic Blekinge–Dala Dolerites.

The dominating texture of the Bispbergs Klack granite is a slightly porphyritic variety with 0.5 mm large K-feldspar phenocrysts in a 2–3 mm sized matrix of K-feldspar, quartz and biotite. Twinning of K-feldspar phenocrysts is relatively common and equigranular varieties of the Bispbergs Klack granite occur locally.

The chemical composition of the Bispbergs Klack granite is very homogeneous and the average content for nine samples is shown in Table 1. Classification in a P-Q diagram reveals a truly granitic composition (Fig. 3a) with a slightly leucocratic and peraluminous character (Fig. 3b). Typical A-type characteristics are displayed by the Rb vs. Y+Nb plot (Fig. 3c) and the flat REE pattern with well-developed negative Eu anomalies (Fig. 3d).

An effort to date the Bispbergs Klack granite by means of the U-Pb in zircon method has not been successful. All fractions plot far below the concordia line, which results in too low accuracy to yield meaningful results.

An intensely mineralized zone, subject to mining during World War II, is found on the eastern slope of the hill. The molybdenite is most commonly hosted by altered varieties of the granite but minor mineralizations in veins and cavities can also be seen. Two types of alteration rocks can be distinguished; a red type with a slightly higher potassium content and a grey type with slightly lower potassium content (Table 1). Molybdenite, chalcopyrite, bornite, chalcosine, pyrite, galena, bismuthinine, fluorite and scheelite have been reported from this ore. A lead isotopic determination of galena in the ores at Bispbergs Klack yielded: $^{206}Pb/^{204}Pb$ = 15.95, $^{207}Pb/^{204}Pb$ = 15.39, $^{208}Pb/^{204}Pb$ = 35.45. This composition is comparable with other galena occurrences in post-orogenic and anorogenic granites in the Svecofennian Domain (cf. Sundblad 1991). Age determinations by the

Fig. 1. Lithological subdivision of the Fennoscandian shield. 1. Jotnian sedimentary rocks, <1.50, >1.26 Ga . 2. Late Sveconorwegian intrusions, c. 1.00–0.85 Ga. 3. The Fennoscandian rapakivi complexes, c. 1.65–1.50 Ga. 4. Younger anorogenic intrusives in SE Sweden, c. 1.40–1.35 Ga. 5. The Transscandinavian Igneous Belt, c. 1.85–1.65 Ga. 6. The Lapland Granulite Belt, c. 2.0–1.9 Ga. 7. The Sveconorwegian Domain, c. 1.76–0.90 Ga. 8. "Late orogenic" Svecofennian intrusives, c. 1.84–1.77 Ga. 9. Early orogenic Svecofennian intrusives, c. 1.95–1.86 Ga. 10. Early Svecofennian sedimentary supracrustals, pre-1.86 Ga. 11. Early Svecofennian volcanics, c. 1.90–1.87 Ga. 12. Archaean greenstone belts and basins, c. 2.9–2.7 Ga. 13. Earliest Proterozoic cover of the Archaean craton, c. 2.5–2.0 Ga. 14. Archaean crust, c. 3.1–2.6 Ga. APPB is the Archaean–Proterozoic palaeoboundary of Öhlander et al. (1993). Frames outline areas of subsequent maps. Thin line marks the excursion route. From Andersson (1997b), modified after Gaál & Gorbatschev (1987).

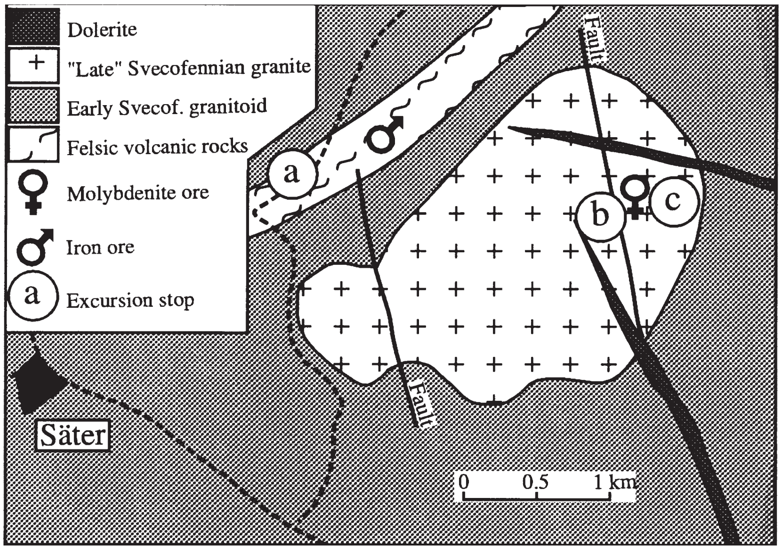


Fig. 2a. Geological map of the Bispberg area.

Re-Os method on molybdenite from the red ore type yielded 1802±7 Ma and on molybdenite from the grey ore type 1781±7 Ma (Sundblad et al. 1996).

1.3.3 THE HÖGBERGET GRANITE

The Högberget granite is located between the two small ancient mining towns Grängesberg and Kopparberg in the western part of the Bergslagen mining district. The Högberget granite forms a c. 1 kilometre wide circular pluton on the western side of the major Malingsbo granite intrusion, cutting through the foliation in the surrounding meta-supracrustal Svecofennian rocks (Bergman et al. 1995). The Högberget granite is grey to redddish grey, massive, fine- to medium-grained and equigranular, and is essentially composed of quartz, plagioclase, microperthitic and graphic orthoclase, microcline, chloritized Ti-bearing biotite, and small amounts of muscovite and fluorite.

The chemical composition of the Högberget granite is similar to that of the Bispbergs Klack granite, although there is a small but distinct difference between these two plutons (Table 1). The Högberget granite has an even more pronounced granitic, leucocratic and peraluminous character and plots within the field of two-mica granites (Figs. 3a–b). A very similar result is obtained in the Rb vs. Y+Nb plot (Fig. 3c), and the REE patterns show well-developed negative Eu anomalies (Fig. 3d).

An age determination by means of the U-Pb in zircon method yielded 1750±10 Ma for the Högberget granite (Bergman et al. 1995). It is however worth noting that (as in the case of the Bispbergs Klack granite) all fractions plot relatively far below the concordia.

The Högberget granite is closely associated with the Wigström W-Mo skarn deposit (Fig. 2b). The Wigström ore was mined during 1978–1981 for tungsten and constitute a 1–25 metres wide zone in a felsic metavolcanic rock (Fig. 2b). The W-skarn is considered to have formed as a result of metasomatic alteration of a previously existing marble horizon in the Svecofennian supracrustal sequence, in conjunction with the emplacement of the Högberget granite. One type of endoskarn and five types of exoskarn have been distinguished based on the mineral assemblage: 1. garnet-hedenbergite-, 2. hedenbergite-scapolite(-vesuvianite)-, 3. hedenbergite-, 4. wollastonite-skarn and 5. impure carbonate rock with variable amounts of diopside and biotite. The garnet has an intermediate composition with a significant grossular component ($An_{15}Gr_{61}Sp+Al_{24}$) and the pyroxene varies from hedenbergite ($Jo_7Di_{25}Hd_{68}$) to diopside ($Jo_3Di_{83}Hd_{14}$). Wollastonite skarn occurs in small amounts in the volcanic rocks outside the main skarn horizon. Endoskarn occurs in the peripheral parts of the Högberget granite and in granite veins cutting through the skarn horizon. Retrograde alteration of the skarn minerals is common leading to saussuritization of scapolite and garnet as well as uralitization of pyroxene.

Age determinations by means of the Re-Os method on two molybdenite concentrates collected in the endoskarn yielded 1807±8 and 1800±8 Ma respectively, which is interpreted to represent the intrusion event of the Högberget granite as well as the formation of the Wigström skarn deposit (Stein et al. 1996).

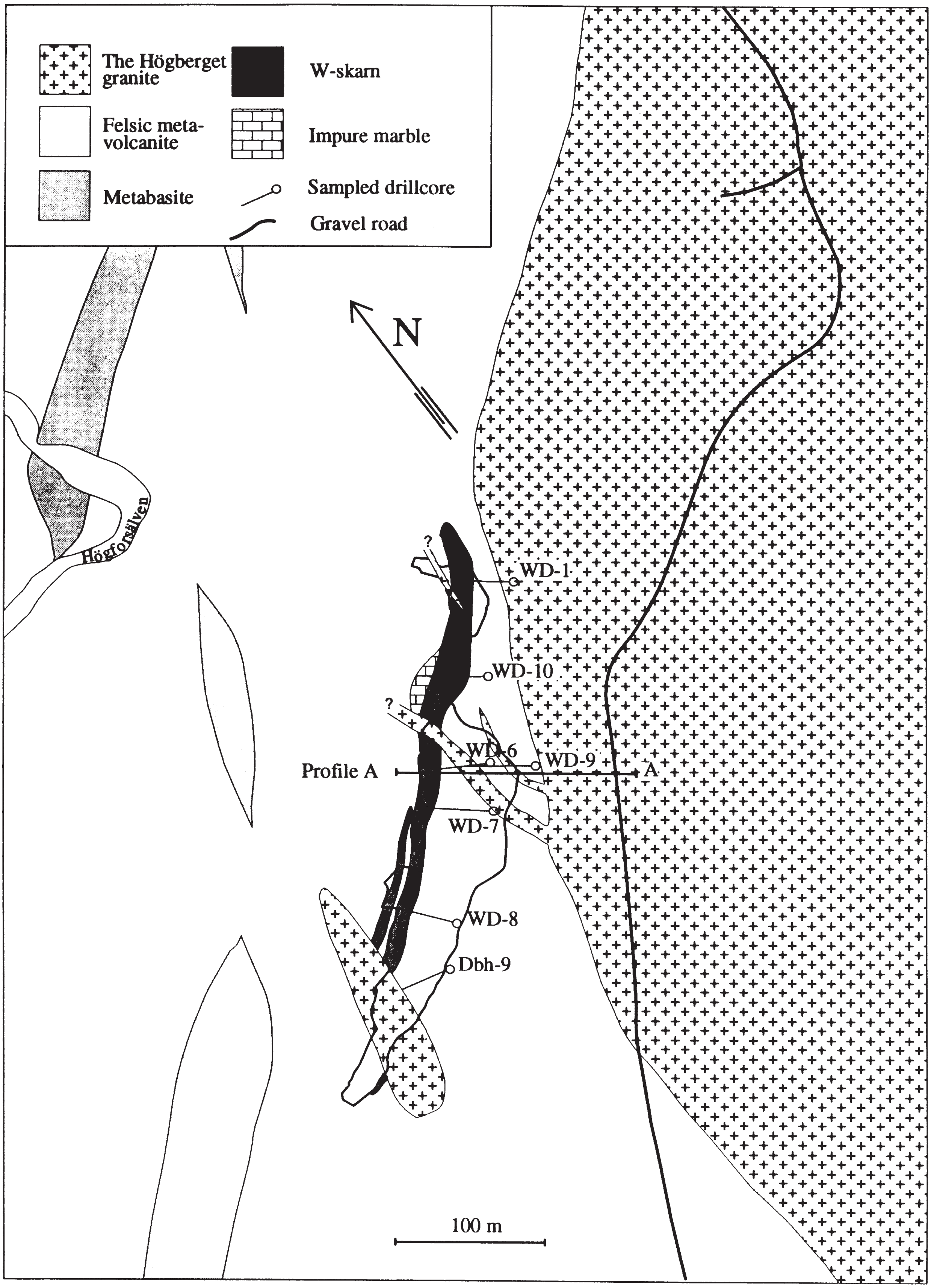
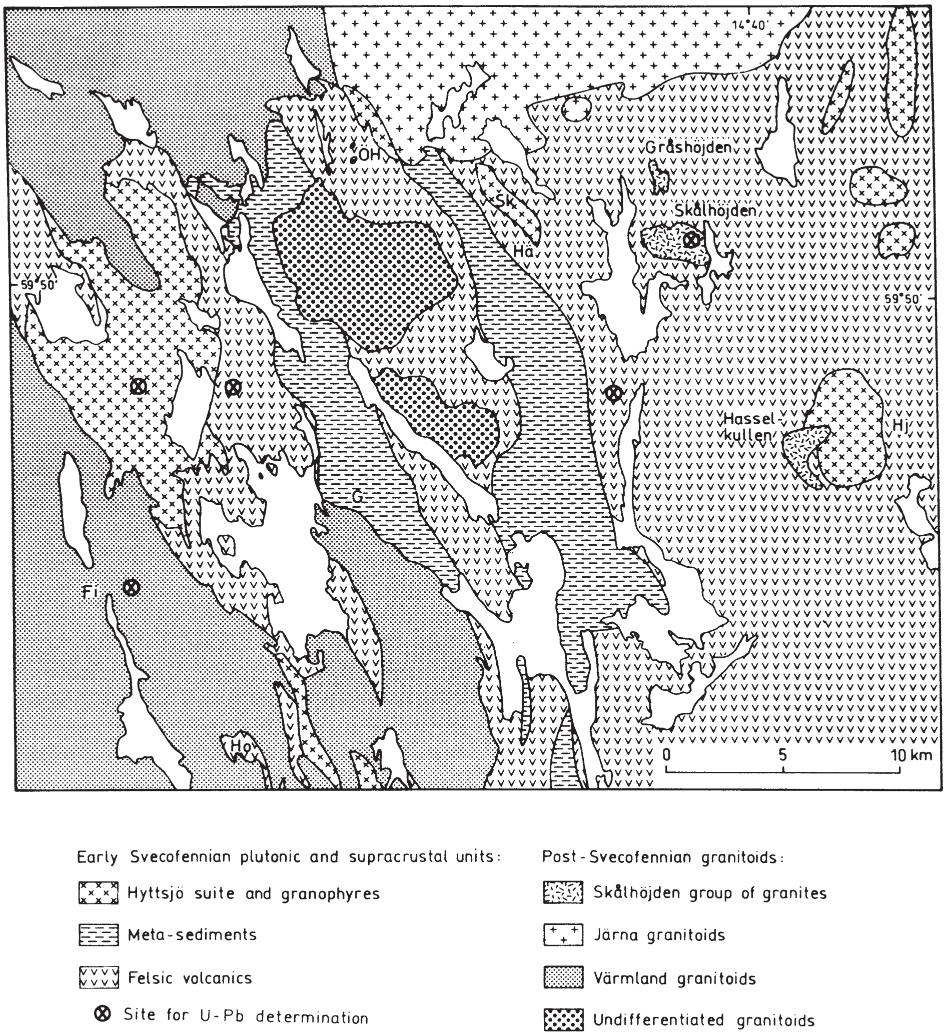


Fig. 2b. Geological map of the Högberget area (after Bergman et al., 1995).

Table 1. Chemical composition of the Bispbergs Klack (average of nine samples, Sundblad unpublished data), Högberget (average of eight samples, Bergman et al., 1995) and Skålhöjden (average of seven samples; Sundblad et al. 1993) granites. The composition of representative samples of the red and grey types at Bispbergs Klack are shown for comparison.

	Bispbergs Klack			Högberget	Skålhöjden
	granite	red ore	grey ore	granite	granite
SiO_2	73.3	74.0	76.6	73.7	76.4
TiO_2	0.24	0.19	0.11	0.11	0.13
Al_2O_3	13.23	12.8	12.3	13.59	12.74
Fe_2O_3	2.54	2.15	1.24	1.47	1.80
MnO	0.05	0.03	0.02	0.04	0.03
MgO	0.42	0.31	0.17	0.10	0.20
CaO	1.15	1.02	1.12	0.71	0.61
Na_2O	3.23	2.57	3.40	3.14	3.83
K_2O	4.89	5.96	4.64	5.73	4.59
P_2O_5	0.07	0.06	0.04	0.03	0.03
LOI	0.68	0.70	0.50		0.29
Ba	565	467	139	405	321
Cr	16	16	17	6	6
Cu	47	104	103	7	11
F	1598	2190	2190	1000	987
Ga	14	9	9	19	-
Hf	7	6	5	-	-
Mo	5	1490	12	-	7
Nb	21	18	30	23	22
Ni	7			12	6
Rb	239	296	250	313	
Sc	3	3.5		3	3
Sr	89	59	45	68	40
Ta	2.8	2.5	7	-	-
Th	33	30	17	34	-
U	13	21	37	-	-
V	16	15	7	1	7
W	0.8	2.0	3.4	-	14
Y	56	64	63	57	69
Zn	70	90	53	26	24
Zr	236	163	98	118	142



L=Långban; *Fi*=Filipstad; *G*=Gruvåsen; *Hä*=Hällefors silver mines; *Sk*=Silverknuten; *ÖH*=Östra Höjden; *Hj*=Hjulsjö; *Ho*=Hornkullen.

Fig. 2c. Geological map of the Skålhöjden area (after Sundblad et al., 1993).

1.3.4 THE SKÅLHÖJDEN GRANITE

The Skålhöjden granite is also located in western Bergslagen (Fig. 2c). It is one of several small granitic plutons which cut the regional foliation in the surrounding Svecofennian metavolcanic rocks, and which have been subject to prospecting activities for molybdenum.

The chemical composition of the Skålhöjden granite is shown in Table 1 and reveals a slightly less evolved character than that of the Bispbergs Klack and Högberget granites, and plots in the adamellitic to granitic fields in Fig. 3a. The Skålhöjden granite is clearly leucocratic but has a less pronounced peraluminous character (Fig. 3b).

The age of the Skålhöjden granite has been determined by means of the U-Pb in zircon method to 1760 Ma (Sundblad et al. 1993), clearly demonstrating that this set of granitic plutons postdates the metamorphic event in Bergslagen. This age, together with the geochemical character of the granite, indicates that a number of the "Late Svecofennian" granites in Bergslagen, particularly those having a high metallogenetic potential for Mo and W, are very similar to anorogenic granites, which may indicate the first expression of non-compressional tectonics, possibly in conjunction with pressure release after the main cratonization processes had ceased.

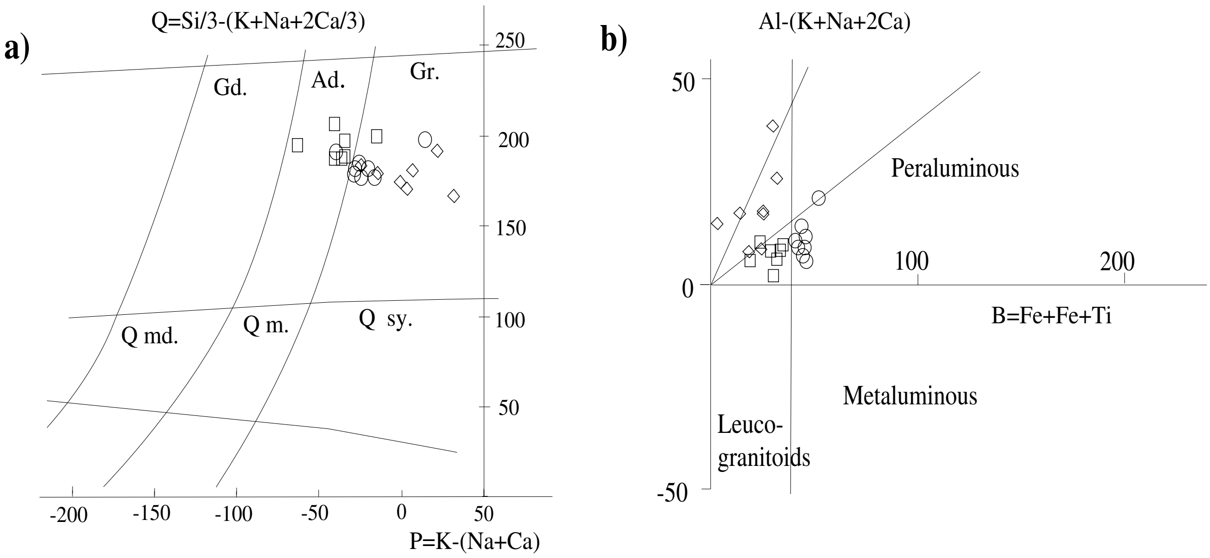


Fig. 3. Chemical parameters of the Bispberg-Högberget-Skålhöjden granitoids plotted in various classification diagrams. Open circles: Bispberg granite, open squares: Högberget granite, open diamonds: Skålhöjden granite.
a) P-Q diagram according to Debon & Le Fort (1982). Gr.= Granite, Ad.= Adamellite, Gd.= Granodiorite, Q md.= Quartz monzodiorite, Q m.=Quartz monzonite, Q sy.=Quartz syenite.
b) A-B diagram according to Debon & Le Fort (1982)

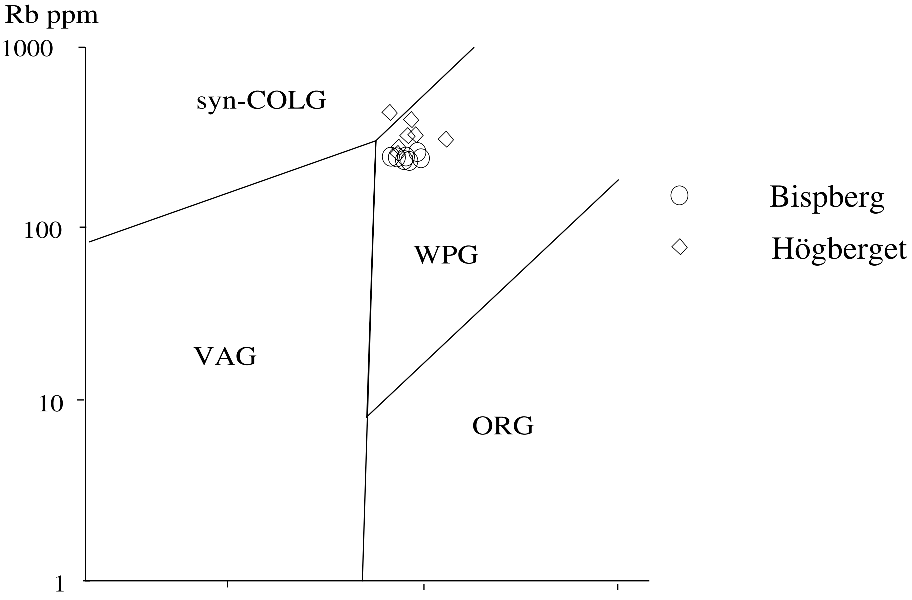


Fig. 3 c) Y+Nb versus Rb diagram for syn-collision (syn-COL), volcanic arc (VA), within plate (WP) as well as normal and anomalous ocean ridge (OR) granites according to Pearce and others (1984).

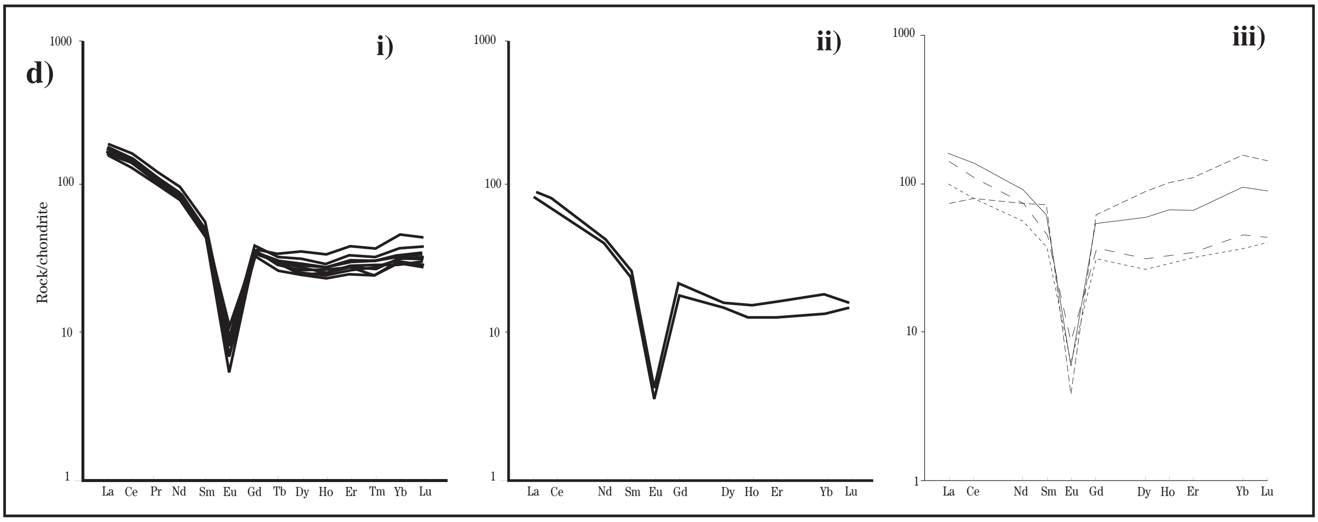


Fig. 3 d) Chondrite-normalized (Boynton, 1984) REE-patterns for i) Bispberg granite, ii) Högberget granite, iii) Skålhöjden granite

1.4. "Post-Svecofennian" granitoids

1.4.1 INTRODUCTION

M. Ahl, U.B. Andersson & K. Sundblad

Some of the largest batholiths in the Svecofennian Domain have commonly been referred to as post-Svecofennian (or postorogenic) granitoids. The most significant of these is the Revsund granitoid complex which occupies vast areas in central Sweden, and the Transscandinavian Igneous Belt which forms the southwestern border of the Svecofennian Domain and extends from the Caledonian Front in southern Norway to southeastern Sweden. Detailed geochemical and isotopic information shows that these "post-Svecofennian" granitoids are very inhomogeneous and constitute a number of groups with highly variable ages and geochemical characteristics. The distinction of post-Svecofennian from Late Svecofennian granitoids was originally based on the presumed temporal relationships to the Svecofennian Orogeny. The increasing number of U-Pb age data which has become available during the last decade has, however, changed these concepts and a considerable overlap in time between the late-orogenic and some of the post-orogenic intrusions is now evident (cf. e.g. Andersson 1991). The distinction between the late- and postorogenic intrusions has also been questioned on structural grounds (Wikström 1984, 1991). It is also evident that the youngest parts of the TIB share most of the characteristics of the anorogenic granitoids in the Svecofennian Domain and contrast markedly with other parts of TIB. This indicates that the anorogenic magmatism was initiated even before the emplacement of the classical rapakivi complexes. A revision of the classical concepts "late orogenic", "post-orogenic" and "anorogenic" magmatic episodes in the Svecofennian Domain is therefore needed.

1.4.2 THE REVSUND GRANITOID SUITE (RGS)

U.B. Andersson, M. Ahl & K. Sundblad

The Revsund granitoid suite (RGS) forms a 1.80–1.77 Ga postorogenic granitoid complex, which is exposed over vast areas in north-central Sweden (Wilson et a. 1985, Patchett et al. 1987, Skiöld 1988, Claesson & Lundqvist 1995). It has been named after the Revsund village in the southern part of the Revsund complex and the information on the Revsund complex will be restricted to this southern area. The batholith complex was first described by Högbom (1894) and Svedmark (1895), and has also frequently been described and discussed in modern literature (Lundqvist 1968, Gorbatschev 1972, Welin & Lundqvist 1977, Persson 1978, Claesson & Lundqvist 1995). The Revsund granitoid suite is commonly distinguished as a batholith complex separate from the Transscandinavian Igneous Belt (e.g. Gaál & Gorbatschev 1987), but has also been included in this belt (Gorbatschev & Bogdanova 1993). The Revsund rocks are characteristically composed of grey, coarse K-feldspar porphyritic granites to quartz monzonites (e.g. Persson 1978, Lundqvist et al. 1990, Claesson & Lundqvist 1995). Inter-

Table 2. Selected chemical analyses of Revsund and Rätan granitoids.

	Revsund granitoids		Rätan granitoids				
Koord. N-S	696735	697680	686455	687460	689885	687780	687850
Koord. E-W	145300	146585	143790	143290	145185	140670	144235
Sample	T 9212	MA 94626	MA 94629	MA 94605	MA 94622	MA 94609	MA 94616
wt%							
SiO_2	66.70	69.7	61.1	64.5	65.7	70.7	76.8
TiO_2	0.69	0.38	0.72	0.64	0.59	0.33	0.09
Al_2O_3	14.00	14.60	17.80	16.40	15.60	14.90	12.90
Fe_2O_3 *t	5.77	2.95	5.09	4.30	4.38	2.47	1.20
Fe_2O_3 **		0.83	2.91	2.76	2.16	1.00	
FeO**		2.01	1.51	1.58	0.43	<0,25	
MnO	0.07	0.06	0.14	0.10	0.09	0.06	0.02
MgO	1.53	0.58	1.51	1.28	1.11	0.60	0.07
CaO	2.08	1.04	2.77	2.76	2.47	1.56	0.31
Na_2O	2.84	2.90	5.60	4.37	3.99	4.12	3.95
K_2O	3.58	6.05	4.07	5.24	4.92	5.26	5.12
P_2O_5	0.23	0.14	0.28	0.23	0.20	0.11	0.03
Su	97.50	98.4	99.10	99.9	99.1	100.1	100.5
LOI	1.50	0.8	1.00	0.7	0.3	0.4	0.3
ppm							
F *	360	820	1200	1170	540	560	
Ba	637	892	1260	1310	1020	636	48
Be	3.09	1.89	3.75	2.76	2.55	2.9	5.11
Co	10.60	<5.88	<5.68	<5.85	7.02	<5.81	<5.89
Cr	53.50	14.3	18.1	17.4	19.9	17.1	19.4
Cu	32.00	21	17.8	14.7	11.6	14.4	8.37
Ga		7.16	11.4	12.3	8.15	9.87	10.6
Hf		5.16	9.69	7.82	6.12	4.59	4.91
Mo	<5.99	<5.88	<5.68	<5.85	<6.13	<5.81	<5.89
Nb	19.80	10.2	18.9	14.9	12.5	13.4	28.9
Ni	20.00	8.98	6.78	8.12	7.97	8.78	10.9
Rb	194		93.2	158	138	158	365
Sc	9.81	<2.35	6.08	5.45	6.17	2.51	<2.36
Sn	10.00	2.53	2.47	3.79	3.11	2.64	4.75
Sr	157	155	393	436	333	291	18
Ta		1.00	2.13	2.01	0.98	1.45	4.42
Th		6.17	15.9	11.1	7.7	15.3	30.5
U		1.39	5.76	3.94	2.07	2.37	6.93
V	70	21	58.1	54	44	26	<5.89
W	<12	0.35	1.13	1.65	0.48	0.22	1.12
Y	27.10	16.6	45.1	28.8	27.3	20.4	25.6
Zn	85.50	22.5	23.7	50.7	61.4	27.4	11.6
Zr	235	198	387	304	244	165	107

mediate rocks are relatively abundant, whereas basic rocks are scarce.

Pink to red types are subordinate, as well as more even-grained varieties (e.g. Lundegårdh et al. 1984, Lundqvist et al. 1990). Volcanic rocks are entirely absent.

The chemical composition of two typical samples of Revsund granitoids are shown in Table 2. Geochemically the RGS shows marked similarities to the Småland–Värmland granitoids (Andersson 1997b), with a general A-type character in the classification diagrams of Whalen et al. (1987), but dominantly volcanic-arc tendencies in the diagrams of Pearce at al. (1984) (Andersson 1997b, Claesson & Lundqvist 1995; Fig. 15). The major element chemistry is metaluminous to peraluminous, centering on an average molecular $Al_2O_3/(Na_2O+K_2O+CaO)$ ratio close to one (Ahl & Sundblad 1994, Andersson 1997b). The most alumina-rich types may contain substantial amounts of sediment-derived material, but generally this rock suite is regarded as formed from relatively dry magmas of I- to A-type derived in the lower-middle crust (Claesson & Lundqvist 1995).

1.4.3 THE TRANSSCANDINAVIAN IGNEOUS BELT (TIB)

1.4.3.1 Introductory remarks

M. Ahl, U.B. Andersson & K. Sundblad

The Transscandinavian Igneous Belt (TIB) forms another major granitoid complex, which traditionally has been referred to as "post-orogenic" in relation to the Svecofennian (or Svecokarelian) Orogeny. TIB can be followed along the southwestern margin of the Svecofennian Domain for at least 600 km and may also be followed beneath the Caledonian cover to northern Norway (Fig. 1). It has been correlated with the Ketilidian Mobile Belt of Greenland and post-Makkovikian granitoids in Labrador (Bridgwater & Windley 1973, Gower et al. 1990 and references therein). Genetic models proposed for the granitoids and porphyries within TIB include emplacement in an Andinotype orogenic environment in connection with an eastward plunging subduction zone further to the west (Wilson 1980, Nyström 1982), an ensialic rift setting (Wilson et al. 1985, Johansson 1988) or alternatively they formed in conjunction with Post-Svecofennian extensional collapse of the overthickened Svecofennian crust (Korja et al. 1993, Korja & Heikkinen 1995). Three major batholith complexes are commonly distinguished within TIB: the Småland-–Värmland granitoids (and associated porphyries), the Dala granitoids (and associated porphyries) and the Rätan granitoids (Fig. 4). The borders between these three igneous complexes are not fully understood. They form two parallel NNW–SSE-trending linear configurations, which rather may suggest major conjugate tectonic breaks than simple magmatic contacts. Recently, Gorbatschev & Bogdanova (1993), also included the Revsund granitoid suite in the TIB. The TIB has been subdivided into three age groups by Larson & Berglund (1992), termed TIB I (1.81–1.76 Ga), TIB II (1.71–1.69 Ga), and TIB III (1.67–1.65 Ga). Recent age data, however, show considerable overlap between the TIB I and II groups, as well as older ages than TIB I, which casts some doubts on this subdivision (see below).

1.4.3.2 Småland–Värmland granitoids (SVB)

M. Ahl, U.B. Andersson & K. Sundblad

The Småland–Värmland granitoids (SVG) (and their associated volcanic rocks, the Småland porphyries) constitute the southern part of TIB (Fig. 1). Rocks in the Småland–Värmland belt can mostly be assigned to TIB I and III (Welin & Kähr 1980, Jarl & Johansson 1988, Mansfeld 1991, Mansfeld 1992, Lundqvist 1993). The TIB III rocks have so far only been confirmed from areas along the western margin of the TIB (e.g. Jarl 1992, Larson & Berglund 1992, Wikman 1993, Wolff et al. 1995, Heim et al. 1996). Recently, also SVG units of somewhat higher ages (c. 1.85 Ga) have been documented by Persson & Wikström (1993) and Wikström (1996). The granitoids show a range of compositions from quartz monzodiorite, quartz monzonite and adamellite to granite, and have generally a coarse-grained porphyritic or equigranular texture. Geochemical data indicate an alkali-calcic affinity and I-type characteristics (Wilson 1980, Zuber & Öhlander 1990). Several examples of exten-sively homogenized hybrids of mafic-felsic magma-mixing have been observed in the TIB granitoids (Andersson 1989, 1991, 1997b), and associated basic rocks are fairly common.

1.4.3.3 Dala granitoids and associated volcanic rocks

M. Ahl, T. Lundqvist & K. Sundblad

1.4.3.3.1 Introduction

The Proterozoic bedrock of northern and central Dalarna, south-central Sweden, was mapped by Hjelmqvist (1966), Lundegårdh (1967) and Lundqvist (1968). It comprises two major units: the Svecokarelian (or Svecofennian) complexes in the south and east, and the Transscandinavian Igneous (or Granite-Porphyry) Belt (TIB; cf. Gaál & Gorbatschev 1987) in the north and west. The Dala granitoids and volcanites form part of the TIB. These lithologies continue westward

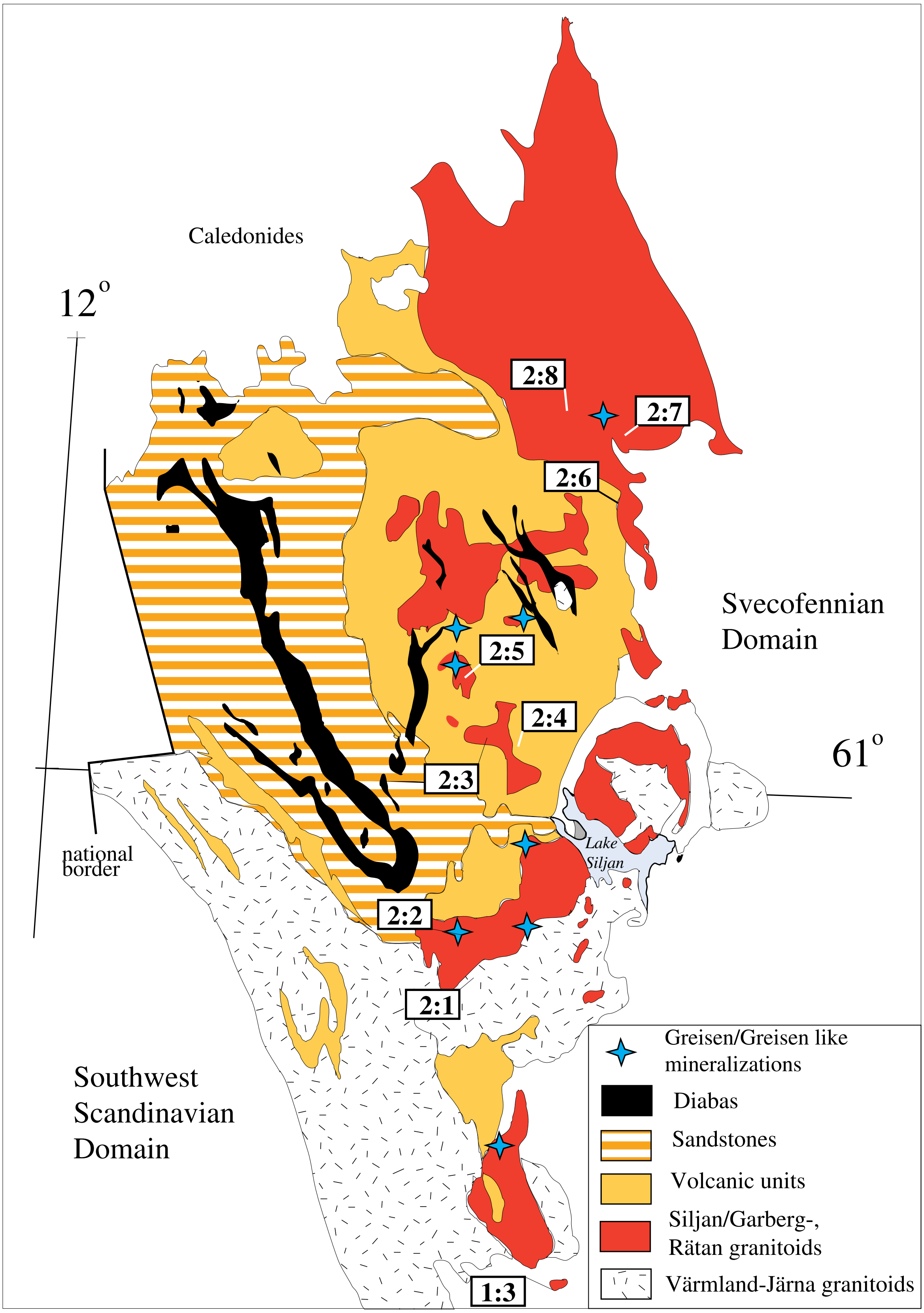


Fig. 4. Simplified geological map of the Dala region. Modified after Hjelmqvist (1966), Lundegårdh & others (1984), Kresten & others (1991) and unpublished prospecting maps.
Excursion localities for the IGCP 315 excursion are indicated.

Table 3. Selected chemical analyses of Järna, Siljan and Garberg granitoids.

	Järna granitoids		Siljan granite		Garberg granite	
Koord. N-S	671723	671552	672571	674855	681165	677635
Koord. E-W	142430	140884	140811	142705	144405	141595
Sample	90078	90020	90077	90095	91308	91313
wt%						
SiO2	62.5	65.7	74.9	75.2	77.4	71.4
TiO2	0.66	0.77	0.18	0.13	0.20	0.34
Al2O3	17.30	15.40	13.00	12.80	12.00	13.80
Fe2O3 *t	5.37	5.07	1.59	1.78	1.43	2.76
FeO	2.44	2.15	0.50	0.86	0.29	0.79
MnO	0.10	0.10	0.04	0.05	0.04	0.08
MgO	1.82	1.25	0.30	0.10	0.18	0.62
CaO	4.39	2.31	1.13	0.67	0.45	1.59
Na2O	3.92	3.58	3.29	3.85	3.34	3.78
K2O	3.59	5.10	4.86	4.93	5.19	4.99
P2O5	0.24	0.25	0.06	0.01	0.03	0.11
Su	99.8	99.5	99.4	99.6	100.3	99.4
LOI	1.0	0.8	0.5	0.5	0.3	0.6
ppm						
F *	1220	1050	530	2750	1160	1020
Ba	1207	1350	371	122	125	518
Be	<1,2	2.4	2.4	5.5	5.4	3.9
Co	11.0	8.1	<5,8	<6	<5,98	<6,07
Cr	8.7	70.8	19.0	16.0	15.6	24.1
Cu	13.0	16.5	8.7	12.0	9.7	8.2
Ga	25.9		15.4	15.8		
Mo	<6,1	<5,88	<5,8	<6	<5,98	<6,07
Nb	<6,1	20.2	<5,8	17.0	17.6	14.5
Ni	17.0	8.3	6.8	23.0	<5,98	<6,07
Sc	11.0	10.2	2.4	<2,4	2.8	4.4
Sn	<6,1	7.5	15.0	9.3	10.7	10.6
Sr	581	299	134	23	38.9	214
Ta	73	48.4	11	<6	<5,98	22.1
Th	16	28.9	24	<12	<12	12.8
U	24	37.9	20	62	25.8	33.4
V	64	91.7	15	47	68.4	57.1
W	162	318	85	203	138	186
Y	27	17	45	29	20	26
Zn	86	23	24	51	27	12
Zr	235	198	387	304	165	107
Zn	86	23	24	51	27	12
Zr	235	198	387	304	165	107

into the ”Tricolor” granite of the Trysil area in Norway (Wolff et al. 1995, Heim et al. 1996), and northward into the Dala-Härdal granites of the Härjedalen area in Sweden (Gorbatschev et al. 1997). They constitute the basement of a maximum c. 800 m thick sequence of continental-type sandstone with minor conglomerate and shale (Dala sandstone, in Norway named Trysil sandstone). This sandstone is included in the Jotnian formations of the Fennoscandian Shield. An intercalation of basaltic, in part amygdaloidal and porphyritic lavas and sills with subordinate tuffs (the Öje basalt) occurs in the Dala sandstone. The age of the sandstone and Öje basalt is not well known, but is constrained between the age of the Dala volcanites (1.70 Ga) and the age of later, cross-cutting sills and dykes of dolerites (the Åsby and Särna dolerites), which is c. 1.20– 1.25 Ga (Patchett 1978). Still younger, c. 900 Ma dolerites (the Blekinge-Dala Dolerites), forming mostly steeply dipping, NNW-trending dykes, cut the older rocks (Patchett 1978,

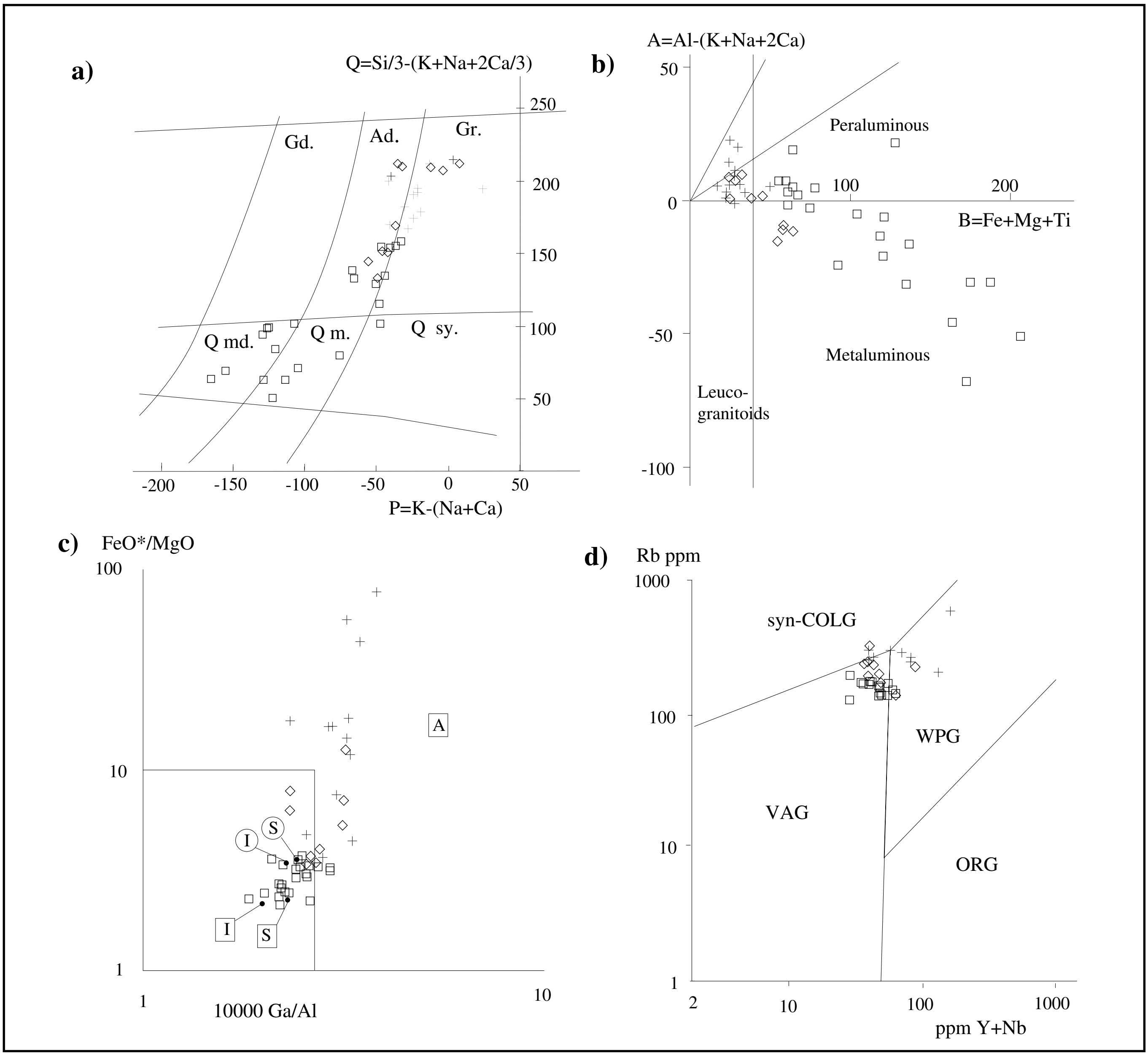


Fig. 5. Chemical parameters of the Dala granitoids plotted in various classification diagrams. Squares: Järna granitoids, crosses: Siljan granites, diamonds: Garberg granites. .

a) P-Q diagram according to Debon and Le Fort (1982). Gr.= Granite, Ad.= Adamellite, Gd.= Granodiorite, Q md.= Quartz monzodiorite, Q m.= Quartz monzonite, Q sy.= Quartz syenite.

b) A-B diagram according to Debon and Le Fort (1982).

c) 10,000 Ga/Al versus FeO*/MgO diagram. I and S in circles are the calculated average values for I- and S-type felsic granites whereas I and S in squares are the calculated average values for I- and S-type granites according to Whalen and others (1987).

d) Y+Nb versus Rb diagram for syn-collision (syn-COL), volcanic arc (VA), within plate (WP) as well as normal and anomalous ocean ridge (OR) granites according to Pearce and others (1984).

Gorbatschev et al. 1987). In the west, and northwest, the Proterozoic basement is covered by a thin sequence of autochthonous Early Palaeozoic sedimentary rocks and Caledonian nappes (Hjelmqvist 1966, Wolff et al. 1995). The youngest rock-forming event of northern Dalarna occurred c. 280 Ma ago (Bylund & Patchett 1977, Welin 1980), with the intrusion of a cancrinite-nepheline syenite (särnaite) and related dykes. The syenite forms a plub in a Dala porphyry inlier in the Dala sandstone west of Särna (Hjelmqvist 1966).

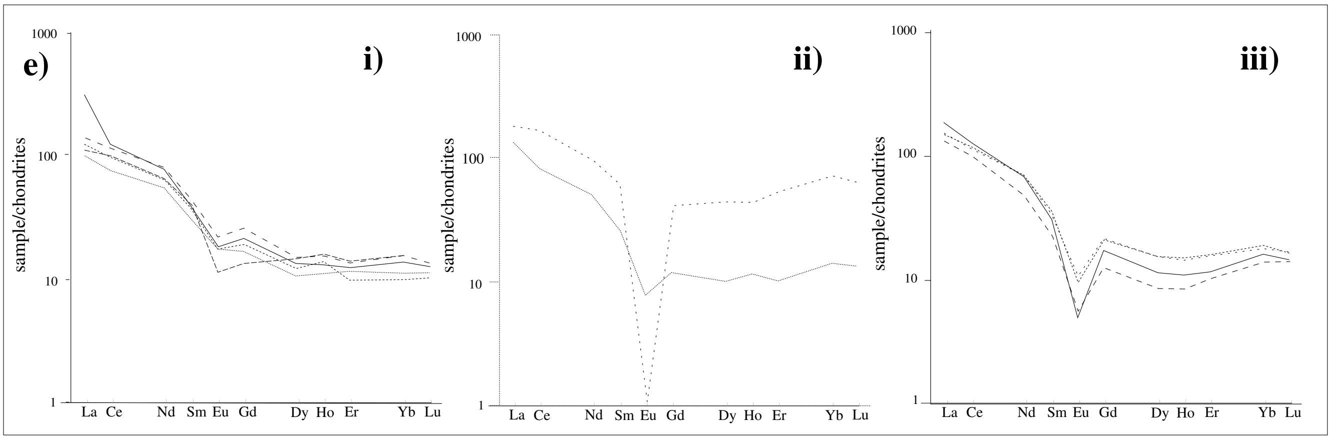


Fig. 5 cont. e) Chondrite-normalized (Boynton, 1984) REE-patterns for Dala granitoids. i) Järna granitoids, ii) Siljan granites, iii) Garberg granites.

1.4.3.3.2 The Dala granitoids

The Dala granitoids and their associated volcanic rocks constitute a significant component (c. 7000 km^2) of TIB between the Småland–Värmland and the Rätan granitoid batholiths (Fig. 4). Earlier studies of the area include Hjelmqvist (1966), Lundqvist (1968), Nyström (1982), Kresten (1986), Kresten et al. (1991), Cruden & Aaro (1992). Several generations of Dala granites can be distinguished; the older of these form pebbles in the conglomeratic intercalations in the Dala porphyrites, the youngest intrude Dala porphyries of high stratigraphic levels (see below). Among the younger granites especially the porphyritic Garberg granite is noted (Hjelmqvist 1966 and Lundqvist 1968). The Dala granitoids have not undergone any major metamorphic or deformative event, but have been affected by burial metamorphism (Nyström 1982). No known anorthosites and only very few pegmatites are associated with the Dala granitoids. The entire area shows an aeromagnetic positive anomaly (Riddihough 1972, Dyrelius 1980). Based on low-altitude aeromagnetic maps, possible ring and radial fractures, and a number of semi-circular structural forms (up to 7–10 km in diameter) were identified in the Dala granitoids (unpublished prospecting material, LKAB prospecting). Features indicating caldera subsidence have also been reported (Nyström 1982). The Dala granitoids constitute a heterogeneous plutonic complex, of which several granitoid types can be distinguished based on textures, petrology and geochemistry. The most common types are the Järna, Siljan and Garberg granitoids. Although the Järna, Siljan and Garberg granitoids were distinguished as separate rock groups already in the last century (Sederholm 1897, Holmquist 1906), the proper spatial relationships between these three types of rocks were not understood until Hjelmqvist (1966) published his 1:200 000 scale map of Kopparberg (now: Dalarna) county. The following varieties of Dala-granitoids can be distinguished.

The *Järna granitoids* (Fig. 4) are massive, fairly coarse-grained (2–5 mm), greyish or greyish red. They are rich in mafic minerals; mainly biotite but also hornblende, as well as basic oligoclase, microcline and idiomorphic titanite. These granites are in places rich in small rounded enclaves, some centimetres in diameter, consisting mainly of amphibole and plagioclase. When the quartz content decreases they grade into quartz-syenite. The Järna granitoids are the only Dala plutonic rocks that have appreciable amounts of associated mafic rocks. Two separate U-Pb determinations of Järna granitoids yielded 1.79 Ga (Åberg & Bollmark 1985, Persson & Ripa 1993).

The *Siljan granite* (Fig. 4) are leucractic and red with a medium to coarse (1–5 mm) grained texture. The main minerals are alkali feldspar, quartz, plagioclase, and sparsely occurring biotite and muscovite. Accessory minerals are magnetite, sphene and fluorite. U-Pb determination of the Siljan granite yielded 1.68–1.70 Ga (Lee et al. 1988, Ahl, in prep.).

The *Garberg* and closely related *Loberget granites* (Fig. 4) are also leucocratic and red but have a more well-developed feldspar porphyritic texture with a fine-grained (c. 0.5 mm) matrix. A tendency to form wiborgitic textures (plagioclase mantled K-feldspar phenocrysts) is noted. There are also syenitic and more fine-grained varieties of Dala granite. A U-Pb zircon age determination of the Garberg granite near Oxberg has yielded 1710±11 Ma (Th. Lundqvist & P.-O. Persson, in prep.). An older, less precise U-Pb age of 1740+79/-46 Ma was obtained by Patchett et al.

(1987). The Siljan and Garberg granites have occasionally miarolitic cavities, porphyritic textures, and are considered to represent subvolcanic intrusions to the volcanic Dala porphyries. A number of small and economically insignificant polymetallic (Sn-Pb-Zn-Au-Ag-Cu-Mo-Be-F) mineralizations with greisen characteristics occur in the Siljan and Garberg granites (Fig. 4).

Dykes of granite porphyry, which are closely related to the Dala granites, occur in several places in northern Dalarna and southern Härjedalen. Dykes of quartz-feldspar porphyry have also been reported to cut the Trysil/Dala porphyries west of the sandstone in the Trysil area of Norway (Wolff et al. 1995).

Geochemical characteristics of Dala granitoids

The average chemical composition as well as the standard deviation for the three groups of Dala granitoids (Järna, Siljan and Garberg) are shown in Table 3. The investigated granitoids show wide compositional variations, especially in their silica contents. The Järna granitoids are relatively primitive and show silica contents between 55 and 71% SiO_2. This is in marked contrast to the more evolved Siljan and Garberg granites showing silica values between 70 and 78% SiO_2 with only a slight overlapping with the Järna granitoids. Many characteristic trends can be observed when plotting individual elements versus the SiO_2 content (corresponding to degree of magma evolution). This is expressed by decreasing contents of Al_2O_3, Fe_2O_3*, MnO, TiO_2, MgO, CaO, and P_2O_5, and increasing contents of K_2O with increasing SiO_2 content. The Na_2O contents are nearly constant. The trace elements behave in a similar way when plotted versus increasing SiO_2 content: decreasing Ba, Sr, V, Cr, Ni, Zn, Zr and Eu, and increasing F, Rb, Be, Sn and Nb. The Ga contents are nearly constant.

The *Järna granitoids* show a wide range of chemical compositions corresponding to the quartz monzodiorite, quartz monzonite, quartz syenite, adamellite and granite fields in a P-Q diagram (Fig. 5a). The Järna granitoids show a trend from the metaluminous into the peraluminous field (Fig. 5b) and the average of the Aluminium Saturation Index (ASI) of Zen (1988) is 0.97. In a Rb-Ba-Sr diagram the Järna granitoids show a low degree of differentiation. Only two samples have Sn contents over the detection limit (6 ppm), and the average value is below 6 ppm. The Järna granitoids plot within the field for I-type granitoids in Fig. 5c and in the field for "volcanic arc granitoids" in Fig. 5d. Representative REE analyses of the Järna granitoids are plotted in chondrite-normalized diagrams (Fig. 5e). The Järna granitoids show $(La/Yb)_N$ ratios between 10.0 and 11.8 (on average 11.0), and have no significant Eu anomalies with $(Sm/Eu)_N$ ratios between 1.8 and 2.7 (on average 2.1).

All *Siljan and Garberg granites* are true granites in the nomenclature of Streckeisen and are restricted to the granite and adamellite fields in a P-Q diagram (Fig. 5a). The Siljan and Garberg granites are slightly peraluminous and plot mostly within the leucogranitic field in an A–B diagram (Fig. 5b). The average of the ASI is 1.02. The Siljan and Garberg granites have high contents of Na_2O+K_2O (on average 8.33), demonstrating an alkaline affinity, but they are still subalkaline in the nomenclature of Irvine and Baragar (1971). Fe/(Fe+Mg) ratios are relatively high (on average 0.90) and Fe^{3+}/Fe_{tot} ratios are high to moderate (on average 0.47). The differentiation trends for the Siljan and Garberg granites can be followed from "anomaly granite" via "normal granite" into "strongly differentiated granite" in a Rb-Ba-Sr-diagram. The Siljan and Garberg granites show enrichment in incompatible trace elements such as Be, Sn and Rb, whereas Ba and Sr are depleted. The fluorine contents are high and range from 190 to 5500 ppm (on average 1980 ppm). Large ion lithophile elements such as Y, Ce and Nb are also enriched, and the average ratio of Y/Nb is 2.5. The relatively high Ga/Al ratios (on average 3.2) in this group are also a distinctive feature for the Siljan and Garberg granites. Other characteristic features for the SiO_2-rich granites (Siljan and Garberg granites) are also high contents of Th and U (Armands & Drake 1978).

The calculated normative corundum values (CIPW) are less then 1% (on average 0.50). In a normative Qz-Ab-Or plot, the Siljan and Garberg granites occupy an area at and near the 0.5 and 1.0 kbar cotectic minimum for hydrous granites of minimum melt composition. A weak tendency is observed for samples with lower normative quartz values to plot off the calculated curve for an ideal hydrous granite and indicate more anhydrous conditions. The Siljan and Garberg granites plot mainly within the field for A-type granites in Fig. 5c. In Fig. 5d the Siljan granites plot within the field for "within plate granites", whereas the Garberg granites plot within the field for "volcanic arc granitoids".

Representative REE data of the Siljan and Garberg granitoids are plotted in chondrite-normalized diagrams (Fig. 5e). One Siljan granite sample displays a pronounced negative Eu anomaly, with $(SM/Eu)_N$ ratio on 56.5 and a $(La/Yb)_N$ ratio on 2.4, while another sample shows a relatively flat pattern with a $(Sm/Eu)_N$ ratio on 3.4 and a $(La/Yb)_N$ ratio on 4.6. The HREE are more depleted in the Garberg granite, with $(La/Yb)_N$ ratios ranging from 6.7 to 12.0 (on average 7.95). The Garberg granite samples have less pronounced negative Eu anomalies, with $(Sm/Eu)_N$ ratios between 3.4 and 6.3 (on average 4.15).

1.4.3.3.3 The Dala volcanites and related rocks

T. Lundqvist

General features

Two major lithological groups together form the Dala volcanites: felsic rocks mainly ranging in composition between rhyolites and trachytes, so-called Dala porphyries (in Norway named Trysil porphyries; Wolf et al. 1995), and predominantly mafic to intermediate rocks comprising basalts, trachybasalts, trachyandesites and minor quartz trachytes, collectively named Dala porphyrites. Sedimentary rocks ("Digerberg formations") occur as intercalations in the volcanic rocks, and mainly include sandstone, in part tuffitic, conglomerate and breccia. They are especially abundant in connection with the Dala porphyrites (Hjelmqvist 1966).

The age of the Dala volcanites is c. 1.70±0.01 Ga (Welin et al. 1993, Th. Lundqvist & P.-O. Persson, in prep.). They were deposited on top of an erosion surface cut into the older, Svecokarelian complexes and c. 1.8 Ga granites and porphyries, and were in turn weathered and eroded before the Dala sandstone was deposited as fluviatile, in part also aeolian sediments (Hjelmqvist 1966, AlDahan 1985, Pulvertaft 1985).

The Dala porphyries are genetically linked with the porphyritic granites and syenites by texturally intermediate (subvolcanic) varieties, and are not always possible to distinguish from latter intrusive Dala rocks. Dala granites and porphyries in Orsa finnmark display similar chemical and modal trends. Both texturally and compositionally they have a clear rapakivi affinity (Lundqvist 1968).

The Dala volcanites were long regarded as unmetamorphic. Frequently observed parageneses of greenschist grade, which are most conspicuous in the Dala porphyrites, were interpreted to be due to deuteric alteration caused by circulating fluids in the volcanic areas. However, as Nyström (1980, 1982 and 1983) pointed out, it is more likely that the alteration is a non-deformational, burial metamorphism.

Dala porphyrites

The Dala porphyrites show a wide range of compositions, from basalt–andesite to (rare) trachyte and quartz trachyte. Trachybasaltic and trachyandesitic compositions are common (Hjelmqvist 1966 and 1982, Lundqvist 1968), see Fig. 6.

The rocks vary in colour between dark grey and reddish brown, often with a patchy and schlieric distribution of red-

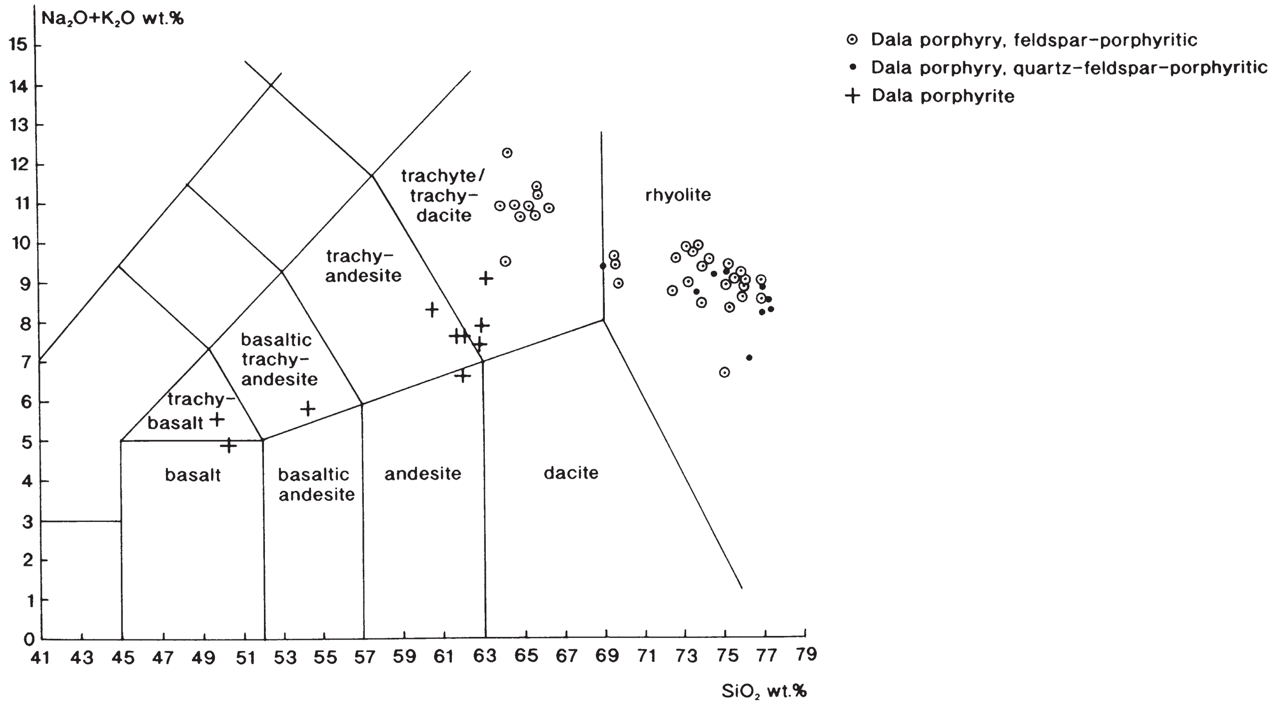


Fig. 6. Total Alkali - Silica diagram (Le Bas & Streckeisen 1991) for Dala porphyrites and porphyries from Kopparberg County. Based on analyses in Hjelmqvist (1966 and 1982), Lundqvist (1968) and Th. Lundqvist & P.-O. Persson (in prep.)

Tab. 4. Selected chemical analyses of Dala volcanites and one Dala granite.

	1	2	3	4	5	6
SiO_2 (wt%)	50.3	63.2	49.70	60.64	75.8	64.4
TiO_2	0.85	0.61	0.92	0.90	0.21	0.58
Al_2O_3	16.0	15.0	17.02	15.39	12.4	16.9
Fe_2O_3	5.3	4.14	4.30	4.14	0.62	1.28
Fe_2O_3*	-	-	-	-	-	-
FeO	3.6	0.99	6.33	1.30	0.45	1.69
MnO	0.15	0.10	0.12	0.08	0.06	0.08
MgO	6.8	1.8	4.72	2.52	0.2	0.7
CaO	8.9	3.5	8.58	4.06	0.5	1.7
Na_2O	2.1	3.9	2.86	3.54	3.2	4.5
K_2O	2.8	5.2	2.70	4.79	6.0	7.8
H_2O+	2.2	1.3	2.19	2.05	0.3	0.5
H_2O-	0.5	0.27	0.21	0.25	0.10	0.22
P_2O_5	0.32	0.21	0.33	0.39	<0.01	0.17
CO_2	-	-	-	-	-	-
F	-	-	0.22	-	-	0.08
S	-	-	0.02	-	-	-
LOI	-	-	-	-	-	-
-O for S,F	-	-	0.10	-	-	0.03
Sum	99.8	100.2	100.12	99.99	99.8	100.6
Zr (ppm)	-	300	-	-	200	300
Sr	750	600	-	-	<100	200
Ba	900	1250	200	-	200	2700
Rb	-	200	-	-	300	100
Nb	-	-	-	-	-	-
Sc	-	-	-	-	-	-
Th	-	-	-	-	-	-
U	-	-	-	-	-	-
Y	-	-	-	-	-	-

1. Dala porphyrite (Lundqvist 1968, Tab. 1 no. 57).
2. Dala porphyrite (Lundqvist 1968, Tab. 1 no. 61).
3. Dala porphyrite (Hjelmqvist 1966, Tab. 16, p. 89).
4. Dala porphyrite (Hjelmqvist 1982, analysis 1).
5. Dala porphyry, feldspar-porphyritic, ignimbritic (Lundqvist 1968, Tab. 1 no. 70).
6. Dala porphyry rich in big feldspar phenocrysts (Lundqvist 1968, Tab. 1 no. 72).

dish and yellowish green tones, in the latter case due to the occurrence of epidote. Phenocrysts are of clinopyroxene, in rare cases also olivine, both of these minerals usually strongly altered to actinolite, epidote, opaque minerals, chlorite, etc. Plagioclase phenocrysts (labradorite–andesine) are extensively altered to sericite, epidote, calcite and prehnite. The matrix is characterized by plagioclase, K-feldspar and the same mafic minerals as in the phenocrysts. Minor amounts of quartz may occur. This mineral and K-feldspar increase in the reddish brown varieties to give quartz-trachytic compositions. K-feldspar does not normally form phenocrysts (a basis for distinguishing the porphyrites from the Dala porphyries), but may occur as corroded xenocrysts. Lundqvist (1968) suggested that mixing of the porphyrite and porphyry magmas gave rise to the compositional range shown by the porphyrites.

Primary structures and textures are usually well preserved in the Dala porphyrites. Amygdaloidal, breccia-like and agglomeratic structures, trachytoidal (flow) and glass-shard textures as well as the already mentioned porphyritic texture are examples.

Dala porphyries

The Dala porphyries range compositionally from rhyolites via quartz trachytes to trachytes (Figs. 6 and 7). They are always porphyritic, with phenocrysts ranging in size between

Tab. 4 (continued). Selected chemical analyses of Dala volcanites and one Dala granite.

	7	8	9	10	11	12
SiO_2 (wt%)	69.86	64.7	76.0	66.4	75.6	73.0
TiO_2	0.30	0.74	0.24	0.88	0.30	0.33
Al_2O_3	14.37	17.5	12.5	15.6	12.7	13.0
Fe_2O_3	1.46	1.7	-	-	-	-
Fe_2O_3*	-	-	1.55	3.68	1.90	2.71
FeO	2.54	1.4	-	-	-	-
MnO	0.07	0.09	0.05	0.15	0.06	0.08
MgO	0.49	0.80	0.18	0.85	0.07	0.62
CaO	0.54	1.9	0.54	1.61	0.50	1.37
Na_2O	2.54	4.2	3.50	4.88	4.25	3.50
K_2O	6.44	6.7	5.09	5.99	5.06	4.59
H_2O+	0.70	0.6	-	-	-	-
H_2O-	0.12	0.2	-	-	-	-
P_2O_5	0.05	-	0.04	0.33	0.04	0.12
CO_2	0.10	-	-	-	-	-
F	0.12	-	-	-	-	-
S	0.48	-	-	-	-	-
LOI	-	-	0.5	0.4	0.3	0.7
-O for S,F	0.23	-	-	-	-	-
Sum	99.95	100.53	100.2	100.8	100.8	100.0
Zr (ppm)	-	-	201	500	398	173
Sr	-	-	37	78	20	164
Ba	350	3100	81	1010	168	355
Rb	-	-	221	98	170	197
Nb	-	-	25	10.9	19.5	21.2
Sc	-	-	<2.4	8.2	<2.3	<2.3
Th	-	-	21	7.5	14.9	16.1
U	-	-	6.5	1.9	4.4	4.4
Y	-	-	27	35	50	19

7. Dala porphyry, feldspar-porphyritic, ignimbritic (Hjelmqvist 1966, Tab. 17 p. 89).
8. Dala porphyry rich in big feldspar phenocrysts (Hjelmqvist 1982, analysis 10).
9. Dala porphyry (Bredvad porphyry), Trängslet (Th. Lundqvist & P.-O. Persson in prep.)
10. Dala porphyry rich in big feldspar phenocrysts (Heden porphyry), Heden (Th. Lundqvist & P.-O. Persson in prep.).
11. Dala porphyry, quartz-feldspar-porphyritic, Rörbäcksnäs (Th. Lundqvist & P.-O. Persson in prep.).
12. Garberg granite, feldspar-quartz-porphyritic, Oxberg (Th. Lundqvist & P.-O. Persson in prep.).

less than a millimetre and c. 2 cm. Phenocryst contents are up to c. 50%, in extreme cases up to 90%, of the total rock volume. The colour is reddish or purplish brown, black or light brown to pink. The vivid colours and hardness of the porphyries make them suitable for polishing to produce ornamental stone (vases, urns, candle-sticks, gravestones etc.), and the porphyries have formerly been much used in local factories, mainly at Älvdalen (e.g. Solders 1939, Lagerqvist & Åberg 1985).

The most common type of phenocryst is a strongly perthitic K-feldspar which is structurally intermediate between orthoclase and microcline (Lundqvist 1968). Plagioclase (oligoclase or albite) is also common among the phenocrysts. It is generally mantled by perthitic alkali feldspar, which also forms second-generation, poikilitic overgrowths on perthitic K-feldspar phenocrysts. Mafic phenocrysts are mostly strongly retrograded to epidote, opaque minerals, chlorite and actinolite, but relics of clinopyroxene may be found.

Quartz is lacking or occurs as a very subordinate phenocryst in the central area of Dala porphyries, i.e. around Älvdalen and in Orsa finnmark. However, quartz occurs as a prominent phenocryst in certain porphyry types (e.g. the Glöte porphyry) in the Härjedalen area north of Älvdalen (Gorbatschev et al. 1997). It is generally corroded and more or less rounded, but has a clear tendency to a bipyramidal

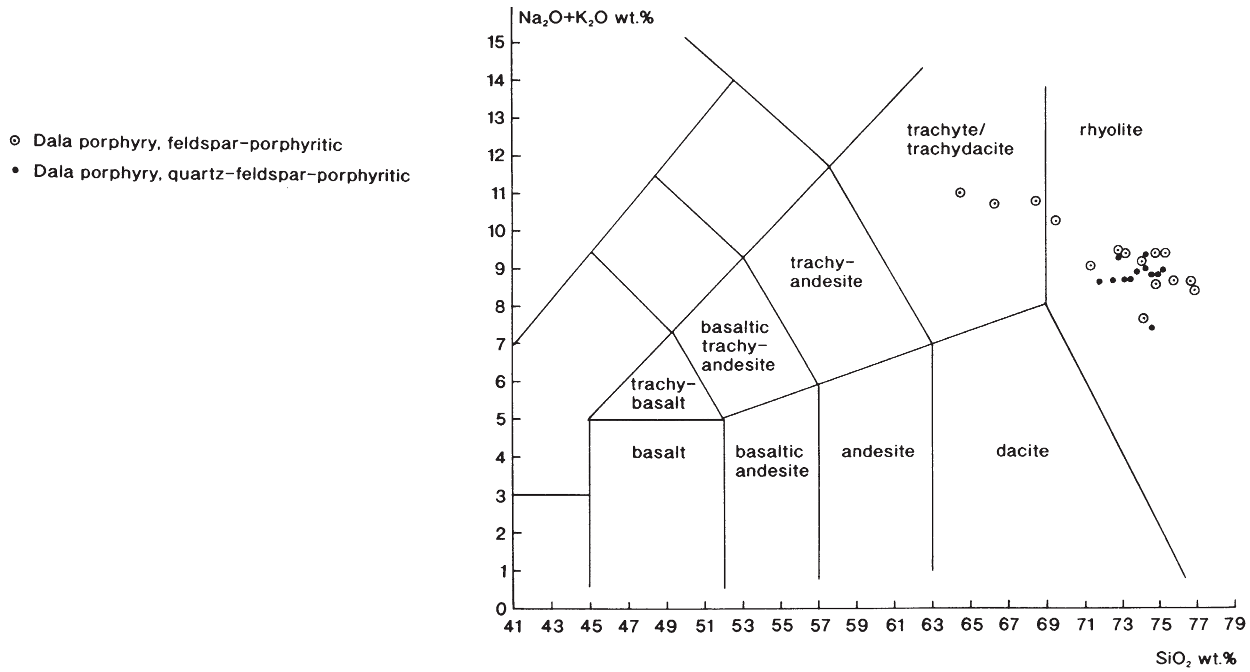


Fig. 7. Total Alkali - Silica diagram (Le Bas & Streckeisen 1991) for Dala porphyries from Jämtland County (Härjedalen). Based on analyses in Gorbatschev et al. 1997.

habit. Quartz-feldspar porphyries west and south of the Dala sandstone area, earlier ascribed to the ”Lower Dala series” by Hjelmqvist (1966), according to recent U-Pb zircon dating are of the same age as the feldspar porphyries of the major Älvdalen–Orsa finnmark area (Th. Lundqvist & P.-O. Persson, in prep.). Therefore, the c. 1.7 Ga porphyries of northern Dalarna (the Dala porphyries) seem to be made up of essentially two types with regard to phenocryst composition: feldspar porphyries and quartz-feldspar porphyries (cf. below).

The matrix of the Dala porphyries mainly consists of quartz and alkali feldspar(s) with subordinate amounts of actinolitic hornblende, chlorite, epidote, opaque minerals etc. Accessories are apatite, zircon and fluorite. The texture of the matrix varies from crypto- or microcrystalline, sometimes micropoikilitic, spherulitic or granophyric, to fine-grained. In the best preserved porphyries glass-shard and eutaxitic textures are common, lithophysae less common. Hjelmqvist (1956 and 1966) and Lundqvist (1968) interpreted the porphyries largely as ignimbrites. Lundqvist (1968)

Tab. 5. REE analyses (Th. Lundqvist & P.-O. Persson in prep.) of Dala porphyries and one Dala granite. Numbers as in Table 4.

	9	10	11	12
La	47.0	123	51.9	38.2
Ce	111	249	119	87.9
Pr	11.6	29.2	15.0	9.75
Nd	44.7	107	55.9	36.1
Sm	7.19	14.3	11.3	4.73
Eu	0.269	2.53	0.870	0.484
Gd	5.00	10.4	9.77	5.22
Tb	1.05	1.58	1.71	0.670
Dy	5.32	7.28	9.49	4.70
Ho	1.02	1.47	1.99	0.930
Er	3.48	3.99	5.81	3.04
Tm	0.534	0.608	0.862	0.396
Yb	4.14	4.13	5.83	3.95
Lu	0.587	0.674	0.899	0.524

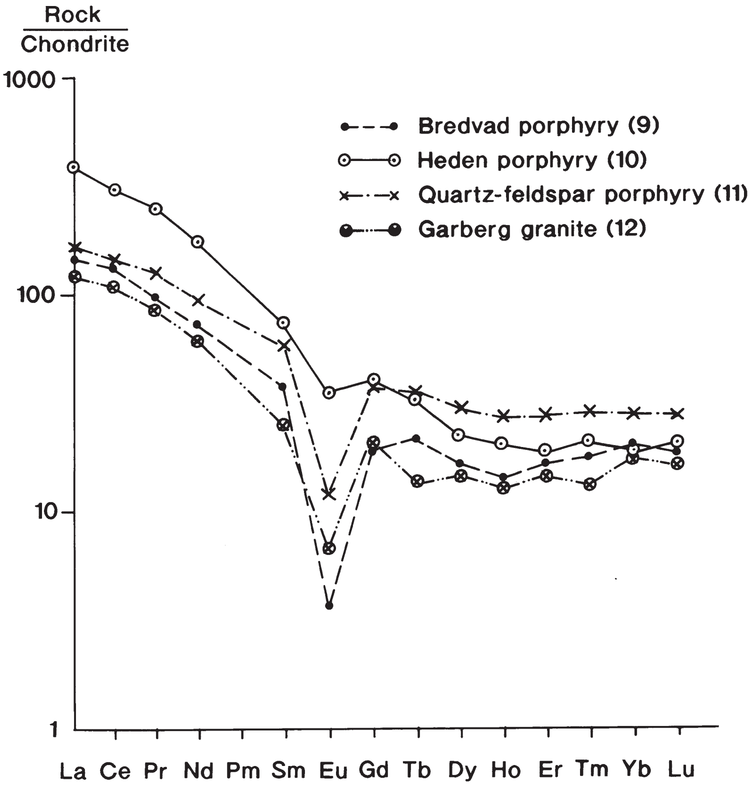


Fig. 8. Chondrite-normalized REE plots (Masuda & Nakamura 1973, Bailey 1991) of three Dala porphyries and one Dala granite (Garberg granite) from Kopparberg County (Th. Lundqvist & P.-O. Persson in prep.). Numbers as in Table 5.

reported varieties of Dala porphyries in which the fiamme of the eutaxitic texture were folded and brecciated by secondary flow ("rheoignimbrites"). In tuffaceous beds in the Dala porphyries accretionary lapilli have been observed, indicating subaerial eruptions (Lundqvist 1968).

The variation in modal and chemical composition from rhyolite to trachyte within the Dala porphyries (and associated granites) of the Älvdalen–Orsa finnmark area is seen in the field mainly as an increase in frequency and size of feldspar and mafic phenocrysts from the former to the latter. Concurrently with this, an increase in frequency of xenoliths of older (Svecofennian) rocks is often noted. Zircon and apatite contents as well as the anorthite content of plagioclase in the phenocrysts also increase towards the trachytic compositions. The chemical composition of the eleven samples of Dala volcanites and one sample of a Dala (Garberg) granite is shown in Tables 4 and 5. From these data it can be seen that the Zr and P contents and Ba/K ratios are higher, and the Rb/K ratios lower in the trachytes than in the rhyolites. These variations have been interpreted by Lundqvist (1968) to be due to accumulation of early-formed crystals to give the trachytic porphyries.

It should be noted that only very few modern chemical analyses of trace elements (including REEs) exist at present for the Dala volcanites. Therefore, it is not possible to draw far-reaching conclusions as to tectonic environment, differentiation etc. The F content is between 0.01 and 0.38% for 14 analysed samples of phenocryst-rich as well as phenocryst-poor porphyries (Hjelmqvist 1966 and 1982, Lundqvist 1968). Niggli k and mg values (42 analyses) range between 0.43 and 0.63, and between 0.05 and 0.34, respectively, and do not appear to be correlated with phenocryst content. Chondrite-normalized REE patterns show an La enrichment of c. 150–400x and a negative Eu anomaly (Fig. 8). The latter is most pronounced in porphyries with relatively few and small phenocrysts. In sample 10 from the Heden porphyry, which is rich in big feldspar phenocrysts, a negative Eu anomaly still exists but is relatively insignificant.

Among the 1.7 Ga Dala porphyries, as established by recent U-Pb zircon dating (Lundqvist & Persson, in prep.), there occur varieties with pronounced textural and chemical rapakivi features. This is the case especially in the feldspar porphyries east of the Dala sandstone area. Although at present modern investigations on these features are rather fragmentary, it appears that there also exist porphyries of this age with less pronounced (or even lacking) rapakivi textures and compositions. There is thus an evident need for future investigations, not only for the effusive porphyries but also for the c. 1.7 Ga granites in these parts of Sweden.

”Digerberg formations”

The sedimentary, in part tuffitic, rocks which form intercalations in the Dala volcanites, mainly in the porphyrites, are arkoses, conglomerates and breccias. The clasts are mostly from various types of Dala volcanites, especially the porphyrites. At low stratigraphic levels different types of Svecofennian supracrustal rocks are important among the clasts, and totally predominate in the basal formations. Thus, between Ämån and Älvho, c. 45 km northeast of Älvdalen, basal conglomerates and talus breccias deposited close to a horst of Svecofennian metasupracrustals contain clasts of Svecofennian quartzite and metarhyolite (cf. Hjelmqvist 1966 and Sjöblom & Aaro 1987b). Similar clasts are found in the basal arkoses, conglomerates and breccias of Orsa finnmark (Lundqvist 1968).

Stratigraphy, chronology and tectonics

Hjelmqvist (1966) subdivided the porphyries and porphyrites of northern Dalarna into two major stratigraphic units: the ”Lower Dala series” and the ”Upper Dala series”. Both were ascribed to the sub-Jotnian complexes of the Fennoscandian Shield, forming the basement of red, continental sandstones of Jotnian type. Recent radiometric dating has resulted in a revised general chronostratigraphy (Th. Lundqvist & P.-O. Persson, in prep.). Thus, the ”Upper Dala series” seems to be of 1.70±0.01 Ga age. The ”Lower Dala series” close to the western and southern borders of the Dala sandstone area is mainly of the same age. At some distance south and southeast of the sandstone area (the Nås–Tyfors and Älgberget areas), older porphyries, of c. 1.8 Ga age, seem to constitute the ”Lower Dala series”.

It should be noted that the Rb-Sr whole rock age of the Dala porphyries having U-Pb ages of 1.70 Ga is 1635±38 Ma (Welin & Lundqvist 1970, Welin 1980). K-Ar ages of Dala porphyries and granites are still lower: 609±30 - 925±45 Ma (Priem et al. 1968, Welin 1980). The reason for the argon loss leading to the low K-Ar ages is not known, but thermal influence from the c. 900 Ma Blekinge–Dala dolerites and the Sveconorwegian events affecting SW Sweden (cf. below) are possible contributing causes.

As a consequence of the new U-Pb dating results the term ”Dala porphyry” should properly include all porphyries with an age of c. 1.7 Ga occurring in northern Dalarna and Härjedalen. For these porphyries, it does not at present seem possible to establish a general litho- or chronostratigraphy. Probably the volcanic area is of a complicated structure, and features interpreted as calderas have been noted (Nyström 1982). However, some general stratigraphic trends can be discerned, and in some smaller areas the lithostratigraphical relations are fairly clear.

In the central, Älvdalen–Mora area, Dala porphyrites with extensive intercalations of sandstone and conglomerate generally occupy low stratigraphic levels (Hjelmqvist 1966). They are overlain by, in turn, phenocryst-rich porphyry, ignimbritic porphyry and Bredvad porphyry (a red, rhyolitic porphyry with millimetre-size phenocrysts of feldspar and minor quartz).

In the Orsa finnmark area, c. 50–60 km northeast of Älvdalen, folded and regionally metamorphosed Svecofennian quartzite, phyllite and ignimbritic, 1867±9 Ma old (Welin 1987) metarhyolite are overlain by a c. 70 m thick basal sequence of arkose, breccia and conglomerate, all strongly silicified and containing clasts of the Svecofennian supracrustals (Lundqvist 1968, cf. also Sjöblom & Aaro 1987a and 1987b). The dip of the basal rocks is gentle (c. 5° –30°) towards the west. On top of the arkose etc. follows a sequence of Dala porphyrites with intercalated sandstone and conglomerate. These are in turn overlain by the largely ignimbritic Dala porphyries. A U-Pb zircon dating of a phenocryst-rich (possibly intrusive), phenocryst-rich Dala porphyry has yielded 1691±5 Ma (Welin et al. 1993). The whole sequence of Dala porphyries and porphyrites probably has a total thickness of several thousand metres (Lundqvist 1968), and the general dip is similar to that in the basal sedimentary rocks (gentle towards the west).

Near Ämåsjön, c. 40 km northeast of Älvdalen, a red, coarse-grained, isotropic, felsic granite has been weathered to an arkose grading upwards into quartz-rich sandstone. This sedimentary sequence is overlain by a rather phenocryst-poor Dala porphyry, and this in turn by a Dala porphyrite (Sjöblom & Aaro 1987b). The basement granite has a U-Pb zircon age of 1785+26/-19 Ma, which is consequently a maximum age for the basal arkose (Th. Lundqvist & P.-O. Persson in prep.).

In the Ämån-–Älvho area, east of Ämåsjön, the basal formations underlying the Dala volcanites are made up of conglomerates and talus breccias. They overlie unconformably a horst structure of steeply dipping Svecofennian quartzites, slates and metarhyolites (Sjöblom & Aaro 1987b).

Northeast of Lillhärdal in Härjedalen, quartz-porphyritic Dala porphyry and Dala porphyrite form the oldest Dala volcanites. Although these rocks are covered by Dala sandstone to the east, they apparently underlie the more westerly, extensive sheets of feldspar-porphyritic and quartz-feldspar-porphyritic Dala porphyry, the latter named Glöte porphyry (Gorbatschev et al. 1997).

The Dala volcanites mainly dip gently, but steep dips are noted near shear zones and faults. In the Malung–Lima area, west of the Dala sandstone, intense shearing along NNW-striking, steep shear zones have affected the porphyries and granites as well as the overlying sandstone (Hjelmqvist 1966 and Th. Lundqvist & P.-O. Persson, in prep.). The stratigraphic relations are not clear due to this tectonic disturbance. Among the porphyries, both feldspar-porphyritic, phenocryst-rich porphyries (Heden porphyry) and quartz-feldspar-porphyritic types are present. They have been referred to the ”Lower Dala series” by Hjelmqvist (1966). According to U-Pb zircon dating they mostly seem to be of 1.7 Ga age, although older porphyries (c. 1.79 Ga) occur as well (Persson & Lundqvist 1993, Th. Lundqvist & P.-O. Persso, in prep.). The shear zones in all evidence are connected with the Sveconorwegian, c. 1.0 Ga orogeny of southwestern Sweden and southern Norway (e.g. Gorbatschev & Gaál 1987).

1.4.3.4 Rätan granitoids

M. Ahl & K. Sundblad

1.4.3.4.1 Introduction

The Rätan granitoids forms a c. 5000 km^2 large, c. 1.70 Ga granitoid batholith to the north of the Dala region without any association to volcanic rocks (Fig. 4). It is in its northwestern parts hidden by Early Palaeozoic platform sedimentary rocks and Caledonian nappes. To the south, the Rätan batholith is bordered by other components of TIB (i.e. the Dala granitoid complex, including the c. 1.69 Ga Siljan/Garberg granites and the c. 1.79 Ga Järna granitoids). The Rätan granitoids were first described by Svedmark (1895). Later contributions include the work by Magnusson et al. (1960), Lundqvist (1968), Gorbatschev (1972) and Welin & Lundqvist (1977).

The Rätan batholith constitutes an unfoliated, rather homogeneous group of intrusions dominated by porphyritic, coarse-grained to equigranular granitoids, with rarely occurring aplites and pegmatites. The ordinary type of Rätan granitoids contains up to 3 cm large, pink, microcline-perthitic phenocrysts, rarely white oligioclase. The equigranular groundmass consists of these two feldspars together with quartz, biotite, titanite and hornblende with remnants of pyroxene. Accessory minerals are magnetite, apatite, and fluorite.

The Rätan granitoids have chemical characteristics similar to the primitive parts of the TIB (the Småland–Värmland and Dala granitoids), i.e. they show an alkali-rich differention trend (Ahl & Sundblad 1994). Welin & Lundqvist (1977) presented a Rb-Sr age determination of the Rätan batholith yielding 1.68 Ga, which is well in agreement with U-Pb determinations, which indicate intrusion ages in the interval 1.70 to 1.66 Ga (Patchett et al. 1987, Delin & Aaro 1992, Ahl et al., in prep). The initial $^{87}Sr/^{86}Sr$ ratio of the Rätan batholith is 0.703 and the ε_{Nd} values vary between +1 to +2, indicating a relatively small contribution from older crustal sources in the magma (Wilson et al. 1985, Patchett et al. 1987).

1.4.3.4.2 Geochemical characteristics of Rätan and Revsund granitoids

The chemical composition of selected analyses of the Rätan granitoids is shown in Table 2. The Rätan granitoids follow a quartz monzonitic, quartz syenitic to granitic magmatic trend, while the Revsund granitoids have a more granodioritic, adamellitic to granitic trend in the P-Q diagram (Fig. 9a). The Rätan (and Dala) granitoids are metaluminous in contrast to the Revsund granitoids, which show a peraluminous trend in the A-B diagram (Fig. 9b). Furthermore, the molar oxide ratios of $Al_2O_3/(Na_2O+K_2O+CaO)$ are slightly less than 1.0, which indicates a weak metaluminous character for the Rätan granitoids, while the Revsund granitoids show a more peraluminous trend. In a Brown’s discrimination plot, the Rätan granitoid samples scatter in the alkali-calcic field, while Revsund granitoid samples plot in the calc-alkaline field.

The agpaitic index is significantly higher for the Rätan granitoids compared with the Revsund granitoids. When the agpaitic index is plotted vs. the Sr content (Fig. 9c), two contrasting trends are revealed; a weakly dipping trend displayed by the Rätan and Dala granitoids and a steep trend displayed by the Revsund granitoids, strongly suggesting significant differences in the magma sources.

The chondrite-normalized REE patterns for eleven Rätan granitoid samples are shown in Fig. 9d together with one sample for the Revsund granitoids. The Rätan granitoid samples show a steeper dipping trend for the LREEs compared with the Revsund granitoid sample, which displays lower REE contents compared with the Rätan granitoid samples. Furthermore, the Rätan granitoid samples display a relatively pronounced negative Eu-anomaly, in contrast to the normal granitic signature displayed by the Revsund granitoid sample. An exceptionally high REE content with a significant negative Eu anomaly is shown by one Rätan sample.

1.4.3.5 Metallogeny of the TIB

M. Ahl & K. Sundblad

Metallic resources associated with the postorogenic granitoid complexes in Sweden are very few. Insignificant Zn-Cu-Pb mineralizations have been documented within the extensive 1.77–1.80 Ga Småland-–Värmland granitoids (Ahl 1989). This pattern is different when the younger and more evolved parts of TIB are concerned, and a number of greisen veins are recorded in the 1.67–1.70 Ga Siljan, Garberg and Rätan granitoids (Fig. 10).

The greisen veins in these granitoid complexes are characterized by polymetallic (Sn-Cu-Zn-Pb-Be-bearing) altera-

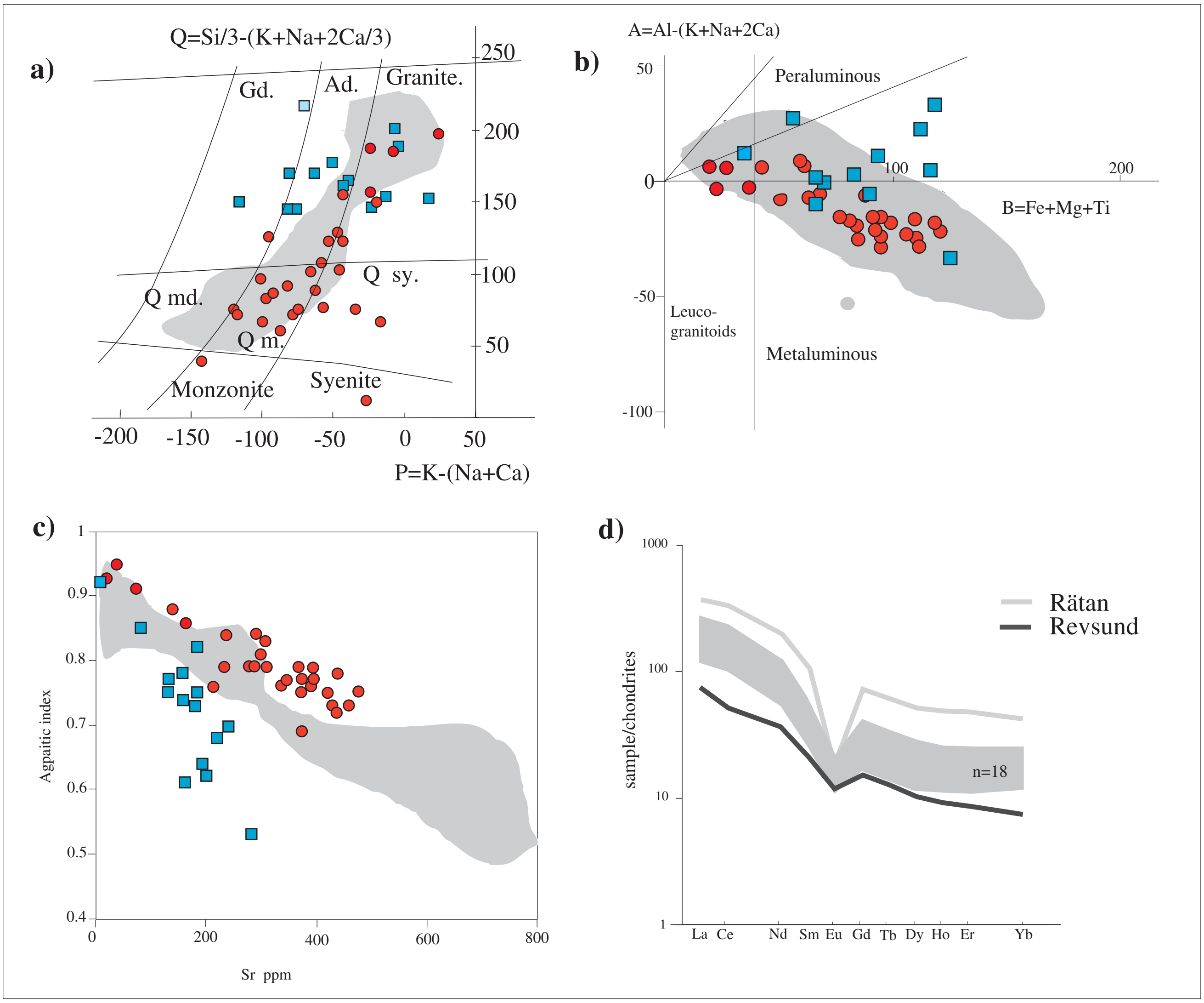


Fig. 9 Chemical parameters of the Rätan och Revsund granitoids plotted in various classification diagrams. Filled circles: Rätan granitoids, filled squares: Revsund granitoids from near Revsund village, shaded grey: Dala granitoids.
a) P-Q diagram according to Debon and Le Fort (1982). Gr.= Granite, Ad.= Adamellite, Gd.= Granodiorite, Q md.= Quartz monzodiorite, Q m.=Quartz monzonite, Q sy.=Quartz syenite.
b) A-B diagram according to Debon and Le Fort (1982)
c) Agpaitic index ((Na+K)/Al) vs. Sr.
d) Chondrite-normalized (Boynton, 1984) REE-patterns for Rätan and Revsund granitoids.

tion zones in the granitoids, which formed syngenetically with the late-stage and most evolved parts of the Dala- and Rätan granitoids (Ahl 1994). The most favourable environment for these mineralizations are the apical parts of late-stage granites, or the immediate surroundings of these intrusions, occasionally even older granitoids in which the anorogenic granites have intruded.

Some of these mineralizations are true greisen veins, defined as a metasomatic quartz-mica rock ± topaz and cassiterite, and enriched in Sn, F, Li, and Be. Other mineralizations are greisen-like alteration zones in granites, which are enriched in Pb, Zn, Cu, W, Mo, As, Fe, Ag and Au. All these mineralizations are small and economically insignificant.

Two different types of occurrences, based on the type of host rock, can be distinguished (Ahl 1994). Type I is hosted by the late-stage (Siljan and Garberg) granites, which probably were responsible for the metal supply to all mineralizations in this region (Sundblad 1991). This type is characterized by a dark alteration zone, enriched in quartz, topaz, mica and chalcopyrite. Type II is hosted by older (Järna) granitoids, close to the roof zone of the late-stage granites. The alteration zone in this type is characterized, by a quartz core, rimmed with white mica and darker peripheral zones.

A comparison between the chemical contents of the grei-

Table 6. Geochemical composition of whole-rock samples from greisen of type I–II and their hostrocks.

	Type I Greisen	Hostrock	Type II Greisen	Hostrock
SiO_2	68.3	75.52	62.4	67.5
$Al_2 0_3$	15.8	12.51	16.8	15.7
$Fe_2 0_3$ *	6.77	1.83	5.46	3
MnO	0.2	0.04	0.321	0.06
TiO_2	0.03	0.15	0.443	0.38
MgO	0.018	0.16	1.32	0.75
CaO	1.03	0.7	3.19	2.8
K_2O	1.08	4.96	6.5	4.38
Na_2O	0.08	3.35	0.234	3.45
P_2O_5	<0.02	0.04	0.146	0.1
Su	93.3	99.3	96.8	98.1
LOI	2.2	0.6	2.6	0.8
F *	47320	2052	32360	1100
Ba	11.1	269	607	850
Be	1.29	4.9	23.3	1.5
Co	<5.8	<6	<6,0	<5.9
Cr	26.7	19.1	34.7	29
Cu	12700	14.5	81.6	8.9
La	39.5	49.6	48.5	51
Mo	<5.7	<6	<6,01	<5.9
Ni	6.04	10.8	9.32	16
Pb	143	<12	<12	<12
Sc	<2.3	3.3	8.09	5.1
Sn	698	17	312	<6
Sr	10.1	57	195	370
V	<6	13	48.1	28
Y	82.9	60	30.7	23
Zn	9490	47	1040	46
Zr	123	165	205	203
W	221	19	20.5	26
Nb	50.1	17.3	13.1	<5.9
Yb	14.2	7.3	3.7	2.4
Ga	20	22	40	20
Rb	363	250	1099	153
Li	100	<10	1300	20

sen zones and their host rock granitoids is presented in Table 6. Type I is depleted in Si, Ti, Mg, K, Na, Ba and Be relative to the host rock and shows an enrichment of Al, Mn, F, Sn, Nb, Rb, Li, Cu and Zn. Type II is depleted in Si, Na, and Ba relative to the host rock and shows an enrichment of a number of elements including Al, Mg, Ti, Mn, Ca, K, F, Be, Cu, Sn, Zn, Nb, Ga, Rb, and Li.

A spectrum of ore mineral parageneses is recorded, which reflects lateral zonation and the type of host rock. Typical greisen minerals (cassiterite, fluorite, white mica, chalcopyrite, sphalerite and galena) occur in both types. Furthermore, the occurrence of topaz is noted in type I, and zinnwaldite in type II (Table 7).

The greisen veins belonging to type II are characterized by a core of quartz, rimmed with zinnwaldite. Other vein minerals are fluorite and calcite. Other minerals (mainly Fe-Ti minerals) are inherited from, or alteration products of, the host-rock.

The greisen mineralizations in the Siljan, Garberg and Rätan granitoids show marked similarities with the greisen

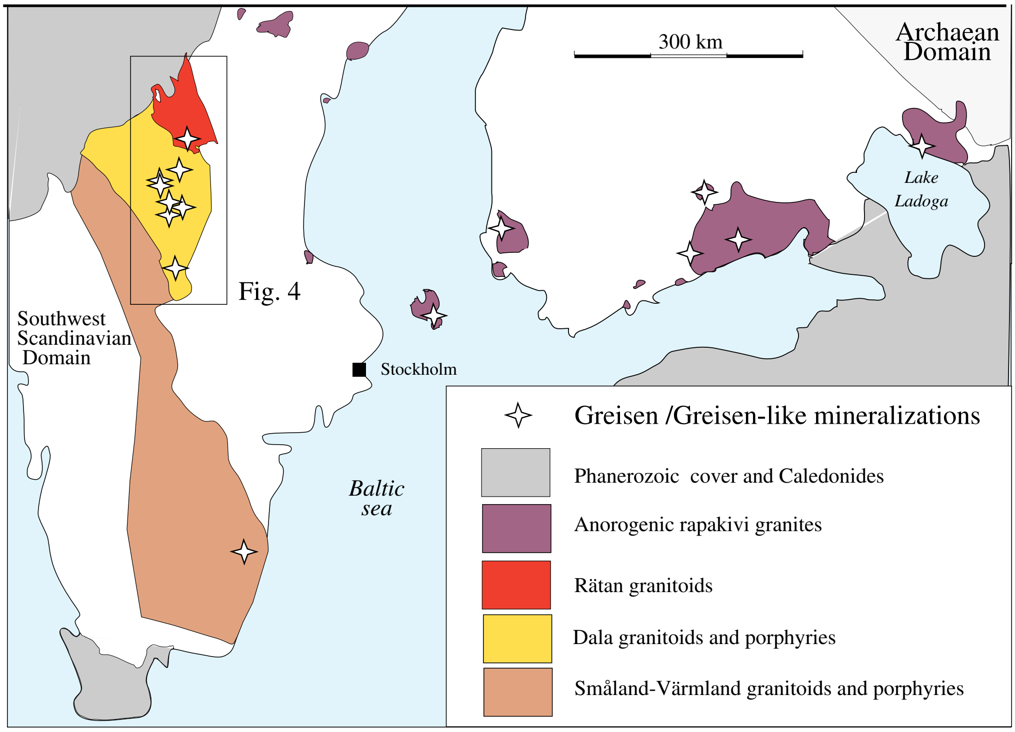


Fig. 10 Map showing miniralizations in rapakivi granite and in associated rocks.

Table 7. Mineralogical variability in type I and II.

	Type I	Type II
Cassiterite	X	X
Topaz	X	?
Fluorite	X	X
Sericite	X	X
Zinnwaldite	?	X
Chlorite	X	X
Pyrite	X	X
Sphalerite	X	X
Chalcopyrite	X	X
Galena		X
Arsenopyrite		X
Pyrrhotite		X
Rutile		X
Ilmenite		X
Hematite	X	X
Calcite		X
Apatite		X

mineralizations in the Finnish rapakivi granites as documented by Haapala (1995 and references therein). This very special mineralization type has not been recorded elsewhere in the Fennoscandian Shield.

1.4.4 CONCLUDING REMARKS ON THE “POST-SVECOFENNIAN” GRANITES IN SWEDEN

K. Sundblad & M. Ahl

Based on the geological, geochemical, geochronological and metallogenetic data presented for the “post-Svecofennian” granitoids in this overview, it is apparant that the youngest igneous components within the TIB (the Siljan, Garberg and Rätan granitoids as well as the Dala porphyries) have a closer affinity to the classical rapakivi complexes than to any of the older igneous components within the TIB (i.e. the Småland-–Värmland and the Järna granitoids) and the Revsund granitoid suite. In this way, the 1670–1700 Ma Siljan and Garberg granites and related volcanic rocks form an equivalent magmatic system to the 1645 Ma Wiborg rapakivi granites and related volcanic rocks. It is thus proposed that these youngest components of TIB should be regarded as one of the initial expressions of extensional magmatism within a stabilizing craton (Ahl et al., in prep.).

2. THE CLASSICAL FENNOSCANDIAN RAPAKIVI GRANITE COMPLEXES

2.1 An overview of the Fennoscandian rapakivi granite complexes, with emphasis on the Swedish occurrences

U. B. Andersson

2.1.1 INTRODUCTION

The classical Fennoscandian rapakivi granite complexes and their associated basic rocks have been in the focus of interest ever since the last decades of the 19th century (e.g. Sederholm 1891, Lundbohm 1893, Högbom 1893, 1899, Holmquist 1899). The rapakivi complexes in Finland have perhaps become more well-known internationally, partly due to their beautiful development of the ovoidal rapakivi texture (especially in the Wiborg batholith), but probably mostly because of the pioneering works of e.g. Sederholm (1923, 1926, 1934), Wahl (1925, 1947), Eskola (1928, 1930), Hackman (1934), Sahama (1945), Savolahti (1956), and Vorma (1971, 1972, 1975, 1976). The Swedish complexes have been studied more sporadically and little modern work has been performed until recently (e.g. Erdmann 1847, Högbom 1894, 1909, 1920, Lundbohm 1899, Sobral 1909, 1913, Frödin 1918, Backlund 1938, von Eckermann 1937, 1938, 1944, 1945, 1946a, b, 1947, Kornfält 1969, 1976, G. Lundqvist 1976, Persson 1978, Welin & Lundqvist 1984, Lundqvist et al. 1990, Andersson 1997a, b).

The suite of Fennoscandian rapakivi complexes comprises seven major batholiths and c. 15 minor intrusions (Fig. 11), extending from the Salmi batholith in Russian Karelia in the east to central Sweden in the west. In addition to these exposed occurrences, the large Riga batholith in western Estonia and Latvia and five minor intrusions in northern Estonia, which are covered by Palaeozoic platform sedimentary rocks, are included in the rapakivi group (e.g. Kirs et al. 1991, Rämö et al. 1996). Rapakivi massifs have also recently been inferred from geophysical data in the Baltic Sea (Fig. 11; e.g. Koistinen et al. 1994).

The rocks of the rapakivi group are also termed Subjotnian (Högbom 1909), since they are often found to form the basement of the Jotnian sedimentary successions in several areas of the shield. The Jotnian formations developed in the time span between the emplacement of the rapakivi complexes and the intrusion of the Postjotnian dolerite dykes (c. 1.50–1.27 Ga; Suominen 1991). Grabens with Jotnian infilling underlain by rapakivi rocks are most extensively developed in the Laitila, Salmi, and Strömsbro areas, but Jotnian sedimentary rocks also occur in the Nordingrå area (e.g. Sobral 1913, Lundqvist et al. 1990), and one presumably Jotnian sandstone dyke has been described from Ragunda (Kornfält 1976). Many Jotnian rocks are, however, not underlain by rocks of the classical rapakivi complexes, but by older rocks. E.g. in the Dala province, the vast Jotnian cover is underlain by volcanic porphyries and granites, which have been assigned to the Transscandinavian igneous belt (TIB, or post-orogenic belt; e.g. Wilson 1980, Nyström 1982, Gaál & Gorbatschev 1987) with ages of about 1.7 Ga (e.g. Lundqvist & Persson 1996; see chapter 1.4.3.3.3), but have also been included in the Subjotnian (e.g. Hjelmqvist 1966).

Some of the Dala granites (notably the Garberg and Siljan granites) and porphyries show close geochemical, petrographical, and metallogenetic similarities with the classical rapakivi granites, whereas others (the Järna granitoids) compare better with the dominantly I-type Småland–Värmland granitoids (Ahl 1991, 1993, and in prep.; chapter 1.4.3.3). If the geochemical and tectonic kinship between the Dala province and the Fennoscandian rapakivi suite can be verified, a new lithological subdivision and tectonic scenario for this part of the shield has to be presented. Of special interest in this respect are the huge amounts of volcanic and sedimentary rocks in the Dala province (e.g. Hjelmqvist 1966). Such rocks are lacking or present only in very small amounts in the rapakivi suite proper (Wahl 1938, 1947, Eklund et al. 1996b).

2.1.2 DISTRIBUTION AND AGES

There seems to be a systematic geographical distribution of crystallization ages of the complexes (Fig. 11). Excluding the Salmi batholith the complexes become progressively younger westwards. The complexes of southeastern Finland and northern Estonia (including the Wiborg batholith) are the oldest, with ages in the range 1.65–1.61 Ga (Vaasjoki 1977, Vaasjoki et al. 1991, 1993, Suominen 1991, Kirs et al. 1991, Rämö et al. 1996), whereas the Salmi baholith and associated rocks are 1.56–1.53 (Suominen 1991, Neymark et al. 1994, Amelin et al. 1997). West of the 1.65-1.61 Ga group there is a roughly north-–south trending “belt” of complexes in the age range 1.59–1.56 Ga (Vaasjoki 1977, Welin & Lundqvist 1984, Vaasjoki et al. 1988, Idman 1989, Suominen 1991, Rämö et al. 1996), from the Riga batholith in the south to the Nordingrå complex in the north. The youngest rapakivi complexes of the shield occur west of this belt (1.53–1.50 Ga; Welin 1994, Andersson & Neymark 1994a, Andersson 1997a, b, Persson 1995, chapter 2.2.6). Recently also the small 1.47 Ga Noran granite intrusion in

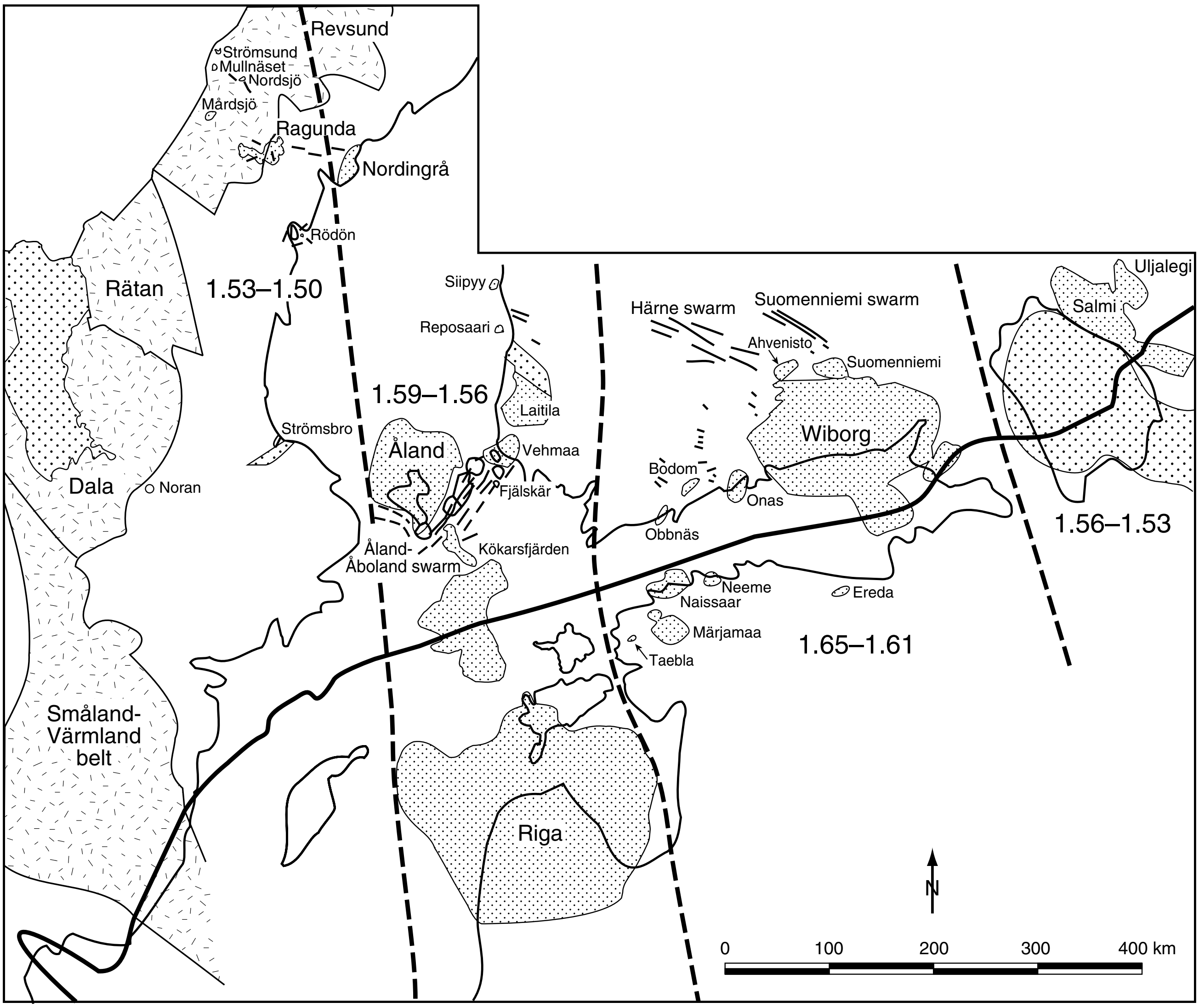


Fig. 11. Distribution in space and time of the Fennoscandian rapakivi complexes. Densely stippled: Rapakivi complexes, lightly stippled: Jotnian sedimentary rocks. Thick solid line marks the northern limit of the Palaeozoic platform cover rocks. The Transscandinavian Igneous Belt (TIB) is outlined in the west. The TIB have been subdivided into the Småland-Värmland Belt, the Dala province, the Rätan batholith, and the Revsund intrusive suite. Except Salmi in the east a systematic younging to the east is apparent. The map is prepared from various sources including Lundegårdh et al. (1984), Lundqvist et al. (1990), Gaál & Gorbatschev (1987), Rämö (1991), and Koistinen et al. (1994). Age compilation from sources stated in the text.

central southern Sweden has been related to the Fennoscandian rapakivi magmatism (Claesson & Kresten 1997). These recent age determinations have revealed that the Swedish complexes belong to the youngest group of rapakivis. This applies to all plutonic rocks dated so far (except Nordingrå): Strömsbro (1500±19 Ma), Rödön (1513±5 Ma, Welin 1994, 1497±6 Ma, Andersson 1997b), Ragunda (1505±12, 1513±9 Ma), Mårdsjö (1524±3 Ma), Nordsjö (1520±3 Ma) and Mullnäset (1526±3 Ma). See Figs. 11 and 12. These complexes also extend geographically from south to north. The northernmost being partly covered by Caledonian rocks (Strömsund, undated).

2.1.3 GEOCHEMISTRY OF SILICIC AND INTERMEDIATE ROCKS

Geochemically (e.g. Vorma 1976, Rämö & Haapala 1995) the rapakivi granitoids in Fennoscandia belong to the anorogenic type of silicic magmatism, with generally higher contents of Si, K, F, Rb, Zr, Hf, Ga, U, Th, Zn, and the REEs

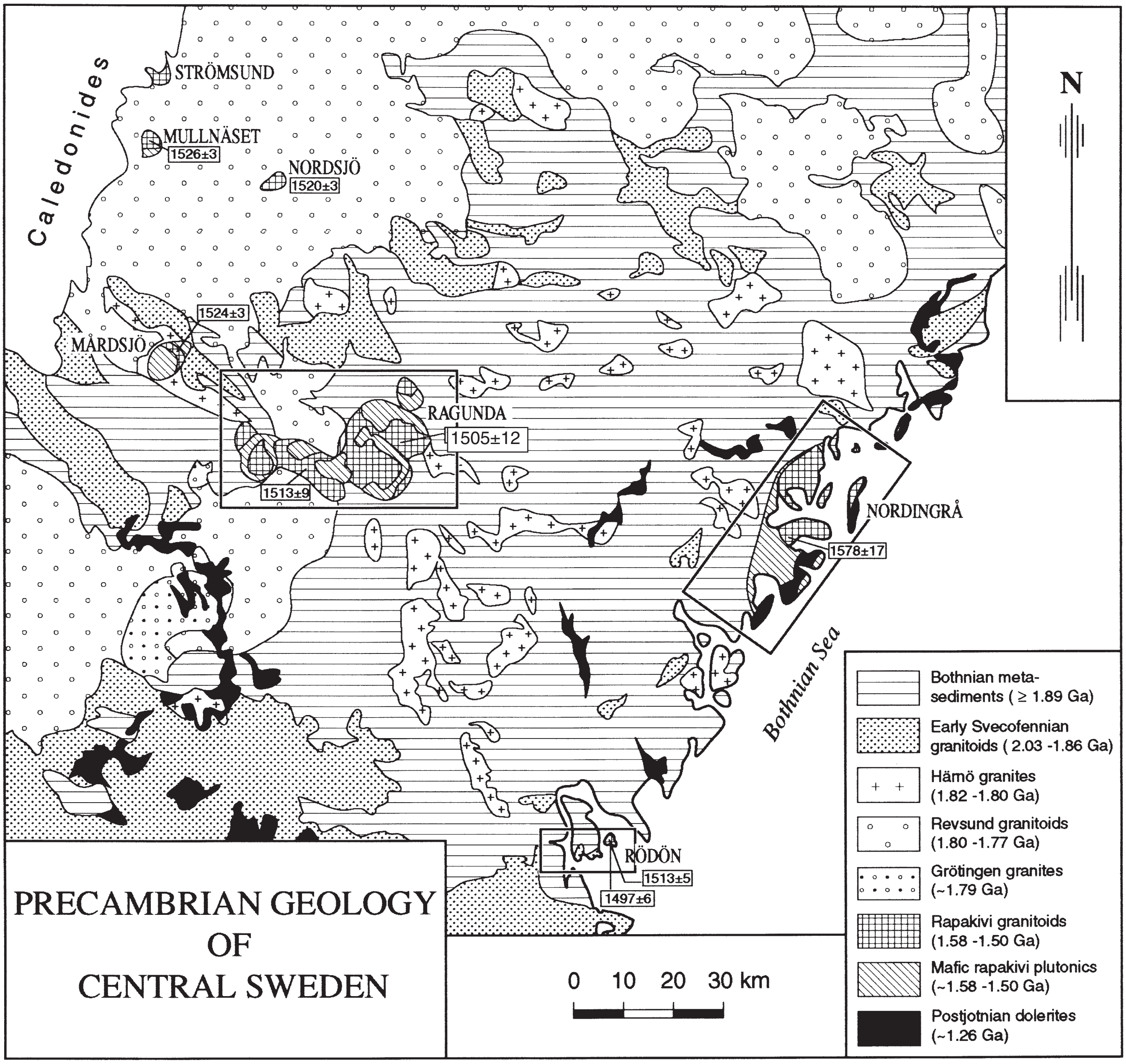
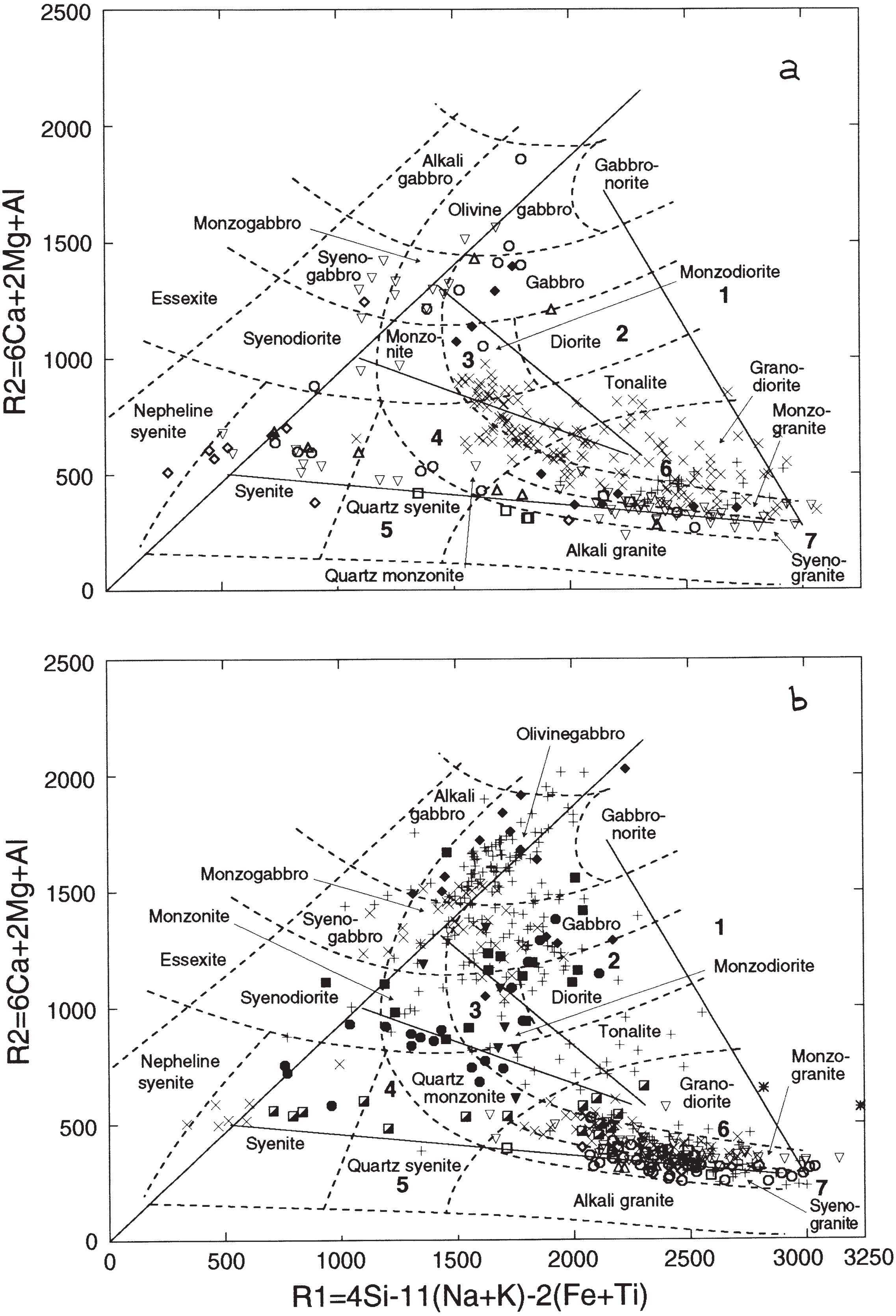


Fig. 12. Geology of central Sweden. Modified after Lundegårdh et al. (1984) and Lundqvist et al. (1990). Ages after Welin & Lundqvist (1984), Andersson & Neymark (1984), Andersson (in prep.), Welin (1994), Persson (1995, subm.). Frames outlines subsequent maps.

(except Eu), as well as higher K/Na, Fe/Mg, and Ga/Al ratios than average granite. Low contents of Ca, Mg, Al, P, and Sr are typical (Rämö 1991, Kornfält 1976, Sahama 1945, Vorma 1976, Haapala 1977, Nurmi & Haapala 1986). The youngest, and most evolved silicic phases, often show lower K/Na ratios and strong enrichment in e.g. F, Ga, Rb, Th, U, Nb, and Sn, and depletion in Ba and Sr (Vorma 1976, Haapala 1977, Edén 1991, Rämö 1991, Andersson 1995, 1997b). A recent comprehensive review by Rämö & Haapala (1995) summarizes the last 100 years of rapakivi research, with main emphasis on the classical Finnish complexes.

2.1.3.1 Intermediate rocks

Geochemically the Swedish complexes are more diverse in character than the Finnish. One significant difference is the major amount of intermediate syenitic rocks that are associated with the complexes of Jämtland–-Ångermanland (Ragunda, Mårdsjö, Nordsjö, and Mullnäset) in central Sweden (e.g. Kornfält 1976, Lundegårdh et al. 1984, Persson 1993 chapter 2.2, Andersson 1994, 1997b), but generally lacking in Finland. Substantial volumes of monzonites and quartz syenites do, however, occur in the Salmi batholith (Sviriden-


a
R2=6Ca+2Mg+Al
2500
2000
1500
1000
500
0
Alkali gabbro
Gabbro-norite
Olivine gabbro
Monzogabbro
Syeno-gabbro
Essexite
Gabbro
Monzodiorite
1
Syenodiorite
Monzo-nite
3
Diorite
2
Tonalite
Grano-diorite
Nepheline syenite
4
Monzo-granite
6
Syenite
Quartz syenite
5
Alkali granite
7
Syeno-granite
Quartz monzonite
b
Olivinegabbro
Alkali gabbro
Gabbro-norite
Monzogabbro
Monzonite
Syeno-gabbro
Gabbro
1
Essexite
2
Monzodiorite
Syenodiorite
3
Diorite
Tonalite
Nepheline syenite
Quartz monzonite
4
Grano-diorite
Monzo-granite
6
Syenite
Quartz syenite
5
7
Alkali granite
Syeno-granite
0
500
1000
1500
2000
2500
3000
3250
R1=4Si-11(Na+K)-2(Fe+Ti)

ko 1968, Neymark et al. 1994) in Russian Karelia. In the Wiborg baholith c. 8% of the rocks are dark coloured varieties of lower silica composition (61–70% SiO_2; Vorma 1976). It has been argued that these lower silica rocks in the Wiborg batholith contain a component of mixing with basic material (Eklund et al. 1991, Andersson 1991). However, some chemical features of these rocks (e.g. high Na_2O and low MgO) as well as the observation of local close-packing of feldspar ovoids suggest that cumulus processes played an important role in their genesis. Nevertheless, relatively abundant labradorite megacrysts as well as rounded mafic enclaves still indicate the operation of mixing processes. Mixing and mingling processes have recently been demonstrated by Salonsaari (1995) in the Jaala–Iitti complex, associated with the Wiborg batholith.

The Swedish rocks classify chemically as quartz syenites, syenites, and alkali feldspar syenites (Fig. 13). They generally display very high Ba (up to 3200 ppm) and Eu (up to 5.6 ppm), and positive Eu-anomalies (Sm_N/Eu_N 0.35–0.93), as well as high Na_2O (up to 5–6%), Al_2O_3 (16–17%) (Andersson 1997b). In the Ragunda syenites these contents are generally slightly lower (Kornfält 1976, Persson, pers. comm. 1996). The mineralogy is dominated by mesoperthitic alkali feldspar, fayalitic olivine, hedenbergitic clinopyroxene (Fe-Mg-silicates are as Fe-rich as those in the associated silicic rocks), Fe-Ti oxides, relatively abundant apatite, and very little free plagioclase (Kornfält 1976, Andersson 1997b). Associated with the syenites in the Nordsjö complex are some trachytic dykes containing phenocrysts of anorthoclase, hedenbergite, Fe-Ti oxides, and apatite. These display a moderate negative Eu-anomaly, but are otherwise geochemically closely similar to the syenites. The dykes thus provide direct evidence of the presence of crystal-saturated syenitic magmas. In general, the syenites also represent original magmas, presumably containing the same phenocryst assemblage as the trachytic dykes, variably enriched in a cumulus component dominated by anorthoclase (exsolved to mesoperthite) as indicated by the geochemistry. The source of the syenites is considered to be undepleted basic and/or depleted silicic lower crust (Andersson 1997b). This lower crustal segment contains an Archaean component as indicted by the low initial ε_{Nd} values (section 2.1.7.1) and the presence of an old generation of zircons in the Nordsjö syenite (Andersson 1997b), recently determined to c. 2.7 Ga (Claesson et al. 1997).

Dykes of peralkaline alkali feldspar syenites have been found in the Suomenniemi batholith in southeastern Finland (Rämö 1991). They have, however, a completely different chemistry (Fig. 14), much more enriched in LILE (except Ba), HFSE, and with distinctly negative Eu-anomalies. They were interpreted by Rämö (1991) to represent a separate localized melting event in the lower crust that produced magmas which intruded the area slightly later. Kornfält (1976) suggested that the syenites and the biotite granites in the Ragunda complex represent two separate intrusive magma batches, where the syenitic magma evolved into hornblende granite, and finally peralkaline residual liquids, whereas the biotite granites were followed by late quartz porphyry dykes. Similar geochemical characteristics for intermediate rocks (monzonites or mangerites) as the Jämtland–Ångermanland syenites have in eastern Canada been interpreted by e.g. Emslie (1991), Emslie & Hegner (1993) and Emslie & Stirling (1993) as resulting from cumulate-enriched rocks.

2.1.3.2 Peralkaline silicic rocks

Peralkaline silicic rocks have also been identified in a few cases in the Jämtland–Ångermanland complexes (Kornfält 1976, Andersson 1997b) and at Ragunda, Mullnäset and Nordsjö, but are most widespread at Strömsund. Corresponding rocks have not been found in Finland. These peralkaline granites are typical hypersolvus granites with only one "zebrastriped" mesoperthitic feldspar and contain alkali amphiboles such as ferrorichterite and riebeckite (Andersson 1997b), and have pronounced negative Eu-anomalies, and e.g. low Ba (18–265 ppm), Sr (6–30 ppm), CaO (0.37–0.66%). See Fig. 14 for comparative geochemistry.

Fig. 13. Geochemical classification of rock types in some of the Swedish rapakivi complexes. Diagram according to De la Roche et al. (1980). Fields 1=Mantle fractionates, 2=Pre-plate collision, 3=Post-collision uplift, 4=Late-orogenic, 5=Anorogenic, 6=Syn-collision, 7=Post-orogenic, after Batchelor & Bowden (1985).

a) Jämtland complexes (excl. Ragunda). Open circles: Mårdsjö complex, open triangles, apex up: Mullnäset complex, open squares: Strömsund granite, open diamonds: Nordsjö complex. Filled diamonds: Strömsbro complex. Open triangles, apex down: Ragunda complex. Inclined crosses: Revsund suite granitoids. Crosses: Härnö granites.

b) The Rödö rocks. open squares: Rödö granite, open triangles, apex up: Rödö aplites, open diamonds: Rödö granite porphyries, open circles: Rödö quartz-feldspar porphyries, stars: Rödö dark schlieren, half-filled squares: Rödö hybrid porphyries, filled squares: Rödö dolerites, filled circles: Rödö "contaminated" dolerites. Filled diamonds: Postjotnian dolerites. Open diamonds, apex down: Laitila batholith. Inclined crosses: Suomenniemi complex. Crosses: Åland batholith.

Sources of data: Andersson (1997a, b), Kornfält (1976), Vorma (1976), Rämö (1991), Eklund (1993, and unpubl. data), Lindberg (unpubl. data), Claesson & Lundqvist (1995), Lundqvist et al. (1990), L. Lundqvist (unpubl. data), Lundegårdh et al. (unpubl. data).

They may represent residual liquids after the crystal fractionation from original syenitic magmas. Fractionating 55–70% of an assemblage of dominantly anorthoclase (c. 80%), clinopyroxene, fayalite, Fe-Ti oxides, and minor apatite (observed assemblage in the syenites and trachytic dykes) is consistent with the geochemistry (Andersson 1997b). The presence of Ca-containing anorthoclase in the fractionating mineral assemblage could drive an initially metaluminous syenitic magma into the peralkaline field (e.g. Bowen 1945, Gittins 1979).

The peralkaline granites in central Sweden are, however, much less enriched in LILE and HFSE compared with the international average presented by Rämö & Haapala (1995) (Fig. 14), which may indicate a less fractionated level or residual accessory phases (e.g. monazite, allanite, apatite, or zircon) in the source region of the Swedish complexes. Residual zircon is indicated in Nordsjö syenites, where a specific type of zircons has been separated yielding Archaean ages (Claesson et al. 1997).

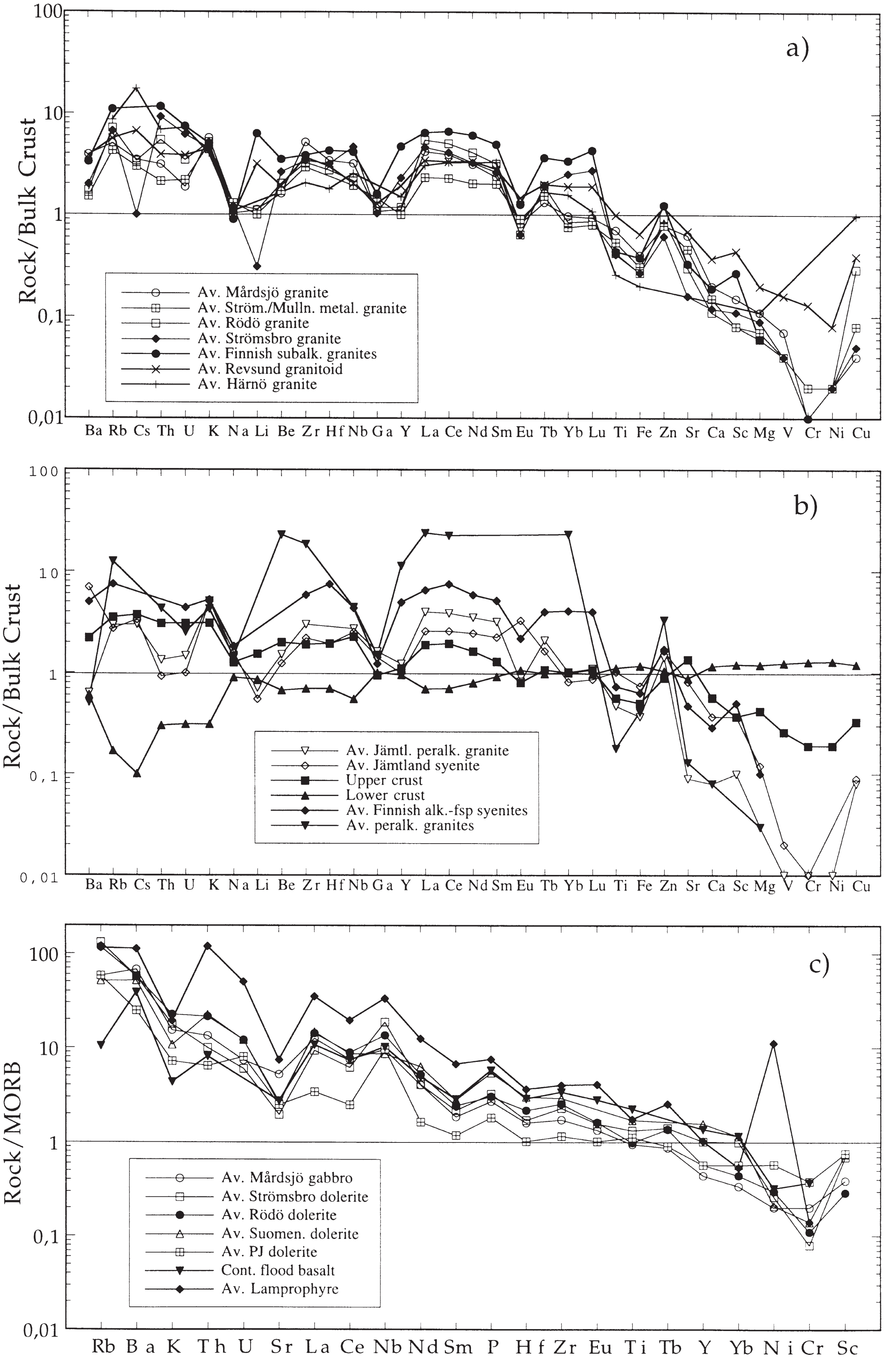
2.1.3.3 Metaluminous (-peraluminous) silicic rocks and a genetic model

Metaluminous to peraluminous granites are also a major component in the Jämtland–Ångermanland complexes. The relation between these, the syenites and the peralkaline granites is enigmatic. Generally, the contact relationships are unsharp and gradual, with some exceptions where the metaluminous-peraluminous granites appear to be younger (Kornfält 1976). Most probably there is no comagmatic relation between the metaluminous-peraluminous granites on one hand, and the syenites-peralkaline silicic rocks on the other hand. The present author favours a model where these two units are generated from different source lithologies in the lower crust (Andersson 1997b). The metaluminous-peraluminous granites can be derived by partial melting of undepleted lower crustal sources of granodioritic-tonalitic composition, as has been proposed for anorogenic granites elsewhere (e.g. Anderson 1983, Creaser et al. 1991, Rämö 1991, Skjerlie & Johnston 1993). Other sources must be sought for the syenitic magmas. Crustal sources are preferred, because extended fractionation from basaltic parents finds little support in the field. E.g. intermediate stages in such a fractionation evolution are entirely lacking and contact relations between the gabbros and syenites are usually sharp, suggesting coeval but not comagmatic magmas. Crustal sources for the syenites are considered to be depleted after a previous granitic melt extraction (the rapakivi magma?), or basic (monzodioritic-dioritic), or a combination of these sources, to be able to generate the syenitic magma chemistry (cf. e.g. Bailey & Schairer 1966, Bailey 1974, Zanvilevich et al. 1995). Crustal sources are also supported by the recent finding of 2.7 Ga zircons in the 1.52 Ga Nordsjö syenite (Claesson et al. 1997). The magmatism was triggered by an incipient extensional event inducing melting in the mantle and generation of the gabbroic magmas, which intruded the lower crust supplying heat for crustal melting. The three different magma units (gabbroic, syenite-peralkaline silicic, and metaluminous-peraluminous granitic), were derived penecontemporaneous from different sources and followed simultaneously crustal pathways to their upper crustal emplacement levels (Andersson 1997b). Similarly, Kornfält (1976) also envisaged three separate magma intrusions.

In the other Swedish rapakivi complexes (Nordingrå, Rödön, Strömsbro) only metaluminous (or slightly peraluminous) granites occur. The metaluminous rapakivi granites in Sweden are generally much less enriched in LILE and HFSE compared to the average Finnish subalkaline rapakivi granite presented by Rämö & Haapala (1995) (Fig. 14). In fact, the differences compared to the Finnish average are generally greater than compared to other (older) granitoid suites in central Sweden (e.g. the c. 1.8 Ga Revsund I- to A-type, and the similarly c. 1.8 Ga Härnö S-type suites). The Härnö suite, however, displays a strongly peraluminous character (Fig. 15), compatible with its derivation from metasediments of the Bothnian Basin (Claesson & Lundqvist 1995), and comparatively higher Cs and Rb contents.

The Revsund suite tends to center on the border between the metaluminous- and peraluminous fields, whereas the rapakivi suites on average are slightly less enriched in alumina (Fig. 15; Andersson 1997b), especially the syenitic rocks. The peraluminous character of the rapakivi suites increases with differentiation, a feature which is especially well-developed in the Rödö rocks (see further chapter 2.4). In comparison with other Fennoscandian rapakivi complexes it is clear that the Laitila complex (Vorma 1976) is significantly more peraluminous in character, as opposed to the Suomenniemi complex (Rämö 1991) which is clearly in the metaluminous field (except the peralkaline syenite dykes).

Fig. 14. Bulk crust (a, b) and MORB (c) normalized average trace element compositions of rocks from Swedish rapakivi complexes, and related rocks. Average upper and lower crust (Taylor & McLennan 1985), continental flood basalts (Thompson et al. 1983), lamprophyre (Bergman 1987), and peralkaline granites (Rämö & Haapala 1995) have been included for comparison. Sources of data: Andersson (1994), Rämö & Haapala (1995), Rämö (1991), Th. Lundqvist (unpubl. data), L. Lundqvist (unpubl. data). Bulk crust and MORB normalizing values are from Taylor & McLennan (1985) and from compilation in Rollinson (1993), respectively.


a)
Rock/Bulk Crust
100
10
1
0,1
0,01
Ba Rb Cs Th U K Na Li Be Zr Hf Nb Ga Y La Ce Nd Sm Eu Tb Yb Lu Ti Fe Zn Sr Ca Sc Mg V Cr Ni Cu
Av. Mårdsjö granite
Av. Ström./Mulln. metal. granite
Av. Rödö granite
Av. Strömsbro granite
Av. Finnish subalk. granites
Av. Revsund granitoid
Av. Härnö granite
b)
Rock/Bulk Crust
100
10
1
0,1
0,01
Ba Rb Cs Th U K Na Li Be Zr Hf Nb Ga Y La Ce Nd Sm Eu Tb Yb Lu Ti Fe Zn Sr Ca Sc Mg V Cr Ni Cu
Av. Jämtl. peralk. granite
Av. Jämtland syenite
Upper crust
Lower crust
Av. Finnish alk.-fsp syenites
Av. peralk. granites
c)
Rock/MORB
100
10
1
0,1
0,01
Rb Ba K Th U Sr La Ce Nb Nd Sm P Hf Zr Eu Ti Tb Y Yb Ni Cr Sc
Av. Mårdsjö gabbro
Av. Strömsbro dolerite
Av. Rödö dolerite
Av. Suomen. dolerite
Av. PJ dolerite
Cont. flood basalt
Av. Lamprophyre

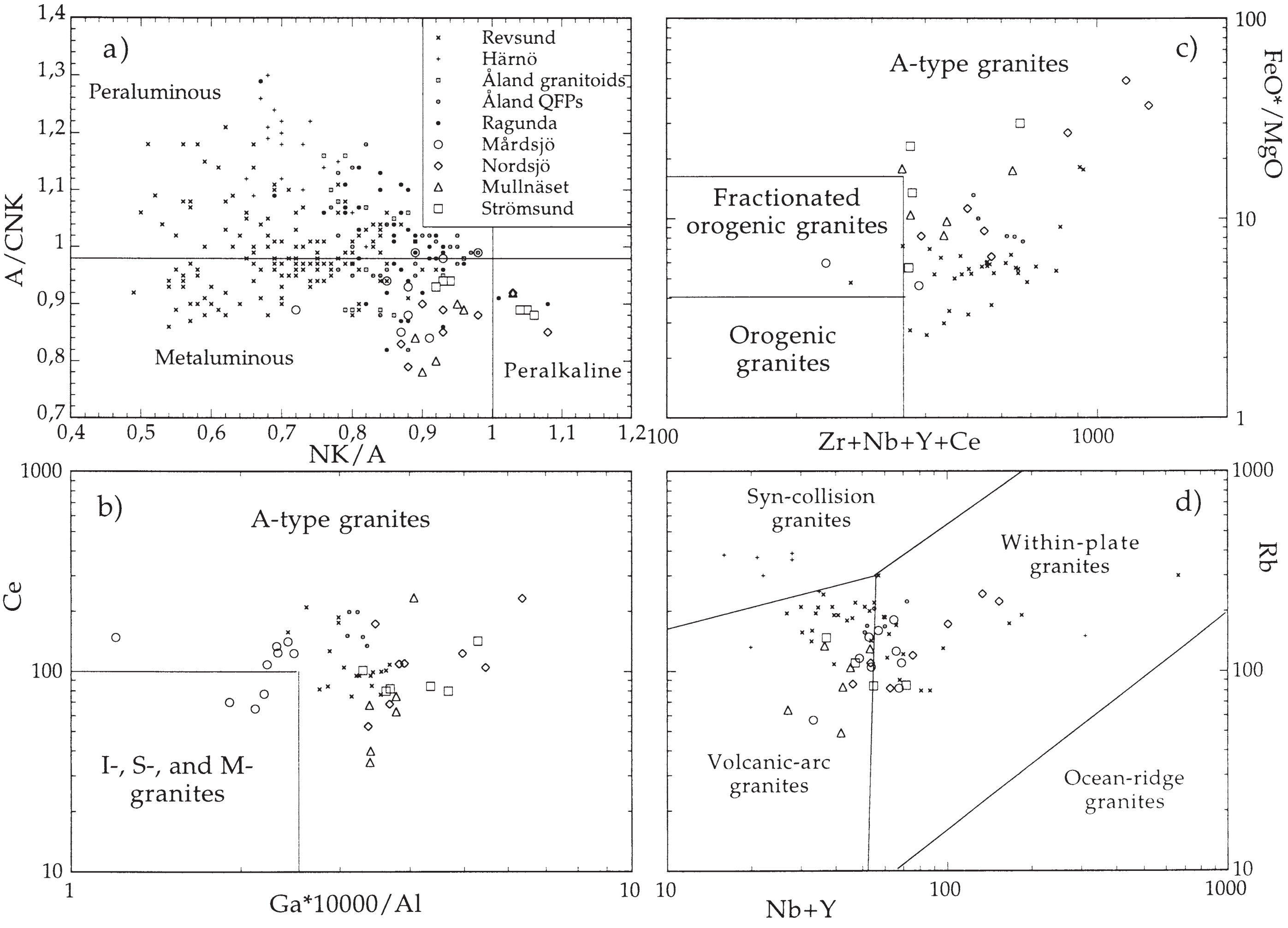


Fig. 15. Geochemical characterization of the silicic-intermediate rocks from the Jämtland rapakivi complexes, some rocks from the Åland batholith, the Revsund granitoid suite, and the Härnö type granites. A metaluminous to peralkaline A-type character is indicated for the rapakivi rocks. Sources of data as in Fig. 13.

This is presumably related to the strong dominance of more evolved, silicic rocks in Laitila compared to Suomenniemi. An influence by assimilation of minor quantities of metasedimentary country rocks which dominate the surroundings of Laitila may contribute to this difference, as metasediments are less abundant in the Suomenniemi/Wiborg area. The Rödö and Strömsbro granites are intermediate in alumina saturation compared to these two Finnish examples, whereas the Jämtland–Ångermanland complexes tend to be more metaluminous, similar to Suomenniemi, except for the more evolved biotite granites in Ragunda (Figs. 15 and 16).

2.1.3.4 Classification

In the geochemical/tectonic classification diagrams of Whalen et al. (1987) silicic rocks from all Swedish rapakivi complexes plot in the field of A-type granites (Figs. 15 and 16; Andersson 1994, 1997b, Persson in prep., Lindh & Johansson 1996), except for a few of the Mårdsjö rocks, similarly to the Suomenniemi rocks (Rämö 1991). The latter differ, however, by having generally higher HFSE contents. Also the Revsund suite plot distinctly within the A-type fields of Whalen et al. (1987), as do a few quartz-feldspar porphyries from the Åland rapakivi batholith in southwest Finland (Eklund et al. 1996b).

In the Rb vs. Nb+Y-diagram of Pearce et al. (1984), the Swedish rapakivis are generally transitional between the volcanic-arc (VAG) and within-plate (WPG) fields (Figs. 15 and 16), unlike the Finnish complexes (Rämö 1991, Rämö & Haapala 1995) where the silicic rocks plot distinctly in the WPG field. Of the Swedish rapakivi granites, only the Strömsbro granite plots entirely in the WPG field. Increasing fractionation in the Rödö suite drives the rocks into the WPG field, and even into the syn-collision field (increasing Rb).

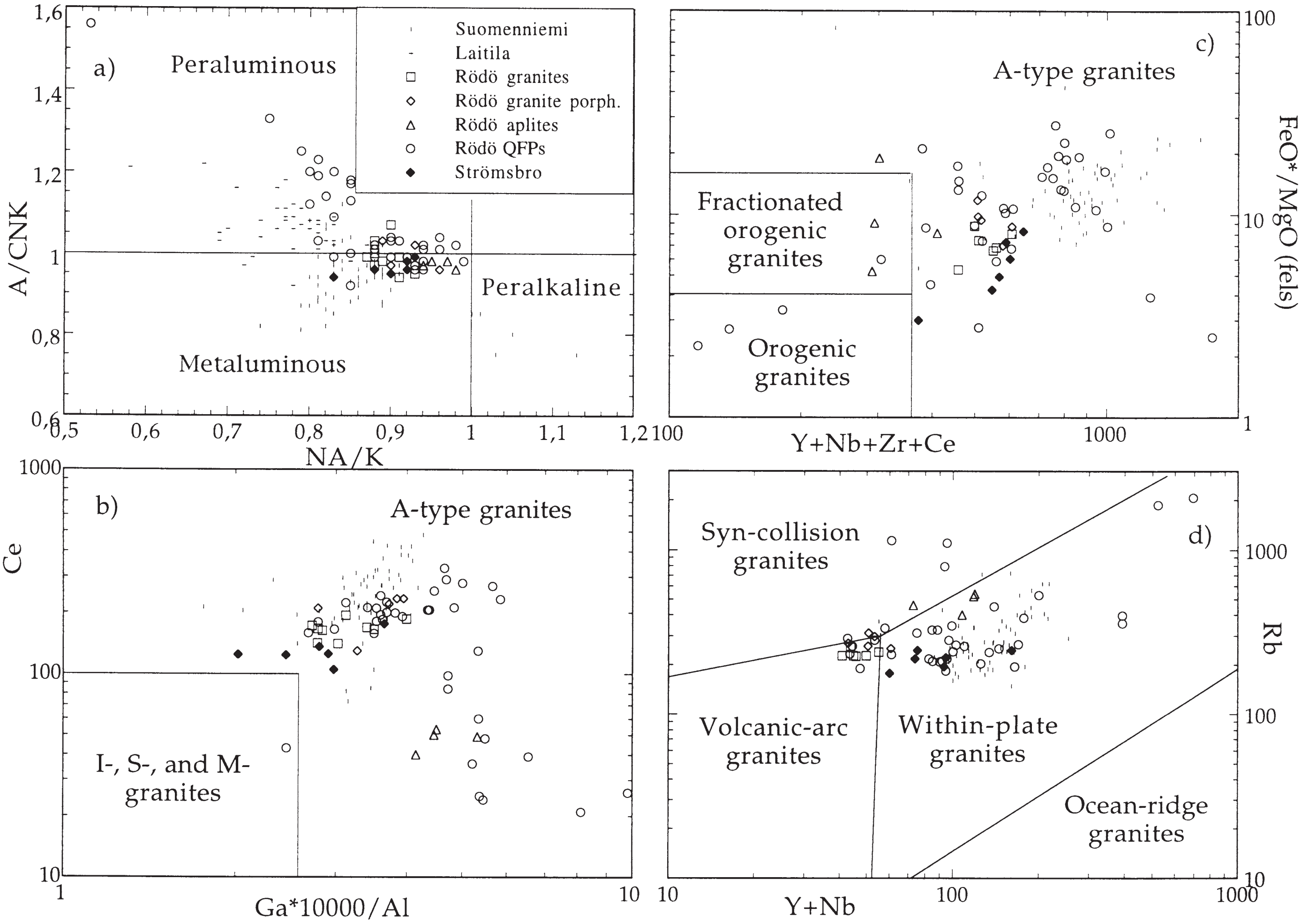


Fig. 16. Geochemical characterization of the silicic rocks from the Rödö rapakivi complex, the Strömsbro granite, the Laitila batholith, and the Suomenniemi complex. The Swedish complexes are metaluminous to peraluminous A-type rocks. The Laitila rocks are distinctly peraluminous, whereas the Suomenniemi rocks are metaluminous. Sources of data as in Fig. 13.

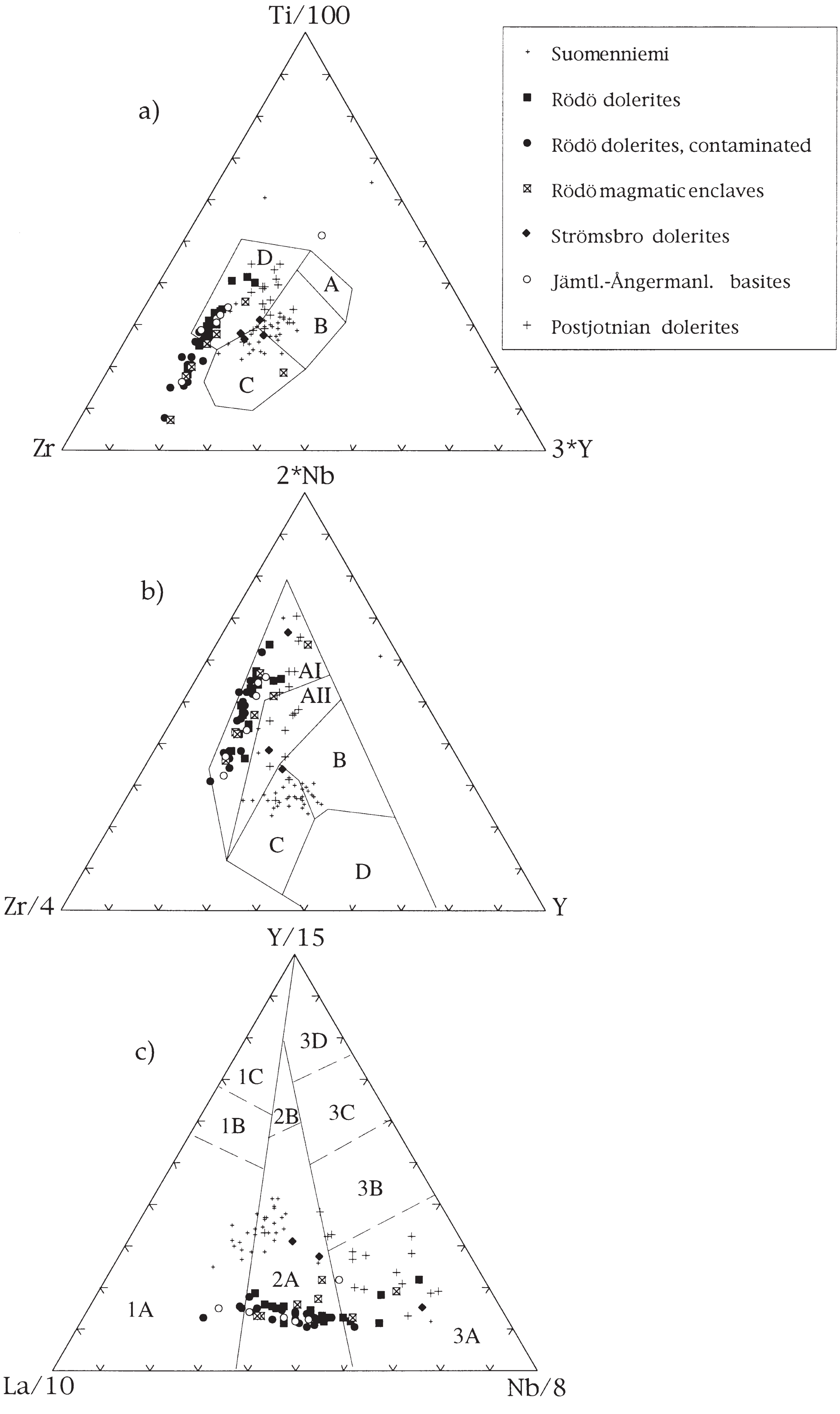
The Revsund suite generally seems to be slightly more VAG in character, even if some samples plot far into the WPG field (Fig. 15). The Härnö granites plot clearly in the syn-collision field in accordance with their S-type character (Claesson & Lundqvist 1995). The Åland quartz-feldspar porphyries are also transitional, similar to the Swedish complexes.

This more transitional character of the Swedish complexes should not be taken as evidence that they are not clearly anorogenic, within-plate complexes, but probably merely indicates slightly different source characteristics compared to their Finnish equivalents, maybe with HFSE-containing minerals left in the residue.

2.1.4 RAPAKIVI TEXTURE

The characteristics of the rapakivi texture have been summarized by Vorma (1976): "i. the ovoidal shape of alkali feldspar insets, 3–4 cm and more in diameter. ii. mantling of the ovoids by oligoclase-andesine shells, 1–3 mm in thickness; some ovoids, however, remaining unmantled. iii. the ubiquitous occurrence of two generations of alkali feldspar and quartz; the idiomorphic older generation of quartz having been crystallized as high quartz". These characteristics apply to the typical wiborgitic and pyterlitic varieties that dominate the Finnish massifs, whereas the large ovoids are missing in the Swedish occurrences, except in the Rödö and to some extent Strömsbro granites. Since these strictly textural characteristics are only fulfilled by a few granites worldwide, Haapala & Rämö (1992) and Rämö & Haapala (1995) have suggested that rapakivi granite should be redefined as any granite with A-type chemical characteristics irrespective of age that, at least in the larger batholiths, contains varieties showing the rapakivi texture.

The origin of the rapakivi texture has been the subject of a longstanding debate and numerous theories have been put


Ti/100
a)
D
A
B
C
Zr
3*Y
2*Nb
b)
AI
AII
B
C
D
Zr/4
Y
Y/15
c)
3D
1C
1B
2B
3C
3B
2A
1A
3A
La/10
Nb/8
+ Suomenniemi
■ Rödö dolerites
● Rödö dolerites, contaminated
⊠ Rödö magmatic enclaves
◆ Strömsbro dolerites
○ Jämtl.-Ångermanl. basites
+ Postjotnian dolerites

forward (see Rämö & Haapala 1995 for a more comprehensive review). Two of the most widely suggested reasons for the plagioclase mantling on the K-feldspar ovoids that merit attention are: 1) magma mixing, and 2) decompression during emplacement. Several authors have suggested that hybridization of a rapakivi magma derived from the crust, e.g. containing unmantled ovoids, by a basic mantle-derived one would shift the magma into the plagioclase stability field causing resorption of K-feldspar and quartz phenocrysts while plagioclase precipitates (e.g. Hibbard 1981, Bussy 1990, Stimac & Wark 1992). Experimental data have verified that this process can operate in magmas of similar composition as the rapakivi granites (Wark & Stimac 1992). However, sufficient contents of Ca are needed to achieve saturation in plagioclase, suggesting that the most silicic rapakivi magmas may not be candidates for this process. These data are consistent with a magma mixing origin for the mantled ovoids in the less silicic, and more Ca-rich, (c. 65–71% SiO_2, Vorma 1976) wiborgites compared to the unmantled pyterlites (c. 75–78% SiO_2) in the Wiborg massif and elsewhere (Eklund et al. 1991, Stimac & Wark 1992).

However, plagioclase mantling also occurs occasionally in highly silicic rapakivi rocks where magma mixing is an unlikely process, which calls attention to other possible mechanisms. Nekvasil (1991) proposed, based on equilibrium calculations in A-type granitic systems, that decompression causes a shift into the plagioclase stability field, whereby K-feldspar and quartz are resorbed. Such effects were also noted by Whitney (1975). The rapakivi granite complexes are typically generated at lower crustal levels and emplaced in the uppermost crust, and generally exhibit evidence of resorption of quartz and K-feldspar irrespective of composition. This mechanism may thus also be applicable to the rapakivi rocks (e.g. Eklund 1993, Eklund et al. 1996a), and is especially evident in the most silicic varieties. The general lack of plagioclase-forming constituents may be the limiting factor, since also the pyterlites show occasional mantling. Most likely, mixing and decompression may operate together, forming the rapakivi texture of many less silicic rapakivi rocks (below c. 70% SiO_2).

2.1.5 ASSOCIATED BASIC ROCKS

Basic rocks associated with silicic rapakivi magmatism occur both as plutonic rocks and dykes. In the Finnish complexes the basic plutonic rocks have only minor areal extension, except in the Ahvenisto complex (Savolahti 1956), whereas in Sweden the associated basic plutonic rocks often constitute large proportions of the complexes, e.g. at Nordingrå, Ragunda, Mårdsjö, and Mullnäset (Lundegårdh et al. 1984, Kornfält 1976, Sobral 1913, Lundqvist et al. 1990; Fig. 12). The latter is also true for the Salmi and Riga batholiths (Neymark et al. 1994, Koistinen et al. 1994). The basic rocks comprise gabbros (norites), anorthosites, and monzodiorites, and belong to anorthositic suites (NAM series), which presumably have differentiated from high-alumina basalt compositions to monzodiorites or monzonites, forming anorthositic cumulates (Fröjdö 1994, Eklund et al. 1994). The geochemical trends also suggest early removal of olivine, ortho- and clinopyroxene. Such cumulates are not observed but most likely reside in the lower crust (Savolahti 1956, Kornfält 1976, Rämö 1991, Eklund et al. 1994). Small amounts of anorthosites are present in Wiborg, Suomenniemi, Ahvenisto, Laitila, and Åland, whereas large volumes of anorthosites are present in Salmi and Riga, but are exposed only at Nordingrå (Sobral 1913, Lundqvist et al. 1990).

2.1.5.1 Geochemistry

The geochemistry of the basic rocks of the Jämtland–Ångermanland and the Rödö dolerites indicates continental, within-plate, alkalic to tholeiitic affinities (Fig. 17), and differ somewhat from the Suomenniemi dykes which are characterized by slightly higher relative Y contents. The spider plot in Fig. 14 compares the average geochemical characteristics of the basic rapakivi-associated rocks from different areas with other rock types. The dykes of the Suomenniemi swarm are generally similar to the Mårdsjö gabbro and Rödö dolerites, except that the former is slightly richer in some HFSEs. The Suomenniemi rocks are strikingly similar to continental flood basalts (Thompson et al. 1983), except for some of the LILE, whereas the Swedish rocks are generally somewhat lower in the HFSEs. All rapakivi-associated basic rocks are less enriched compared to average lamprophyre (Bergman 1987). The Postjotnian dolerites (from the Rödö area) generally have a distinct pattern with significantly lower abundances of both LILE and HFSE, and a characteristic positive anomaly for Nb.

Fig. 17. Geochemical characterization of the basic rocks associated with the Swedish rapakivi complexes (excl. Nordingrå), the Suomenniemi dykes, and some Postjotnian dykes. The Swedish rocks tend to indicate continental, within-plate, alkalic to tholeiitic affinities. The Suomenniemi rocks differ in having higher relative Y contents, in some diagrams suggesting more orogenic type chemistry. The Postjotnian dykes differ by having higher relative Nb and Ti contents, perhaps indicating slightly more alkalic character.
Sources of data: Andersson (1997a, b), Rämö (1991). Diagrams after Pearce & Cann (1973)(a), Meschede (1986)(b), and Cabanis & Lecolle (1989)(c). Explanation of the fields can found in the original publications and Andersson (1997b).

2.1.5.2 Similarities to other complexes

The Fennoscandian rapakivi complexes show many similarities with rocks elsewhere in the world (Rämö & Haapala 1995). Noteworthy are the voluminous s.c. AMCG (anorthosite-mangerite-charnockite-granite) suites of Labrador and the Grenville province in eastern Canada, which have both textural and chemical kinship with the Fennoscandian rapakivi suites (e.g. Emslie 1978, 1991, Ryan 1991). Anorthosites and other mafic rocks as well as intermediate rocks are areally much more important there than in Fennoscandia (except in Sweden), but granitoids also occur abundantly, and some of these have extremely well-developed rapakivi textures (e.g. Ryan 1991).

2.1.5.3 Dyke rocks

Dyke rocks, both basic (dolerites) and silicic (quartz-feldspar porphyries, QFPs), occur abundantly associated with the rapakivi complexes. In SE Finland the large (over 200 dykes; Laitakari 1991) Häme dyke swarm extends from the northernmost parts of the Wiborg area northwestwards about 250 km (Laitakari 1991). It contains, together with the spatially associated Suomenniemi dyke swarm, mainly dolerites and minor QFPs (Rämö 1991). In SW Finland the large (about 500 dykes) Åland–Åboland dyke swarm trends NE from SE of the Åland batholith up to the Vehmaa batholith (Lindberg et al. 1991). Also this swarm contains both basic and silicic components, but dolerites form the majority. In both swarms composite QFP-dolerite dykes occur, formed by intermingling of basic and silicic magmas in the same conduits (Eklund & Lindberg 1992, Rämö 1991), and giving rise to numerous delicate (disequilibrium) textures (e.g. Andersson & Eklund 1994). In Sweden a few doleritic dykes are associated with the Strömsbro (Asklund 1939, Andersson 1994, 1997a, chapter 2.5) and Mårdsjö (K.-A. Kornfält pers. comm. 1995, L. Lundqvist pers. comm. 1997) complexes, and relatively more numerous, both dolerites and QFPs, with the Ragunda (Kornfält 1976, Persson this volume) and Nordsjö (Lundqvist et al. 1990) complexes, but exceptionally many, and diversified, with the Rödö granite (Holmquist 1899, Andersson 1997b, chapter 2.4). Few or no dykes have been found in association with the Nordingrå and Strömsund complexes. Numerous silicic-hybrid porphyry dykes have been emplaced between the Nordingrå and Ragunda complexes (Lundqvist et al. 1990).

2.1.6 GEOPHYSICAL DATA AND TECTONIC SETTING

Geophysical modelling by Laurén (1970) suggested that the large Finnish rapakivi massifs constitute relatively thin sheets (<10 km) of low density material with a deeper root in the margin. Elo & Korja (1993) have modified this interpretation based on gravity and magnetic studies of the Wiborg batholith. They conclude that the upper 30 km is dominated by several separate rapakivi granite intrusions with an intercalated thin (at 8–14 km depth) layer with relatively high seismic velocities, interpreted to represent gabbro-anorthositic rock types. Mafic underplated rocks and mantle upwelling are indicated in the lower crust beneath the low-density upper crust (Elo & Korja 1993). The crust is thinner (42–46 km) in an E–W direction along the Gulf of Finland where the rapakivi complexes have intruded, compared to elsewhere in the Svecofennian (>46 km) (Korja et al. 1993). The crust in southern Finland underwent post-Svecofennian extension along deep crustal detachment zones that caused this thinning (Korja et al. 1993, Korja & Heikkinen 1995), which was associated with mafic underplating, crustal fusion, and generation of the bimodal rapakivi complexes (Haapala & Rämö 1992, Korja & Heikkinen 1995). Crustal thickness in central Sweden, where the major Swedish complexes have been emplaced, is about 48 km, gradually becoming thinner northwards (cf. Korja et al. 1993). An extensional regime is thus less obvious in this part of the shield. The general paucity of dyke swarms in association with the Swedish complexes, compared to their Finnish equivalents, makes the tectonic setting even more diffuse. Perhaps these discrepancies indicate that the extension in southern Finland developed to a more advanced stage, before it ceased, compared to central Sweden, where extension was only incipient. The apparently smaller volume of magma as well as the larger proportion of syenitic and peralkaline rocks may also indicate a more limited magma generation in central Sweden compared to southern Finland.

The extensional event that was instrumental in the generation of the rapakivi complexes is related by Korja and coworkers (1993, 1995) to collapse of the overthickened crust formed during the preceding Svecofennian orogeny, suggesting a tectonic-magmatic relation between the orogeny and the rapakivi magmatism. Vorma (1976) and Hubbard & Branigan (1987) have previously noted similarities in composition between the postorogenic Svecofennian intrusions and the rapakivi rocks, and suggested that the rapakivi magmas were formed already during the Svecofennian orogenic event and were later tapped from lower crustal levels intermittently during postorogenic (c. 1.80–1.77 Ga) and Subjotnian times. However, most previous workers have considered the rapakivi magmas as truly anorogenic, generated by heat input in the lower crust caused by the coeval mafic magmas (see Rämö & Haapala 1995 for a more thorough discussion).

The geophysical modelling suggests a sheetlike form of the rapakivi granite intrusions with feeder channels in the

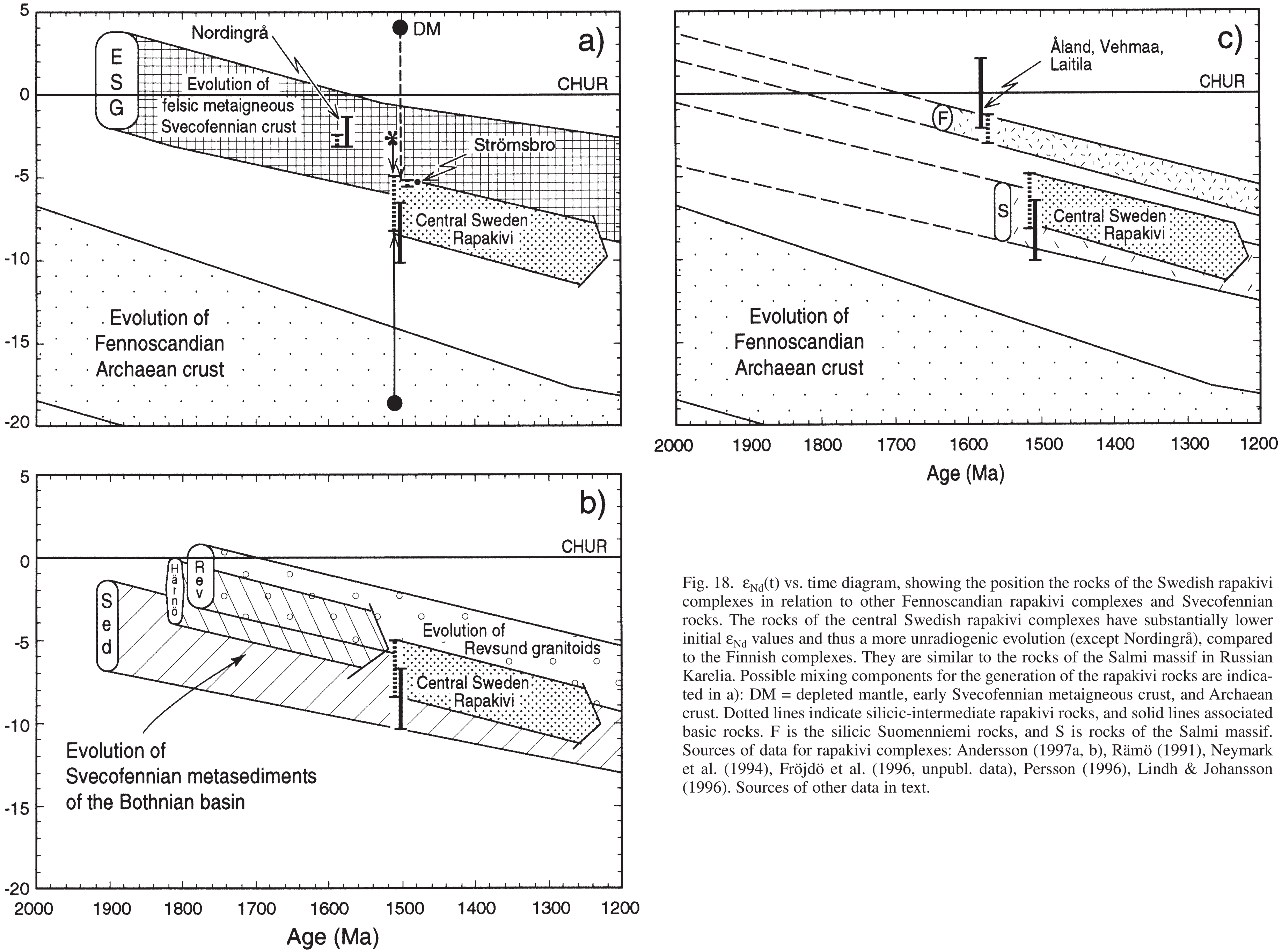


Fig. 18. $\varepsilon_{Nd}(t)$ vs. time diagram, showing the position the rocks of the Swedish rapakivi complexes in relation to other Fennoscandian rapakivi complexes and Svecofennian rocks. The rocks of the central Swedish rapakivi complexes have substantially lower initial ε_{Nd} values and thus a more unradiogenic evolution (except Nordingrå), compared to the Finnish complexes. They are similar to the rocks of the Salmi massif in Russian Karelia. Possible mixing components for the generation of the rapakivi rocks are indicated in a): DM = depleted mantle, early Svecofennian metaigneous crust, and Archaean crust. Dotted lines indicate silicic-intermediate rapakivi rocks, and solid lines associated basic rocks. F is the silicic Suomenniemi rocks, and S is rocks of the Salmi massif. Sources of data for rapakivi complexes: Andersson (1997a, b), Rämö (1991), Neymark et al. (1994), Fröjdö et al. (1996, unpubl. data), Persson (1996), Lindh & Johansson (1996). Sources of other data in text.

margin (Laurén 1970, Elo & Korja 1993). This shape suggests that the rapakivi magmas may have intruded by relatively rapid flow to the emplacement levels through localized channels (feeder dykes), and then spread out laterally (e.g. Elo & Korja 1993, Rämö & Haapala 1995). The silicic rapakivi magmas must have been low-viscous to be able to follow fracture zones in the crust up to their final high emplacement levels. This is in accordance with the experimental data which show that high F contents drastically lower the viscosity of highly silicic magmas, due to depolymerization of the melt (e.g. Dingwell et al. 1985, 1993). A sheetlike form is also inferred for the Nordingrå granite, directly overlying the gabbro-anorthosites (Lundqvist et al. 1990). Aeromagnetic data from the Ragunda complex strongly suggest that the magmas have intruded in several pulses successively younging eastwards (Lundqvist et al. 1990, Persson this volume, and in prep.).

The high proportion of exposed basic rocks in several of the Swedish complexes compared to their Finnish counterparts is most likely the result of deeper levels of exposure, like many of the Labradorian examples (e.g. Emslie et al. 1994). It is noteworthy also that the granitoids in the Swedish occurrences associated with voluminous basic components generally lack the typical coarse, porphyritic ovoidal rapakivi texture, and hence are even-grained or small-porphyritic (cf. Kornfält 1976, Lundqvist et al. 1990). This may be related to their relative spatial closeness to the hot associated basic rocks, where different thermal conditions prevented the ovoid growth. Furthermore, the sparse development of the rapakivi textures in the Swedish granites (except Rödön) closely associated with basic plutonics, is plausibly connected to deeper exposure levels compared to their Finnish equivalents, since the typical rapakivi textures develop during decompression while the magma intrudes at subvolcanic levels, <3 km (Nekvasil 1991, Eklund et al. 1996a).

2.1.7 ISOTOPES

2.1.7.1 Nd isotopes

Recently acquired Sm-Nd isotope data (Andersson & Neymark 1994a, Andersson 1994, 1997a, b Fröjdö et al. 1996, Persson 1996, Lindh & Johansson 1996, Lindh et al. 1996) for the central Swedish complexes display distinct features (Fig. 18). Data from Ragunda and the minor complexes north of it, and Rödön, show $\varepsilon_{Nd}(1.50)$ values in the range -10.1 to -4.8, with an average of c. -7. This includes both silicic, intermediate, and basic rocks.

2.1.7.1.1 Silicic-intermediate rocks

These low initial ε_{Nd} values are below the time-integrated evolution of the early Svecofennian metaigneous rocks (Fig. 18), as opposed to the initial ε_{Nd} values for the rapakivi granite complexes in Finland (Rämö 1991, Andersson, Fröjdö & Eklund in prep.) which are encompassed by the Svecofennian Nd evolution. In the latter case the rapakivis were thus interpreted to be derived from early Svecofennian protoliths (Rämö 1991, Rämö & Haapala 1995). For the Swedish complexes protolith components with significantly more negative $\varepsilon_{Nd}(1.50)$ values have to be invoked. The early Svecofennian metasediments of the Bothnian Basin have $\varepsilon_{Nd}(1.50)$ in the same range as the rapakivi complexes (average -7.1; Welin et al. 1993, Claesson 1987, Claesson & Lundqvist 1995, Patchett et al. 1987, Miller et al. 1986, Andersson 1997a, b), but are petrologically untenable as source rocks. Due to their mica-rich composition they would yield strongly peraluminous melts, similar to the Härnö suite granites (Claesson & Lundqvist 1995). Metaigneous sources of granodioritic-tonalitic compositions are the most fertile protolith material for the generation of A-type granitic magmas by high temperature anatexis in the lower crust (e.g. Anderson 1983, Clemens et al. 1986, Creaser et al. 1991, Emslie 1991, Skjerlie & Johnston 1993), and are likely to contain enough biotite and K-feldspar to generate the LILE-rich rapakivi magmas. If such a source is envisaged it must be composed of a mixture of Archaean and early Svecofennian material where the Archaean component is around 35–40%, based on mass balance calculations from published data (Andersson & Neymark 1994, Andersson 1997b). Appropriate rocks with ages in the span c. 2.6–1.96 Ga (covering the DM-ages of the rapakivis, Andersson 1997a, b) have not been identified in the Svecofennian, not even in metasedimentary detritus (Gaál & Gorbatschev 1987, Claesson et al. 1993), and are thus regarded as an improbable protolith. On the other hand, if the rocks are considered to be mixtures between depleted mantle (DM) and Archaean sources the Archaean component is also 20–40%, depending on the assumed Nd content of the mantle-derived material. Thus, since crustal sources are implied for A-type rapakivi magmas, this strongly suggests the presence of a major Archaean basement component in the lower crust of central Sweden, which necessitates a revision of the plate tectonic concepts in use. The Archaean component has recently been verified by ion-probe data from 2.7 Ga zircons discovered in the Nordsjö syenite (Claesson et al. 1997).

Data for the Nordingrå complex are much less negative ($\varepsilon_{Nd(1.58)}$ -3.2 to -1.5, including both granites and gabbro/anorthosites; Andersson 1994, Fröjdö et al. 1996, Lindh & Johansson 1996, Lindh et al. 1996). The granites of Nordingrå fit into the Nd evolution of the early Svecofennian metaigneous rocks (Fig. 18), and may be derived entirely from such protoliths. This does, however, not preclude Archaean and DM components in the granite magmas. The presence of Archaean components is also here strengthened by the low initial ε_{Nd} values of the associated basic rocks (see below). Similarly, the Strömsbro rocks are slighly less negative compared to Rödön etc. (Fig. 18; Andersson 1994, 1997a), but slightly more negative than the Nordingrå and Åland rocks, possibly implying slightly more of an Archaean component.

2.1.7.1.2 Basic rocks

The low initial and overlapping ε_{Nd} values of the associated basic rocks are less reconcilable. The completely overlapping nature of the initial values of the granitoids and basic rocks might be taken to indicate a common source in the mantle. However, these low values would mean a strongly enriched mantle, with major proportions of admixed Archaean material. Furthermore, an enriched subcontinental mantle would presumably have to exist for some significant geological time, but no such enriched mantle has been detected neither of higher age in the early Svecofennian (e.g. Huhma 1986, Patchett & Kouvo 1986, Patchett et al. 1987, Björklund & Claesson 1992), nor of lower age in Postjotnian times (Claesson 1987, Rämö 1990, Andersson 1997a, b, Patchett et al. 1994). On the contrary the basic rocks are generally mildly to strongly depleted. A (DM) mantle origin for the basic rocks requires substantial additions of Archaean material in the crust (20–40%). Bulk crustal assimilation is not appropriate since this would alter the original basic composition into some intermediate rock, which is not observed.

Emslie and coworkers (e.g. Emslie & Hegner 1993, Emslie et al. 1994) have suggested a model to solve this problem, which may also be appropriate here (Andersson 1997b, Fröjdö et al. 1996). After the extraction of the rapakivi granitoid magmas from their lower crustal reservoirs, a residue dominated by plagioclase and pyroxene is left behind. This hot residue should be spatially closely related to the mantle-derived magmas that generated the crustal melting, and thus be readily available for assimilation in the mafic magmas. This model is attractive in several respects, since it can explain both the strong enrichment in plagioclase components in the melts that facilitates the massive precipitation of plagioclase (relatively low in Ca for basic rocks, generally andesine-labradorite; cf. Ashwal 1993) and anorthosite formation, as well as the low and with the felsic rocks overlapping initial ε_{Nd} compositions (cf. Emslie et al. 1994). Furthermore, the assimilation of major amounts of plagioclase-pyroxene residual material would not alter the original mantle-derived composition in such an obvious way. Assimilation of minor amounts of less depleted crustal material is, however, also indicated (Lindh et al. 1996, Andersson 1997b). A displacement towards compositions where pyroxene rather than olivine is stable (together with plagioclase) is anticipated as is also indicated by e.g pyroxene coronas around olivines in the Nordingrå gabbros (Lundqvist et al. 1990). Apparently, lower crustal sources and residues in the Nordingrå region contain smaller proportions of Archaean components than in the rest of central Sweden. Archaean components in the residues are, however, likely since mixing with purely early Svecofennian residues would require unreasonably high crustal proportions in the magma, unless not all Svecofennian source rocks are in the least radiogenic range ($\varepsilon_{Nd(1.58)}$ ca -5; cf. Fig. 18).

2.1.7.2 Other isotopes

Pb-Pb isotopes for feldspars have been obtained for the minor complexes north of the Ragunda complex (Mårdsjö, Nordsjö, Mullnäset, and Strömsund; Andersson & Neymark 1994b, Andersson 1997b). These have lowradiogenic compositions with $^{207}Pb/^{204}Pb$ values spreading between the evolutionary curves for Archaean lower crust ($\mu = 8.00$) and mantle ($\mu = 9.17$) as devised by Rämö (1991). No regular systematics between Pb isotopic and rock composition exist. Two of the samples have very low-radiogenic compositions ($^{207}Pb/^{204}Pb = 15.02$, $^{206}Pb/^{204}Pb = 15.29$, $^{208}Pb/^{204}Pb = 34.97$), similar to those obtained by Neymark et al. (1994) for the Salmi complex, consistent with a major Archaean contribution to the magmas. Feldspars from the Finnish complexes are much more radiogenic and no Archaean influence have been detected (Rämö 1991). Pb isotopic whole rock data from the silicic rocks of the Rödö suite extrapolate to initial compositions in the range of the Jämtland feldspar data, suggesting a similar involvement of Archaean components. In the Nordsjö syenites a specific type of zircon (dark, turbid, slightly elongated, L:B c. 3:1) has been separated. These zircons contain inherited components indicating an age of at least 2390 Ma ($^{207}Pb/^{206}Pb$ age from conventional U-Pb age determination), probably older, i.e. at least 900 Ma older than the crystallization age of the rock (1520±3 Ma, Andersson 1997b). The actual age of these zircons was recently constrained by ion-probe work to 2700±40 Ma (Claesson et al. 1997). All this Pb isotopic evidence supports the interpretation of the Nd data that major very old components are present in the lower crustal source regions of the rapakivi magmas in central Sweden.

Limited amounts of Sr isotopic data have been obtained from the minor Jämtland complexes and Rödön (Andersson 1997b). The Sr isotopic system is severely disturbed, especially in the silicic rocks, giving unrealistically low initial values (<0.700). Interpretations of those data that appear undisturbed therefore have to be done with great caution. Only one granite has a reasonable $^{87}Sr/^{86}Sr\,(1.52)$ value (0.7027), which may support lower crustal derivation.

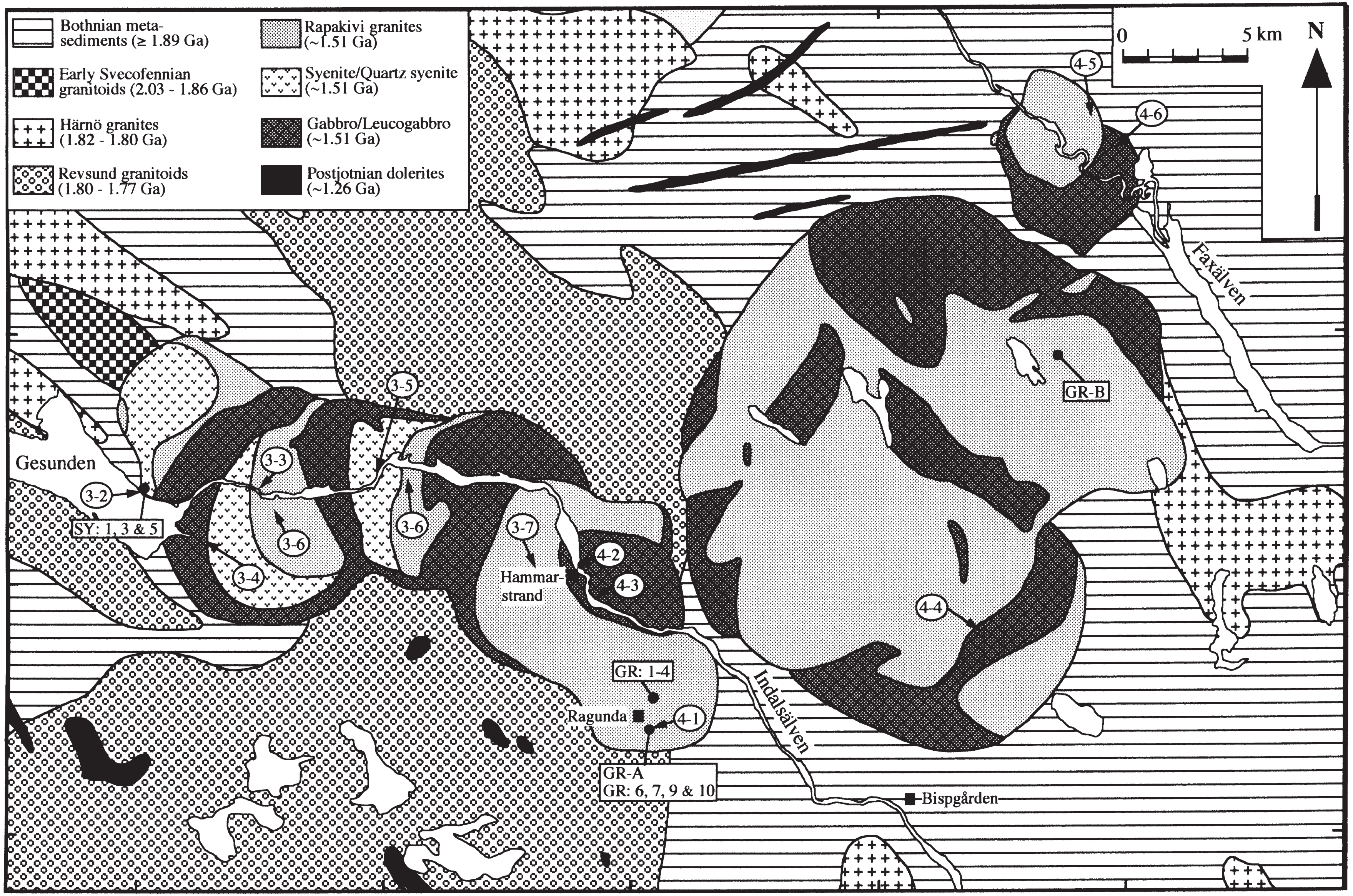


Fig. 19. Geologic map of the Ragunda complex (Persson, submitted). Compiled from Kornfält's observations, new field observations and from the aeromagnetic map (Fig. 20). Excursion localities for the IGCP Project 315 excursion are indicated by numbers in circles. Sample localities for Rb/Sr and U/Pb are indicated by numbers in squares.

Reasonable initial Sr ratios for the basic rocks in northern Jämtland and the Rödö dolerites range between 0.703 and 0.710. If the lower crustal residues, thought to dominate in the assimilated material, have low $^{87}Sr/^{86}Sr$ ratios, a significant proportion of less depleted (upper) crustal material (e.g. metasediments) has to be added to some of the Rödö doleritic magmas.

2.2 The Ragunda rapakivi complex

A. I. Persson

2.2.1 INTRODUCTION

The Ragunda rapakivi complex is situated in central Sweden, on both sides of the boundary between the counties of Jämtland and Västernorrland. The rocks of the complex are well exposed in the steep banks of the river valleys (Indalsälven and Faxälven), which are sometimes rather inaccessible due to the rough topography. In between the rivers, however, the degree of exposure is lower. Fortunately for the geologist the forestry has in the last twenty years been very intensive in the area, which has resulted in a large number of new road cuts.

As early as 1847 the rocks of the Ragunda massif were reported by Erdmann. The Ragunda complex was later very cursorily described by Lundbohm (1893), and in Lundbohm´s description of the rocks of Västernorrland County (1899), which was accompanied by a map at the scale of 1:500 000. The geology of the Ragunda massif was described and discussed in greater detail by Högbom (1893, 1894, 1899, 1909). Högbom (1894) mapped the Jämtland part of the Ragunda massif at the scale of 1:500 000. In 1899, Högbom published a map of the Jämtland part of the Ragunda massif at the scale of 1:125 000. Högbom (1899, 1909) argued that the Ragunda massif was a laccolith. More recently, the Ragunda massif has been mapped and investigated by Kornfält (1969, 1976). He published a more detailed map of the Ragunda massif showing that the laccolith hypothesis was incorrect. Since 1991 the Ragunda complex has been extensively studied by Persson (in prep.). New geochemical and isotopic investigations have been carried out together with new mapping. The aeromagnetic measurements, which were performed by LKAB Prospektering AB during the late seventies, have been interpreted, supported by petrophysical measurements (*in situ* magnetic susceptibility measurements). The following text is to a large extent compiled from the new investigations of the Ragunda complex by Persson (1993; 1995; 1996; submitted, and in prep.).

2.2.2 GEOLOGICAL SETTING

The geology of central Sweden and south-central Finland is dominated by the rocks of the Bothnian Basin. The area is situated between two volcano-sedimentary districts, the Skellefte District in the north and the Bergslagen District in the south, and bounded in the west by the Caledonides and the Transscandinavian Igneous Belt. The Swedish part of the Bothnian Basin is dominated by early Svecofennian metasediments, mainly marine metagreywackes (Lundqvist et al. 1990). They are metamorphosed to varying degrees. In large areas, extensive migmatization occurs. In the Basin, four distinct generations of granitoids are identified. These are traditionally described as early-, late-, post- and anorogenic relative to the c. 1.9–1.8 Ga Svecofennian orogeny.

Early Svecofennian granitoids, 2.03–1.8 Ga (Claesson and Lundqvist 1995, Welin et al. 1993), comprise a calc-alkaline suite of mainly tonalites and granodiorites. Volcanic rocks are restricted and mostly mafic. The Late Svecofennian granitoids (1.82–1.80 Ga; Claesson & Lundqvist 1995) were intruded after the main phase of Svecofennian deformation and regional metamorphism. They are mainly of granitic composition and associated with abundant pegmatites. The granitoids are generally peraluminous and have S-type characteristics. The postorogenic, 1.80–1.77 Ga, Revsund granitoid suite (Claesson & Lundqvist 1995) occupies the area towards the west. This suite shows a wide range in composition, from granite to quartz monzodiorite (Persson 1978, Lundqvist et al. 1990). It is characterized as an I-type granite, with occasional A- or S-type signatures (Claesson & Lundqvist 1995, Persson 1978).

The western Fennoscandian rapakivi suite (Fig. 12), consists of two major (Ragunda and Nordingrå) and at least five minor complexes (Strömsund, Mullnäset, Nordsjö, Mårdsjö and Rödön). Typical for most of the classic Finnish rapakivi complexes is the preponderance of silicic rocks. In the Swedish massifs, also a substantial amount of mafic rocks occur. The Ragunda complex is exceptional among the Fennoscandian rapakivi granites as it contains, besides large amounts of mafic and silicic rocks, also a substantial volume of syenite and quartz syenite.

The rocks of the rapakivi group are also termed Subjotnian (Högbom 1909), since they are often found to form the basement of the Jotnian sedimentary successions in several areas of the shield. Jotnian sandstone has been reported from the Nordingrå area (e.g. Sobral 1913, Lundqvist et al. 1990). In the Ragunda complex, sandstone has been found at one locality, in the Western Massif as a fissure filling striking E–W.

A large number of Postjotnian dolerite dykes are found in central Sweden. These dykes are younger than the rapakivi massifs. According to a K-Ar isochron dating they were formed c. 1200–1250 Ma ago (Welin & Lundqvist 1975, Welin 1979; cf. also Suominen 1991). One flat-laying sheet of dolerite is found in the Ragunda Complex, intruding syenitic rocks. The Postjotnian dolerites have been referred to as the Central Scandinavian Dolerite Group (Gorbatschev et al. 1979).

2.2.3 THE ROCKS OF THE RAGUNDA COMPLEX

The Ragunda complex covers an area of approximately 550 km^2. It was previously (Kornfält 1976) mapped as one complex with a small satellite massif called the ”Holmstrand complex”, situated northeast of the main Ragunda complex. In more recent work by Persson (submitted) a reviewed map of the Ragunda complex (Fig. 19) has been compiled from Kornfält´s observations, new field observations and from the aeromagnetic map discussed in the following section. According to the geological map, the Ragunda complex consists of three defined massifs, the Western, Central and Eastern (= Holmstrand) Massifs.

The Ragunda rocks cut sharply across the surrounding early Proterozoic Svecofennian plutonic and supracrustal rocks. The Central and Eastern Massifs are surrounded by structurally well-preseved metagreywackes. To the west, the Central Massif abuts on migmatized metagreywackes. A small body of the late orogenic Härnö granite is located at the eastern boarder of the Central Massif. The Revsund granite surrounds most of the Western Massif. The westernmost part of the latter intrudes migmatized metagreywackes and a small body of an early Svecofennian granitoid. The contacts between the rocks of the Ragunda complex and the country rocks seem to be more or less vertical. Brecciation of the older country rocks is common and xenoliths of these rocks occur frequently in the contact areas.

The Ragunda complex consists of three major rock groups: 1) gabbro (including a small amount of leucogabbro), 2) syenite and quartz syenite, 3) amphibole-biotite and biotite granite. Some minor amounts of hybrid rocks are also found in the complexes besides a large number of acid and basic dykes.

At the present erosion level, the Ragunda complex includes about 30% gabbro and leucogabbro, 5% syenite and quartz syenite, 65% hornblende-biotite and biotite granite as well as a minor volume of felsic and mafic dykes.

2.2.3.1 Gabbro

The gabbro is mostly a fine-grained or fine- to medium-grained, blackish grey to dark grey rock. Also fine- to medium-grained gabbro varieties occur, containing white megacrysts (2–12 mm) of plagioclase. The dominating mineral is a zoned plagioclase. The core is composed of labradorite and the marginal zone of andesine or oligoclase. The mafic minerals are mainly clino- and orthopyroxene and biotite. The clinopyroxene is probably a ferroaugite and the orthopyroxene a ferrohypersthene (Kornfält 1976). The pyroxenes are sometimes altered to amphibole. Olivine occurs sporadically in the analysed thin sections. Approximatly 65% of the analysed samples have normative olivine (Persson unpubl.). Ilmenite, magnetite and pyrite are always present; in some thin sections they are abundant. In the Eastern Massif a small isolated outcrop of leucogabbro occurs (excursion stop 4:6). Compared to the gabbro, the leucogabbro differs macroscopically by its larger grain-size (plagioclase grains are normally over 1 cm in length), and microscopically, among other things, by its higher plagioclase content (c. 65–75% of the rock). In the northeastern part of the Central Massif, a gabbro outcrop consists of patches of the coarse-grained leucogabbro within the normal gabbro. There are no sharp contacts between these two rocks.

The gabbro is always more or less intensely penetrated by granite. In certain cases it is difficult to decide whether the granite or the gabbro is the predominating rock. Typical magma mingling structures have been observed in the whole complex, most frequently in contact zones between gabbro and granite intrusions. Field evidence shows that mingling must be due to coexistence of granitic and gabbroic magmas. The gabbro shows chilled and crenulated margins against the granite. Some relationships, e.g. apophyses of granite in gabbro, suggest that some of the mafic rocks were partly consolidated when invaded by silicic magma. The fine-grained crenulate margins of the mafic (gabbro) rock are regarded as the result of chilling of high-temperature, low-viscosity, mafic magma against relatively cool and viscous silicic magma. Incomplete mixing of magmas has occurred on scales ranging from the formation of metre-size pillows through centrimetre-size inclusions to complete dispersion with incorporation of xenocrysts into the silicic magma. The contrasted liquidus and solidus temperatures, and various cooling rates of individual pillows are reflected in a diversity of structures and textures commonly occurring in a single exposure (Fig. 37).

2.2.3.2 Syenite and quartz syenite

The syenitic and quartz syenitic rocks occur only in the Western Massif. They are found as three separate intrusions. They are normally medium- to coarse-grained, and greyish green to greyish red. The syenite and quartz syenite consist mainly of perthitic orthoclase (Kornfält, 1969). Film, vein and patch perthite occur. The patch perthite consists of oligoclase. The patches may in places grow into larger plagioclase crystals with the same optical orientation as the minor patches within one single potash feldspar crystal. Practically all the plagioclase of the syenite occurs in this way.

Quartz is present in all analysed thin sections, but the amount in some of the rocks is less than one percent. The mafic minerals are mainly clinopyroxene, amphibole, and olivine. The chemical composition of the pyroxene corresponds to ferroaugite (Kornfält 1976). Olivine is present in all analysed thin sections; the chemical composition corresponds to fayalite ($Fo_{6.5}$ $Fa_{93.5}$; Kornfält 1976). The opaque minerals occurring in the syenite are mainly ilmenite and pyrrhotite together with small amounts of chalcopyrite and pyrite. Titanomagnetite occurs sporadically. A few percent of biotite is present in the rocks. Accessory minerals are apatite, which occasionally exceeds one percent, fluorite and zircon.

Only one contact between syenite and a biotite granite has been found. This contact is situated in the westernmost part of the Western Massif (excursion stop 3:2). The contact is sharp and dips c. 45° to the west. Approximately 15 m to the east of the contact, the syenite is found as xenoliths together with gabbro xenoliths in the granite.

2.2.3.3 Amphibole-biotite granite

Two major types of amphibole-bearing granite occur in the Ragunda complex. This was pointed out already by Kornfält (1976). In more recent work by Persson (in prep.) this distinction is based on the mineral contents and chemical character of the rocks. The first type (Type-A) contains as a rule either olivine or minerals secondary after olivine. It also contains a monoclinic potash feldspar or mixed structures comprising both monoclinic and triclinic potash feldspar (Kornfält 1969). In this way, they resemble the syenitic rocks. Another similarity is that the potash feldspar is similar to that in the syenites; it has vein and patch perthites, and virtually all plagioclase in this type of amphibole-bearing granite occurs as patch perthite (cf. the syenite).

The second type (Type-B) of amphibole-bearing granite is similar to the biotite granite. The plagioclase (oligoclase) occurs mainly as discrete crystals. Olivine or minerals secondary after olivine do not occur. The quartz content is remarkably low (in the most primitive ones) compared to that in type A.

The amphibole-bearing granite of type B is only described from the Eastern Massif (Holmstrand) by Kornfält (1976). In the new investigation by Persson, a large hornblende-biotite granite occurrence has been mapped in the eastern part of the Western Massif, around the village of Ragunda. This hornblende-biotite granite does not resemble the hornblende granite described as type A. The mafic minerals of the hornblende-biotite granite at Ragunda contain almost equal amounts of hornblende and biotite (some of the hornblende granite in type A also contains almost equal amounts of hornblende and biotite). The plagioclase (oligoclase) occurs mainly as discrete crystals. Olivine and minerals secondary after olivine do not occur. The quartz content is slightly higher than in the most silicic hornblende granite at Holmstrand, and slightly lower than in type A. The hornblende-biotite granite at Ragunda is more similar to the most evolved type in Holmstrand, type B.

2.2.3.4 Biotite granite

The most frequent granitic rock is a medium- to coarse-grained biotite granite. This granite varies in colour, grain-size and texture. As a rule it is more or less porphyritic with abundant rectangular K-feldspar megacrysts (normally up to 1 cm) in a medium-grained matrix. Granophyric, even-grained and fine-grained varieties occur. The megacrysts are occasionally plagioclase-mantled. Plagioclase in the biotite granite occurs both as exsolved patches in the potash feldspar, but most of the plagioclase is found as discrete crystals. In all granite varieties (incl. the amphibole-biotite granites), quartz frequently appears as drop quartz with crystals up to 8 mm in diameter.

Micropegmatitic intergrowths of quartz and potash feldspar are common, especially in the margins of the potash feldspar crystals. In the more pronouncedly porphyritic varieties, larger (c. 1 cm) subhedral or sometimes euhedral potash feldspar crystals occur in a medium-grained (1–2 mm) granophyric matrix. Quartz forms partly large (2–8 mm), approximately euhedral grains (drop quartz), partly small (<1 mm) anhedral grains intergrown with the potash feldspar forming a granophyric texture. Anhedral quartz grains occur also between the potash feldspar crystals.

Magnetite and ilmenite are found in all samples. Zircon and fluorite are present as accessory minerals in all samples, whereas allanite occurs more occasionally. Fluorite sometimes exceeds one percent.

A fine-grained, red, mostly porphyritic granite has been found within the Ragunda Complex. A somewhat larger occurrence in the Eastern Massif has been mapped (cf. Fig. 19). The fine-grained biotite granite is generally pale red, with sparse euhedral phenocrysts (1–3 mm) of potash feldspar. Somewhat more frequently, euhedral phenocrysts (1–2 mm) of quartz are found. Plagioclase may occasionally occur as sericitized phenocrysts. The matrix is fine-grained with micropegmatitic intergrowths of quartz and potash feldspar. The phenocrysts occupy only 5–15% of the volume of the rock.

Aplitic granite occurs together with the biotite granite in the gabbro-forming narrow dykes. Small narrow pegmatite dykes occur very rarely in the gabbro breccia. Only a few aplite dykes have been observed in the granites. The aplites are narrow (<1 m), greyish red to red and have hardly any mafic minerals. No pegmatite dykes have been found in the complex.

A *granite porphyry* has been mapped in the Central Massif (Fig. 19). It is fine-grained, greyish brown to brownish grey, with c. 1 cm long, pink, euhedral phenocrysts of potash feldspar. Phenocrysts of light green, euhedral plagioclase measuring c. 5 mm in length are also found. Drop quartz is also found, measuring 3–5 mm in diametre. Both biotite and hornblende are found as phenocrysts. The matrix is fine-grained, and therefore this porphyritic rocks is a little too coarse-grained to be termed porphyry.

2.2.3.5 Acid and basic dykes

The Ragunda complex and surrounding country rocks are cut by a number of basic and acid dykes. The width of the dykes ranges from a few decimetres to twelve metres, but is normally around two metres. Most of the discovered dykes are found in the Western Massif. This is probably due to the higher degree of exposure in this part of the Ragunda complex. In the Western Massif, the dykes generally trend between E–W and NW–SE and dip vertically or steeply to N–NE. A pronounced exception is a set of diabase dykes at Krångede (excursion stop 3:3) which trends NW–SE, and dips gently to the south. It has been possible to follow one of these dykes for thirty metres. The dyke narrows from three metres to a few centimetres and finally pinches out. At this locality there is also a vertically dipping diabase. The diabase dykes are greyish black, fine-grained, often porphyritic with phenocrysts of plagioclase. In two dykes, pyrite has been seen as small aggregates. None of the observed dykes is wider than three metres. According to Piper´s (1979) palaeomagnetic investigation of the diabase dykes found in the western part of the complex, there are dykes which are closely linked to the intrusion of the Ragunda gabbro but also dykes which presumably are considerably younger.

Most of the acid dykes are found in the Western Massif. Most of the acid dykes are quartz-feldspar porphyries (QFP). They are normally bluish grey or brownish red. Some QFPs have a colour zoning from the central part towards the contact on both sides of the dykes. A QFP dyke at the hydro-power station at Hammarstrand shows this kind of zoning. The dyke is at least 7 metres wide, but the western margin is not shown, because it has been removed by blasting. The central part of this dyke (at least 6.5 m) is fine-grained, brownish red and towards the contact the groundmass becomes aphanitic and the colour changes to bluish-black. The chemical composition remains on the whole unchanged (Kornfält 1976, Persson unpubl.). It should be noted that a dyke less than 2 metres wide shows the same colour zoning as the larger one at Hammarstrand and that most of the discovered QFP's are around 2 metres and show either a bluish grey or brownish red colour. In the Western Massif (excursion stop 3:5) there also occurs a phenocryst-free acid dyke, 3 metres wide, which is very fine-grained to aphanitic even in the central part of the dyke. Even fine-grained and fine- to medium-grained granite dykes occur.

In the Central Massif, the degree of exposure is lower and so is the known occurrence of dykes. A general trend is not obvious here, since some of the dykes have an unknown strike and dip. However, it seems as if the dykes trend more or less E–W. The largest dyke of the Ragunda complex (excursion stop 4:3) is a 12 metres wide composite dyke. It is found in the Central Massif and strikes E–W. This dyke is composed of 2 m wide, basic, bluish grey margins and an 8 m wide, central, brownish red quartz-feldspar porphyry. A five metres wide QFP dyke of the same kind as that at Hammarstrand is also found in the Central Massif.

In the Eastern Massif, a five metres wide composite dyke occurs. A grey, fine-grained plagioclase-porphyritic rock intruded first. This intrusion has an aphanitic contact towards the country rock. Later, an intrusion of fine-grained, greyish red quartz porphyry followed and brecciated the first dyke.

2.2.4 AEROMAGNETIC INVESTIGATION OF THE AREA

In recent work by Persson (submitted), *in situ* magnetic susceptibility measurements have been performed on the different rock types in the Ragunda complex and surrounding country rocks, for the evaluation of the aeromagnetic data. The susceptibility measurements on the gabbro give high values, normally between 0.02 and 0.05 SI units. The syenite ranges from low to moderate values (0.001–0.02 SI) and the granites generally give low values (0.001–0.008). The country rocks show very low values. The metagreywackes range between 0 and 0.0005 SI units and the Revsund granite between 0 and 0.0003 SI units. The gabbro of the Western Massif is generally higher (0.04 SI) than the gabbro of the Central (0.02 SI) and Eastern (< 0.015 SI) Massifs. Even in the Western Massif, values as low as 0.002–0.02 SI units have been obtained. These low values most often come from the fine- to medium-grained, plagioclase porphyritic gabbro. This gabbro variety seems to be more frequent in the Central Massif than in the Western Massif. The granites generally have a value around 0.0035 SI units, but at some localities, the susceptibility is very low (0.0001 SI). These low values have for example been obtained from the amphibole bearing granite in the Eastern Massif and from the westernmost granite intrusion of the Western Massif.

The aeromagnetic measurements were performed by LKAB Prospektering AB in the late seventies. The interpretation of the magnetic patterns has been performed from aeromagnetic maps at the scale 1:200 000 with a pixel-size of 50 x 50 m. The flight altitude was 30 m. Thanks to the Geological Survey of Sweden it was possible to produce a

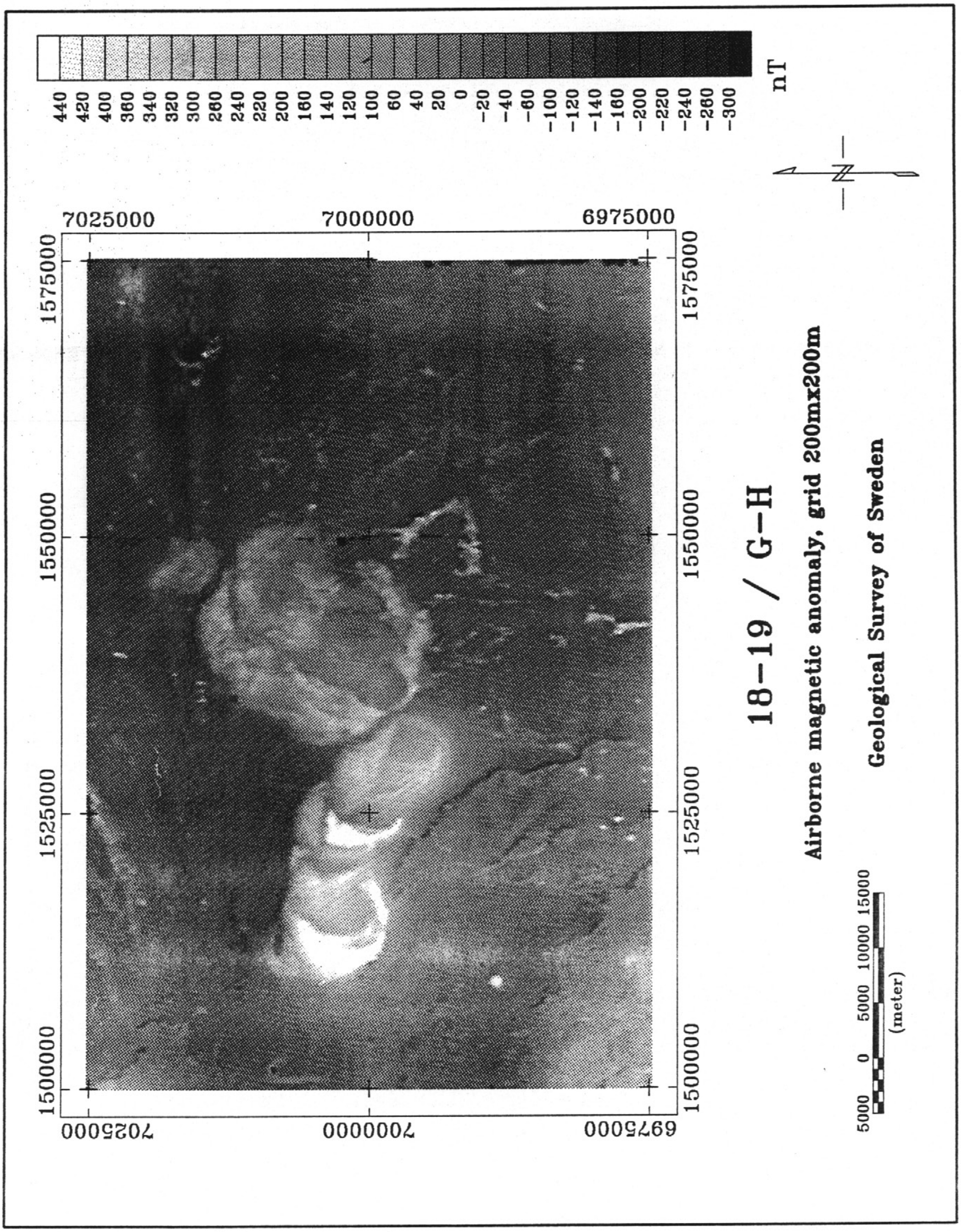


Fig. 20. Aeromagnetic map of the total field of the Ragunda area. Coordinates in the Swedish National Grid. (Persson, submitted.)

digital outprint of the data. This map, with a pixel-size of 200 x 200 m, is displayed in Fig. 20.

The total magnetization of a rock is mainly a function of its content of magnetite (cf. Thompson & Oldfield 1986, and references therein). Thus, aeromagnetic regional surveys of the magnetization intensity result in maps showing the regional variation in magnetite content. When regional magnetic data are interpreted in terms of magnetic intensity, they can be used for a tectonic analysis of the map area (e.g., Henkel 1991). Structural analysis of aeromagnetic maps gives important information of the shape and age relations of various magnetic structures (truncation relations). In the case of the Ragunda complex, the internal magnetic patterns, contacts and magnetization levels give much information about the internal structures and age relations between the different intrusion pulses in the Ragunda complex.

In the aeromagnetic map (Fig. 20), the Ragunda complex clearly stands out as a magnetic anomaly (the brighter the pattern, the higher the intensity of the magnetization). It can be separated into three different intrusion areas, the Western, Central and Eastern Massifs. The country rocks have a very low magnetization level. From the aeromagnetic map it is not possible to discriminate between the metagreywacke and the Revsund granite. This is in agreement with the magnetic susceptibility measurements on the country rocks. The intensity of the magnetization shown in the aeromagnetic map has a good correlation with the in situ magnetic susceptibility measurements. The Western Massif consists of a more or less linear intrusion suite composed of approximately circular gabbro, syenite and granite intrusions, younging from west to east. The younger, more easterly intrusions cut through the older, westerly ones (Fig. 20). In the magnetic map, this is seen as a series of incomplete circles overprinted in the eastern parts by younger circular intrusions. This interpretation suggests that the westernmost part of the massif is older than the hornblende-biotite granite at the village Ragunda.

According to the aeromagnetic map, gaps exist between the Western and Central Massifs as well as between the Central and Eastern Massifs. Outcrops consisting of metagreywacke are found between the Eastern and Central Massifs. Between the Western and Central Massifs, no outcrops are found; the area is a valley occupied by a small river. The distance between outcrops on both sides of the valley is approximately 1 km, i.e. the same as the distance between the two massifs indicated on the aeromagnetic map.

The magnetic pattern of the Central Massif does not show any obvious linear intrusion sequence. Instead, the magnetic pattern forms a cloudy structure on the magnetic map. The highest magnetization levels are mostly found near the margins and coincide with the gabbro. According to field observations, granite dominates more in the Central Massif than in the Western Massif. Syenitic rocks are only found in the Western Massif. If there were a fault between the Western and Central Massifs, different erosion levels could be expected. No field evidence has been found to support the existence of a fault between the Western and Central Massifs, nor does the aeromagnetic map show any fault between them. The aeromagnetic pattern in the border zone between the Western and Central Massifs has a curved outline, which corresponds to circular intrusions. The interpretation for the Central Massif suggest, that the first intrusion pulses have been overprinted by later intrusions, in most cases of a more silicic composition. The latest intrusions can be found as intact circular intrusions in the aeromagnetic map.

The Eastern Massif stands out as a distinct magnetic anomaly northeast of the Central Massif. Outcrops consisting of metagreywacke are found between the Eastern and Central Massifs. This is also indicated in the aeromagnetic map by a low magnetization level between the massifs. The Eastern Massif is a small centred complex with only two major pulses, a gabbro closely followed by a granite.

2.2.5 GEOCHEMISTRY

Chemical compositions of the rapakivi granites of southeastern Fennoscandia have several characteristics that make them distinct from other granite suites. These include high SiO_2, K_2O, F, Rb, Ga, Zr, Hf, Th, U, Zn, and REE (except Eu) abundances as well as high K/Na, very high Fe/Mg and Ga/Al ratios, and low abundances of CaO, MgO, Al_2O_3, P_2O_5, and Sr (e.g. Vorma 1976, Rämö 1991, Rämö & Haapala 1995).

To constrain the chemical composition of the Ragunda complex 111 analyses have been performed (Persson in prep.). The rocks are classified on basis of their content of major elements according to the scheme designed by Debon and Le Fort (1982). The P-Q-diagram displayed in Fig. 21 shows that the mafic rocks fall in or close to the gabbro field, the intermediate and acid rocks in the syenite (sy), quartz syenite (qsy) and granite (gr) fields. Two samples collected from a mixed/mingled rock type fall in the quartz monzodiorite (qmzdi) field and in the granodiorite (grd) field. All acid dykes fall in the granite field except two samples, which are found in the adamellite field. The two types of amphibole-bearing granites have been separated in the P-Q-diagram and given the following symbols: filled circles correspond to type A and open circles to type B. The numerous samples of type B falling close to Q=150 are all collected from one specific intrusion pulse (around the village Ragunda).

The Ragunda granites show the typical compositional features of the rapakivi granites of southeastern Fennoscandia, outlined above. They have a relatively wide span of

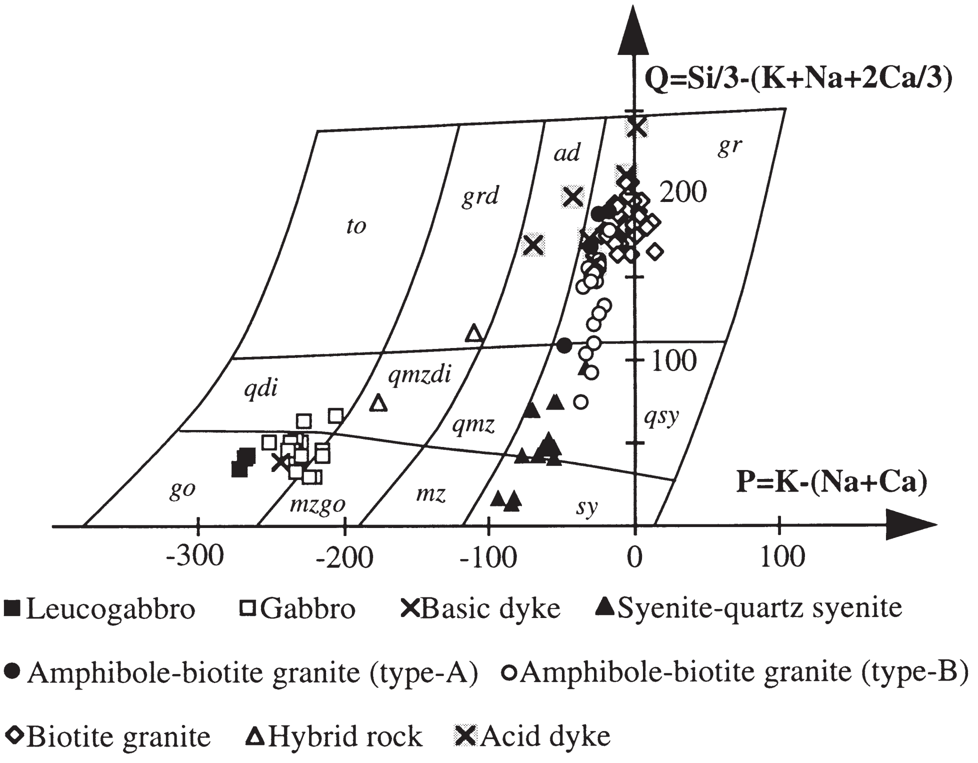


Fig. 21. P Q-classification diagram according to Debon & Le Fort (1982).

SiO_2 contents ranging from 66.6 to 76.4 wt%. They exhibit very high FeOt/(FeOt + MgO) ratios ranging from 0.88 to 0.99 (Fig. 22a), and high alkali contents, the sums of Na_2O and K_2O ranges from 8.2 to 10.7 wt% (the sum decreases with increasing SiO_2) (Fig. 22b) and high K_2O/Na_2O ratios (average 1.52). The abundance of CaO (average 0.66 wt%), MgO (ranging from 0.02 to 0.26%), P_2O_5 (ranging from 17 ppm to 489 ppm, average 00) is low. The granites are metaluminous to peraluminous (Fig. 22d; molecular $Al_2O_3/(CaO+Na_2O+K_2O)$ ranging from 0.90 to 1.06. They also show alkaline affinities (e.g., relatively high Na_2O+K_2O) but all of the granites (with two exceptions) are subalkaline (Fig. 22c), as the molecular $(Na_2O+K_2O)/Al_2O_3$ ratio is less than one. Two of the amphibole bearing granites (type A) are peralkaline. These amphibole-bearing granites contain small amounts of an alkali amphibole. This is reflected by normative acmite in the samples.

Regarding trace elements, the granites are high in F (ranges from 770 to 3630 ppm, average 1988 ppm), Rb (157 to 396 ppm, average 269 ppm), Ga, Zr, Th. Distinctive compositional features of the granites are also the high Ga/Al ratios (average 3.8×10^{-4}) and wide ranges in Rb/Ba and Rb/Sr ratios. The granites are pronouncedly enriched in LREEs relative to chondrites. La/Yb_N ratios are within the range 10 to 30. All granites have moderate to strongly negative Eu anomalies (Eu/Eu* = 0.32 to 0.02).

According to the discrimination diagram of Whalen et al. (1987) the granites plot into the A-type granite field (Fig. 23). Besides the high Ga/Al ratio, A-type characteristics of the rocks are clearly visible in the high contents of Zr, Nb and Ce. In the tectonomagmatic discrimination diagrams of Pearce et al. (1984) the granites plot in the within plate granite field.

The syenitic rocks have SiO_2 contents ranging from 58.5 to 67.7 wt%. Like the granites, they have very high FeOt / (FeOt + MgO) ratios ranging from 0.87 to 0.99 (Fig. 22a). The samples plot clearly in the alkaline field in Fig. 22b, yet all of the samples are subalkaline according to the NK/A vs. silica diagram (Fig. 22c).

Besides their lower SiO_2 contents (there is a small overlap), the syenites differ from the granites in higher Al, Na, Ti, P, Mn and Fe abundances. The trace elements F, Rb, Th and Hf are lower and Ba, Sc and Eu higher than in the granites. The REE abundances and chondrite-normalized REE-patterns for the syenitic rocks are similar to those of the granites. One distinctive feature of the ”true” syenites is a pronounced positive Eu anomaly (Eu/Eu* = 2.40 to 1.90). The quartz syenites have almost none or very weak Eu-anomalies.

The gabbroic rocks have SiO_2 contents ranging from 50.4 to 54.9 wt%. The molar $Mg/(Mg + Fe_{tot})$ ratio varies between 0.57 and 0.37 for the gabbro. For the leucogabbro the Mg numbers range from 0.62 to 0.66. The CaO contents for the gabbro are between 7.36 and 8.86 wt% and 10.27 to

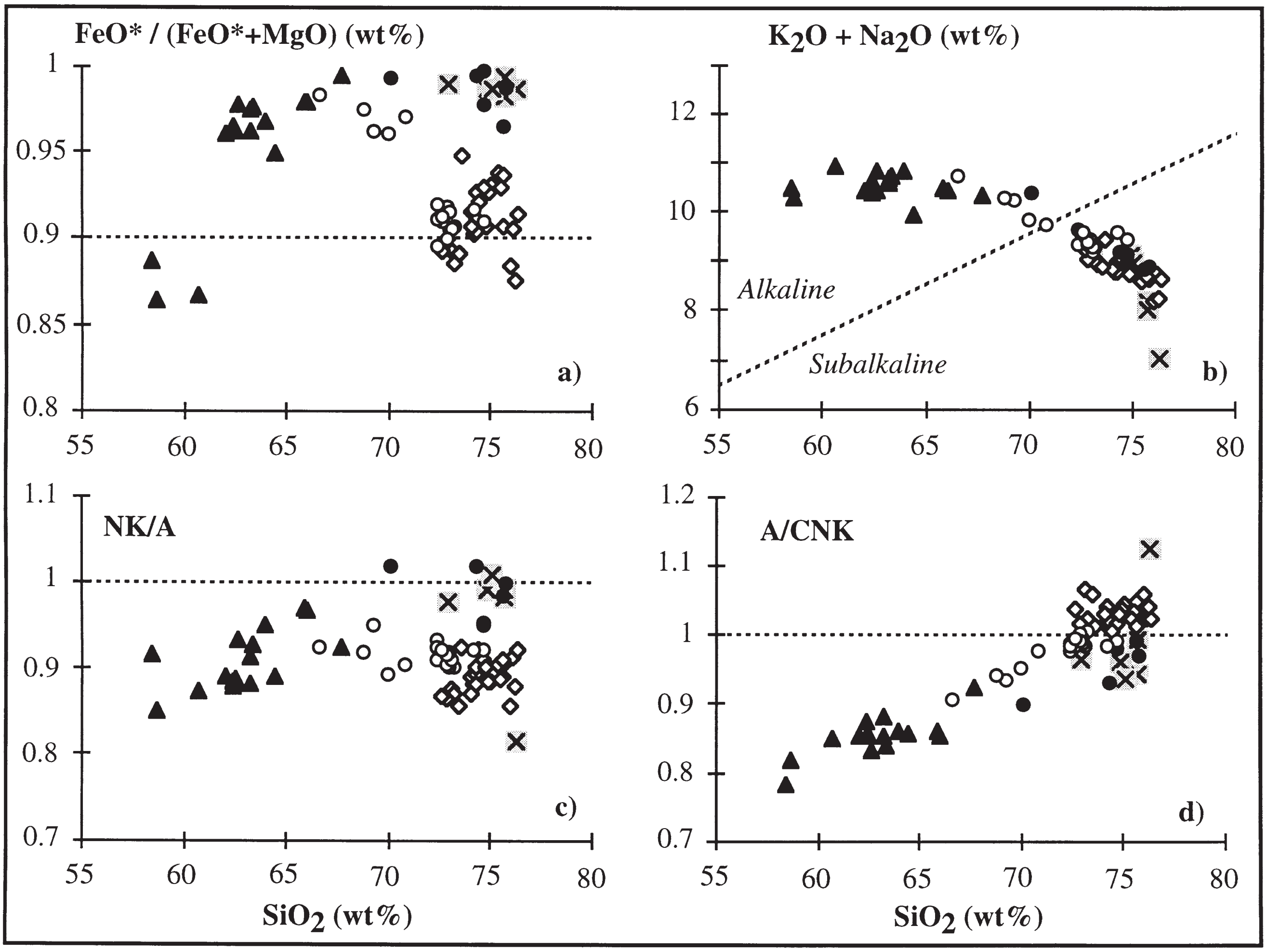


Fig. 22. Analyses of the intermediate and acid rocks of the Ragunda complex (Persson, 1995; in prep.) plotted in (a) FeO*/(FeO*+MgO) vs. SiO_2 , (b) K_2O+Na_2O vs SiO_2, (c) NK/A vs SiO_2 and (d) A/CNK vs. SiO_2 variation diagrams. FeO* denotes total iron as FeO, NK/A molecular (Na_2O+K_2O)/Al_2O_3 ratio, and A/ANK molecular Al_2O_3/(CaO+K_2O+Na_2O) ratio. Line separating the alkaline and subalkaline fields in (b) is from Irvine and Baragar (1971). Symbols are as in Fig. 21 (for the intermediate and acid rocks).

11.03 wt% for the leucogabbro. The potassium content is high for the gabbro (average 1.62 wt%) and leucogabbro (average 0.96 wt%). The basic rocks are characterized as within plate rocks (Pearce & Cann 1973).

Chondrite-normalized REE-patterns for the gabbro show moderate enrichment in the LREE. The La/Yb_N ratios are within the range 8.06 to 15 (average 11.49). The gabbros do not show any Eu anomaly (Eu/Eu* = 1.07 to 0.97). The leucogabbro is slightly less enriched in the LREE than the gabbros. The La/Yb_N ratios for two samples are 7.01 and 9.28. The leucogabbros have a positive Eu anomaly (Eu/Eu* = 1.38 and 1.90)

The geochemical trends clearly show that the syenite is not a hybrid rock formed by magma mixing between acid and basic magmas. If mixing had occurred between the acid and basic magmas, straight lines on element-element plots would have been produced. This is not the case for the syenites in the Ragunda complex. The syenites have too high TiO_2, Al_2O_3, MnO, K_2O, Na_2O, P_2O_5, Ba and Eu and too low MgO, CaO and Sr to be consistent with the mixing hypothesis. However, hybrid rocks which are consistent with the mixing hypothesis do exist in the complex.

2.2.6 GEOCHRONOLOGY AND ISOTOPE GEOCHEMISTRY

Kornfält (1976) reported a Rb-Sr age of 1320±30 Ma for the syenites and granites in the Ragunda complex. A recalculation of this age using the decay constant recommended by Steiger & Jäger (1977) gave an Rb-Sr age of 1292 Ma. It has been a common observation in the Svecofennian of Sweden that Rb-Sr ages tend to be younger than rock crys-

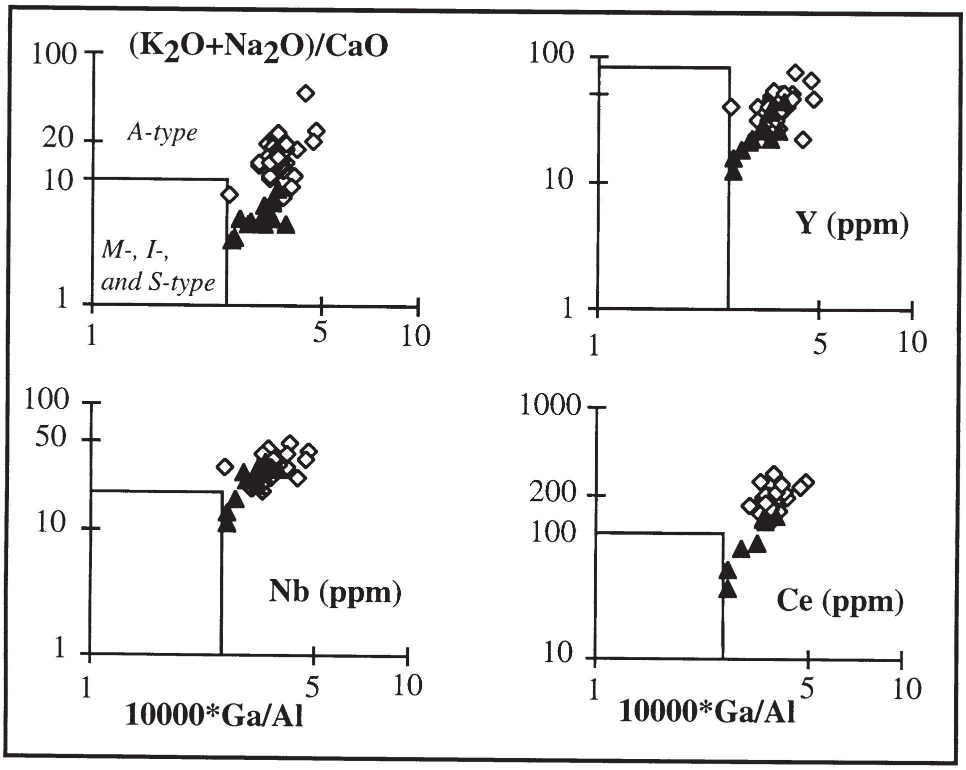


Fig. 23. A-granite classification of the intermediate and acid rocks of the Ragunda complex according to Whalen et al. (1987). Symbols: closed triangles - syenites and quartz syenites; open diamonds - granites.

tallization. This is for instance the case observed in the Nordingrå rapakivi complex (Welin & Lundqvist 1984). In a more recent study by Persson (1995, and submitted) two granite varieties were sampled for U-Pb zircon age determation and some new samples for Rb-Sr whole-rock dating were also collected. The sample localities are shown in Fig. 19. Sample GR-A (coarse-grained hornblende-biotite granite) from the village Ragunda yields a discordia line with an upper intercept age of 1513 ± 9 Ma (Fig. 24a). This is a very well defined discordia line with one concordant fraction, which gives the emplacement age of this rock. Sample GR-B (medium-grained, equigranular biotite granite) from the Central Massif yields a discordia line with an upper intercept age of 1505 ± 12 Ma (Fig. 24b). This is also a well defined discordia line with one fraction close to the concordia line.

The samples for the former Rb-Sr age determination of the Ragunda felsic rocks (i.e. syenites and granites) were collected over the entire outcrop area of the complex (Kornfält pers. comm.). The new Rb-Sr samples for the granites and syenites were collected from two discrete intrusion bodies: the granite around the village Ragunda and the syenite in the westernmost intrusion, close to Lake Gesunden. The data from the samples of the hornblende-biotite granite do not define an isochron. Six out of eight samples fall on a trajectory representing an age of 1233 ± 96 Ma (MSWD = 1.28). The initial $^{87}Sr/^{86}Sr$ ratio is 0.7311 ± 0.0147. The ”age” is 281 Ma lower than the zircon age of the same rock, sample GR-A.

Three samples from the syenitic rocks were analysed for their Rb-Sr isotopes. The best-fit regression line (MSWD = 3.86) yields an age of 1515 ± 71 Ma which, within the limits of errors, agrees with the zircon ages. The initial $^{87}Sr/^{86}Sr$ ratio is 0.7024 ± 0.0030.

Sm-Nd data (Persson 1996, and in prep.) from the three rock groups of the Ragunda complex, give negative ε_{Nd} values for the intrusion age 1.51 Ga. Measured ε_{Nd} values range between -7.2 and -8.0 for the gabbro in the Western Massif, and one sample from the Central Massif gives -10.1. The leucogabbro in the Eastern Massif gives -6.5. The syenitic rocks in the Western Massif range between -7.8 and -8.5 and the granitic rocks between -6.2 and -7.6. These values are much lower than the values for corresponding rapakivi granites in Finland (-0.2 to -3.1; Rämö 1991) and from the neighbouring Nordingrå massif (-2.5 to -3.0; Andersson 1994, Lindh & Johansson 1996), but similar to those from the Salmi massif in Russian Karelia (-5.7 to -8.1; Neymark et al. 1994, Rämö 1991) and the small rapakivi complexes north of Ragunda and Rödön (-8.5 to - 4.8, with an average of -7.0; Andersson & Neymark 1994a, Andersson 1997b).

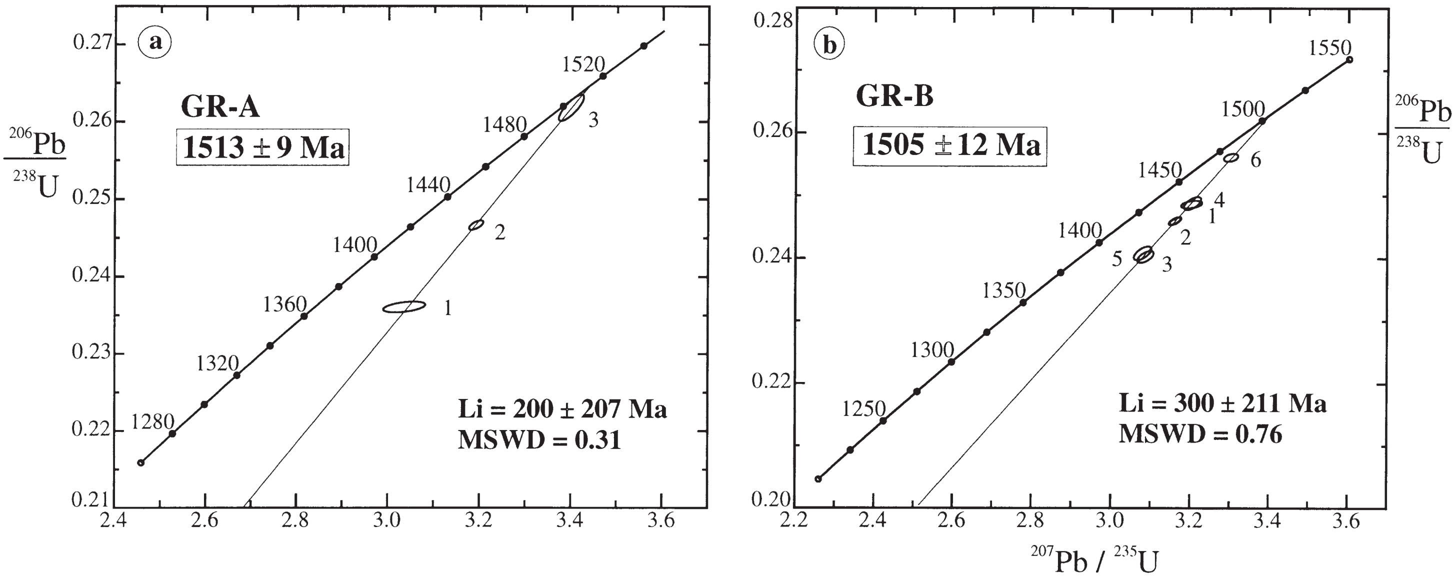


Fig. 24. Concordia diagram showing U-Pb analyses of zircon fractions (Persson, 1995; submitted) from a) GR-A (hornblende-biotite granite) and b) GR-B (medium-grained, equigranular biotite granite).

The Finnish rapakivi granites are believed to represent anatectic melts of 1.9 Ga Svecofennian crust (Rämö 1991). The strongly negative values of the Salmi massif, which is located at the border zone between the Archaean basement and 1.9 Ga crust, imply that there was a significant contribution of older crustal material to these granites. The ε_{Nd} values from the Ragunda rocks also suggest a significant involvement of old crustal components.

2.3 The Nordingrå massif

T. Lundqvist, A. Lindh, U.B. Andersson, S. Fröjdö & S. Claesson

2.3.1 INTRODUCTION

The Nordingrå rapakivi-type massif is situated in central Sweden, on the coast of the Bothnian Sea, between latitudes c. 62° 50' N and 63° 10' N. The region is characterized by a relatively high topographic relief (Höga Kusten, "High Coast"), and includes the area of maximum post-glacial uplift in Scandinavia. The highest ancient shorelines are here found at c. 285 m a.s.l. (J. Lundqvist 1987). Good opportunities for studies of the rocks and their structures exist along the well-exposed wave-washed shores of the Gulf of Bothnia.

The Nordingrå massif has been mapped and investigated by Lundbohm (1899), Sobral (1913), von Eckermann (e.g. 1938), G. Lundqvist (1976) and Lundqvist et al. (1990). In the latter paper an extensive reference list also to other, more detailed investigations, is given. The following account of the major features of the Nordingrå massif is mainly based on Lundqvist et al. (1990).

2.3.2 GENERAL GEOLOGY

Three rock types form the major constituents of the Nordingrå massif: granite, gabbro and leucogabbro/anorthosite (see map, Fig. 25). The granite occupies the northern parts, whereas in the south the massif is composed of gabbro in the west and leucogabbro/anorthosite in the east.

The rapakivi rocks (granite, gabbro and leucogabbro/anorthosite) were emplaced at c. 1580 Ma (Welin & Lundqvist 1984) into a Palaeoproterozoic crust composed of Svecofennian, c. >1.95–1.87 Ga old metagreywackes (cf., e.g., Lundqvist et al. 1990 and Wasström 1993) with intercalated, mainly mafic metavolcanites, deposited in what has been called the Bothnian Basin (Hietanen 1975). These metagreywackes etc. were intruded by dominantly c. 1.89–1.87 Ga old early orogenic plutonic rocks (tonalite, granodiorite with minor gabbro, in part ultramafic, diorite and granite), after which the whole complex was folded and regionally metamorphosed to medium and high grades during the Svecokarelian (or Svecofennian) orogeny at c. 1.84–1.80 Ga. Metamorphism was of low-pressure type, and abundant migmatites were formed. Subsequently, the late orogenic granites (dominantly of S type) and related pegmatites of c. 1.82–1.80 Ga age intruded (Romer & Smeds 1994, Claesson & Lundqvist 1995). In the north and west, large volumes of postorogenic, mainly megacrystic, I- to A-type

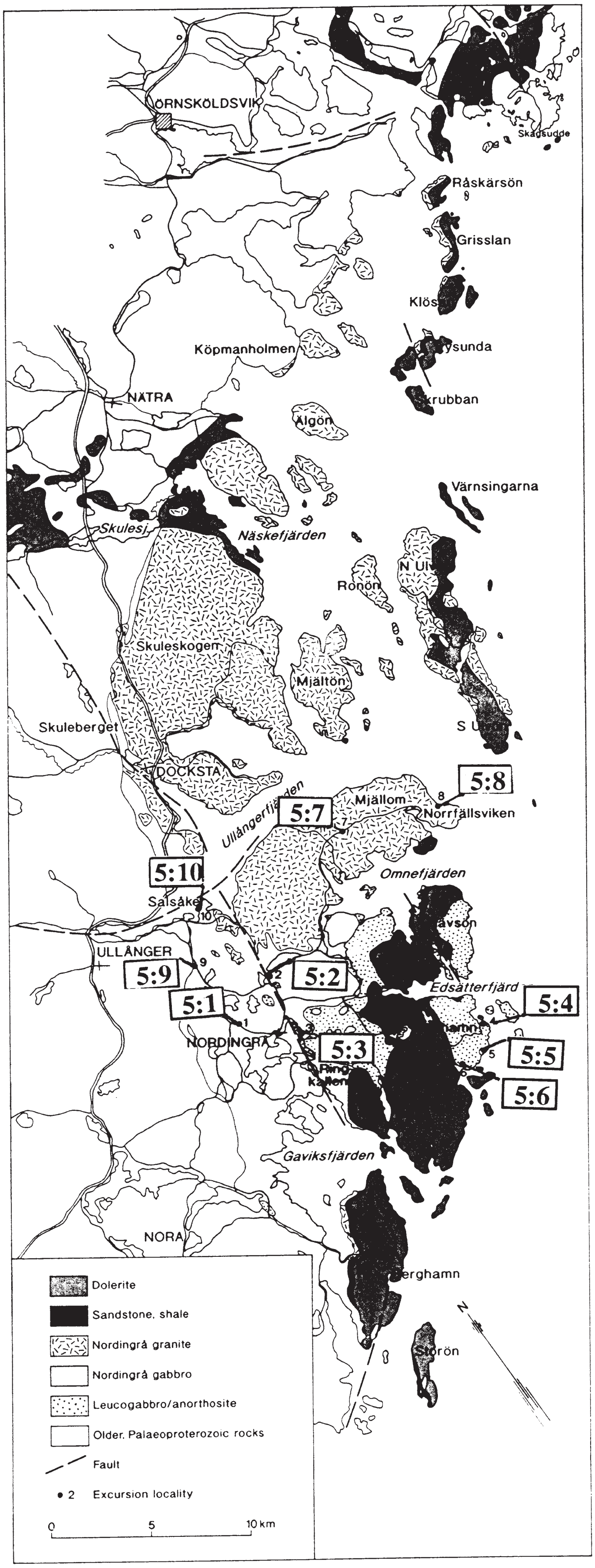


Fig. 25. Bedrock map of the Nordingrå–Skagsudde region. Based on Larson (1980) and Lundqvist et al. (1990). Excursion localities for the IGCP 315 excursion are indicated.

granite (Revsund granite) were formed somewhat later (1.80 –1.78 Ga; see Claesson & Lundqvist 1995 and references therein). Rocks from the interval 1.80–1.58 Ga are unknown from the vicinity of Nordingrå. Although some shear zones and faults were probably active by this time, the rapakivi plutonic rocks are in all evidence anorogenic, as they were emplaced into a cratonized crust.

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. The most conspicuous hornfels alteration is found in xenoliths occurring in the Nordingrå granite in beautiful intrusive breccias situated at the northern extreme of the massif near Skagsudde. Cordierite and hypersthene are the most important minerals formed in the metagreywacke xenoliths. In the metabasalt xenoliths, hypersthene is most prominent among these minerals. Orthopyroxene-biotite thermometry has yielded temperatures around 750°C for one such xenolith (Andersson 1994). In the Skagsudde region, a potassium feldspar porphyroblastesis, presumably also some remobilization, took place in a megacryst-bearing early orogenic granitoid situated in what is probably the roof of the Nordingrå granite (Lundqvist 1973). Through this sub-surface connection the Nordingrå granite is likely to continue to the small skerries of Bonden, 60 km northeast of Skagsudde, where a similar rapakivi granite is exposed (Nilsson & Kero 1989).

Results from gravimetric surveys along NW–SE and E–W profiles have allowed H. Henkel to interpret the three-dimensional structure of the Nordingrå massif in the following way (see Lundqvist et al. 1990): The granite of the northern parts of the massif probably forms an approximately 1 km thick sheet on top of the gabbro. This interpretation rests on the presence of a positive gravity anomaly that characterizes the granite area. In the west, the contact to the gabbro dips below the metagreywackes. According to the gravimetric data, the three-dimensional relations between gabbro and leucogabbro/anorthosite can be interpreted to indicate that the latter rocks form a c. 1 km thick sheet on top of c. 5 km of gabbro.

Dykes related to the Nordingrå massif are rare. At Skagsudde peculiar pegmatitic dykes cutting the granitoid of the roof probably emanate from the Nordingrå granite (Lundqvist 1973). Circa 11 km SSE of the town of Örnsköldsvik, at the contact of the Nordingrå massif with Svecofennian metagreywacke, there is a small occurrence of a porphyritic doleritic rock, which may be a dyke variety of the gabbro.

In the region between the Nordingrå and Ragunda massifs, c. 30–45 km west of Nordingrå, numerous dykes occur. They are up to c. 12 m wide and have an east–west strike and a vertical dip. The dykes consist of a granite porphyry, which resembles rapakivi rocks, together with various hybrid rocks of intermediate composition. Probably they are related to the igneous activity centred at Nordingrå and/or Ragunda. However, no radiometric age determinations of these dykes have been performed. In this connection it should be pointed out that according to available isotope data the Ragunda massif is approximately 70 Ma younger than the Nordingrå granite (cf. chapter on the Ragunda massif).

The post-rapakivi evolution of the Nordingrå area involved uplift, erosion and faulting. In situ weathering breccias and arkoses formed as a thin blanket on top of a flat surface cut into the rapakivi granite, leucogabbro/anorthosite and gabbro. They constitute the basal layers of a succession of mostly reddish, arkosic sandstone and intercalated dark shale and conglomerate (cf. Fig. 25). These sedimentary rocks are included among the Jotnian formations of the Fennoscandian Shield. These observations made Högbom (1909) coin the term Subjotnian for the rocks of the Nordingrå massif and other rapakivi rocks of the Shield.

The sandstone formation, which to-day is preserved as an up to 65 m thick sequence, forms an outlier of extensive, c. 1000 m thick, deposits in the Bothnian Sea. It is capped by a dolerite sill of c. 250–300 m thickness (Fig. 25). The dolerite is of alkali basalt type (see Lundqvist & Samuelsson 1973 and Larson 1973, 1980). According to a K-Ar isochron dating it was formed c. 1200–1250 Ma ago (Welin & Lundqvist 1975, Welin 1979, cf. also Suominen 1991) as a well-developed complex of layered intrusions (the Ulvö Dolerite Complex, see Larson 1980). Due to pre-dolerite faulting these intrusions in part have a roof of leucogabbro/anorthosite, although they rest on top of the sandstone; e.g. on the isles of Ulvöarna the dolerite intrusions occur within the Nordingrå rapakivi granite, which here constitutes the roof as well as the floor of the dolerite complex.

A major lopolithic dolerite intrusion took place at a somewhat deeper level than the Ulvö Dolerite Complex. It appears as a semi-circle-shaped structure in the geological map of the area; it has a diameter of 90 km. The northernmost parts of this lopolith cut through the Nordingrå granite near Köpmanholmen. Major occurrences of similar dolerites are found further inland (the Central Scandinavian Dolerite Group of Gorbatschev et al. 1979).

Faults have affected the Nordingrå massif as well as the sandstone and dolerite (cf. Larson & Magnusson 1979). In particular, north–south, steeply dipping faults are noted. One of these runs from Salsåker in the north through Vågsfjärden to Gaviksfjärden in the south. Two north–south trending faults, where the western blocks have been thrown down, displace the sandstone and dolerite on Rävsön and the island of Trysunda.

2.3.3 THE ROCKS OF THE NORDINGRÅ MASSIF

2.3.3.1 Gabbro and leucogabbro/anorthosite

Gabbro and anorthosite are intimately related to each other and linked by transitional rocks, mainly leucogabbro and leuconorite. In all evidence they are comagmatic. The leucogabbro with minor anorthosite occupies a more easterly position within the Nordingrå massif. von Eckermann (1938) assumed an easterly, gently dipping contact between the leucogabbro/anorthosite and the gabbro. This contact was suggested to be approximately conformable with the dip of the overlying sandstone formation and the dolerite sill; thus, the leucogabbros/anorthosites would be situated on top of the gabbro. von Eckermann's (1938) model for anorthosite genesis, which involves floating of early formed plagioclase crystals in a gabbro-anorthosite magma, was founded on this assumption. However, the contacts between gabbro and leucogabbro/anorthosite, where exposed, are mostly irregular. Furthermore, a number of localities in the gabbro display rhythmical layering and lamination, which show no consistency in strike and dip. Although the leucogabbro/anorthosite, according to gravimetric investigations, has been interpreted to overlie the gabbro (see above), the closer geometrical relations between the two rock types thus remain unknown, but they are clearly more complicated than assumed by von Eckermann (1938).

The following account of the gabbro-leucogabbro-anorthosite complex is mainly based on G. Lundqvist (1976) and Lundqvist et al. (1990).

In outcrop, the gabbro can sometimes be seen to form dykes in or to brecciate the leucogabbro/anorthosite. There are inclusions of true (white) anorthosite as well as rare gabbro-like inclusions in the normal, grey leucogabbro/anorthosite. These facts, along with frequent observations of different gabbro types (coarse-, medium- and fine-grained) in contact with each other, indicate a close, comagmatic relation between gabbro, leucogabbro and anorthosite and a multiple intrusion character.

The gabbro is dark grey in colour, usually medium- or fine-grained, but sometimes coarse-grained. Especially the latter types have a tendency to weather to gravel. The modal composition of the gabbro is dominated by plagioclase, mainly in the compositional range c. 50–55% An. The mineral is frequently normally zoned. Thus, variations between 30 and 60% An occur. In porphyritic varieties, the plagioclase occurs in centimetre-size crystals as well as in the matrix. It should be noted that some ”porphyritic” gabbros evidently formed by disintegration of leucogabbro/anorthosite inclusions. In such cases scattered plagioclase crystals are found in the gabbro close to the inclusions.

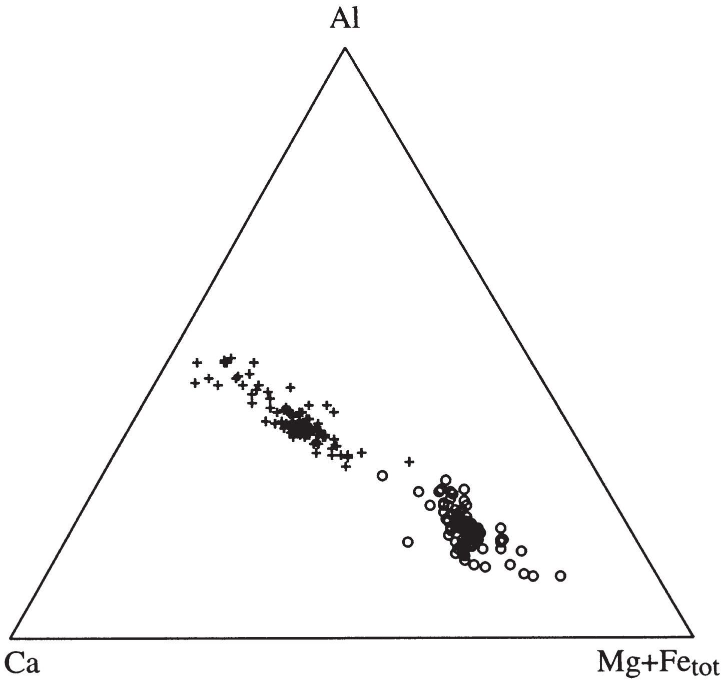
Olivine is a normal constituent of the gabbro, but the percentage varies strongly. The fo content ranges between c. 10 and 50%. Reaction rims of orthopyroxene have been observed. Iddingsite, serpentine and magnetite are secondary after olivine.

Two pyroxenes occur in the gabbro: orthorhombic and monoclinic. They form discrete crystals as well as lamellar, drop-like or more irregular intergrowths. The compositional range of the orthopyroxene is 25–60% en, and that of the clinopyroxene 30–70% of the Mg end member. When clinopyroxene is the host, the intergrowth tends to be finely lamellar (earlier called diallage cleavage).

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 in relation to the major minerals. Their contents may be raised in schlieren in the gabbro. This leads to monzogabbroic and monzodioritic compositions. High contents of orthoclase and quartz, at times accompanied by common hornblende, calcite, epidote and prehnite, occur sometimes in reddish, pegmatoid or granitoid dykes and schlieren in the gabbro. Dykes of a fine-grained quartz-albite rock are also noted.

The following short summary of the chemical composition and its variation is based on 134 chemical analyses of gabbro. The sampling covers almost completely the outcrop area of the gabbro. Most of the rocks can be described as a noritic gabbro or gabbroic norite based on their chemical and normative composition. However, according to the classification scheme designed by Debon & Le Fort (1982) the variation range includes monzogabbro. No primitive rocks exist. The Mg# number varies between 0.071 and 0.374. The rock with the highest Mg# number has all the same 1.5% TiO_2 and 0.5% K_2O. Gabbro exists with TiO_2 contents ranging up to 6.6%; this is, however, abnormal (cf. Fig. 26). The next highest value is 4.5%. The potassium content is also extremely high. It attains 3% with an arithmetic mean of 1.5%. The chemical variation of the gabbro suite approximately follows ”normal” magmatic trends, even if the analytical results scatter conspicuously. The variation cannot be explained by fractional crystallization. Fractionation of clinopyroxene and olivine can be invoked to explain some of the variation. To attain the very high iron enrichment (FeO contents up to 24.0% (+ 8.2% Fe_2O_3)) from a primitive parent would require at least 75% fractionation (cf., e.g. the Skaergaard magma). This would lead to a highly viscous and immobile rest magma. The normative mineralogical composition compares well with the modal composition. The partly very high normative orthoclase content is striking. The highest content is 18%. The very special chemical composition of the rapakivi gabbros is probably due to contamination from the crust. Contamination explains orthopy-



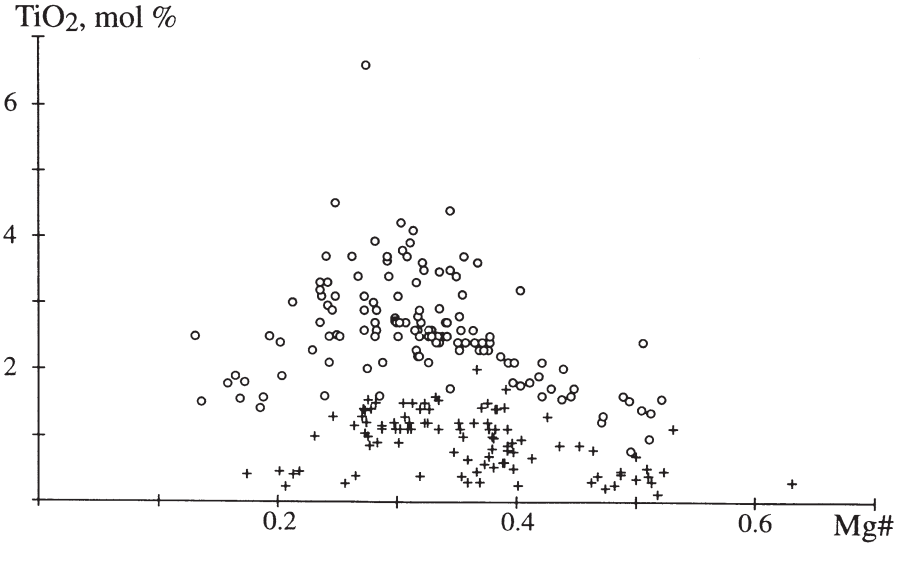


Fig. 26. Chemical composition of gabbros (open rings) and leucogabbros/anorthosites (crosses). N = 232. Note the well-defined trend in the Al - Ca - Fe_{tot}+Mg diagram. There is a clear separation between the leucogabbros/anorthosites and the gabbros. This is illustrated here for Ti but the diagram is equally valid for any major element. Leucogabbros/anorthosites are not restricted to a small part of the "differentiation" range (expressed as Mg#) but occur over about 90% of the range. Molar proportions are used in both diagrams.

roxene formation from a reaction between the olivine component in the magma and excess silica in the crust and gives plagioclase and additional orthopyroxene due to a reaction between the clinopyroxene component of the magma and excess aluminium of the contaminant. An increased plagioclase component in this Fe-extreme gabbro environment explains the separation of anorthositic rocks.

The Ni contents are very variable but mostly not very high. They vary from below the detection limit to about 200 ppm. The absolute majority of the rocks has Ni contents below 100 ppm. Cr contents vary less. They are mostly between 50 and 100 ppm, but higher as well as lower contents occur. There seems to be no clear correlation between Ni and Co. Ba/Sr ratios are high for gabbroic rocks, which can also be taken as an indication of contamination.

The REE patterns of the gabbro have a gentle negative slope. The (La/Lu) normalized ratio is around 5±1. Eu anomalies vary from near zero to positive.

The term leucogabbro is used here for coarse-grained rocks in the Nordingrå massif with a plagioclase content between c. 70 and 90%. Rocks with higher plagioclase contents are referred to as anorthosite. Anorthosite makes up c. 20% of the total anorthosite+leucogabbro volume. Extremely feldspar-rich, white anorthosite varieties occur as inclusions with diameters of up to some tens of metres in ”normal” leucogabbro/anorthosite (block structure of Ashwal 1993) or in gabbro.

In the leucogabbro/anorthosite, the plagioclase crystals are 1 to 4 cm in length. Occasionally larger plagioclases are seen, attaining diameters up to some decimetres. Such giant crystals also form important constituents of peculiar varieties of anorthosite, which occur as inclusions(?) in the normal leucogabbro/anorthosite (e.g. excursion locality 5:5).

The total compositional range of the plagioclase of the leucogabbro/anorthosite is c. 48–67% An. However, the anorthite content usually falls between c. 60 and 65%, and is therefore somewhat higher than in the plagioclase of the gabbro. A weak zoning is sometimes observed. Bent and broken twin lamellae occur. Bluish or greenish, labradorizing cores of the crystals are found at some localities. Needle-shaped microlites of ilmenite, probably also magnetite, are seen in the microscope with a high magnification.

Secondary alteration to sericite, prehnite, epidote and calcite is rather common in the plagioclase of the leucogabbro/anorthosite. In particular some varieties with a relatively high content of interstitial K-feldspar are affected by such alteration. These rocks have a characteristic pinkish-greenish colour.

The mafic minerals of the leucogabbro/anorthosite are mainly a uralitic hornblende, which more or less completely replaces former pyroxenes, clinopyroxene with c. 60% of the Mg end member, olivine, reddish brown biotite and opaque minerals. Orthopyroxene may occur among the pyroxene relics in the uralitic hornblende (cf. below).

Olivine forms small rounded crystals, which are more or less altered to serpentine or amphibole. Ilmenite is the dominating opaque mineral. The magnetite content is low in the western leucogabbro/anorthosite (west of the sandstone and dolerite), but higher in the eastern and the easternmost parts of the western leucogabbro/anorthosite, possibly due to oxidation caused by the dolerite intrusion (Magnusson 1983). Sulphides are mainly represented by pyrrhotite. Small amounts of prismatic apatite are also noted.

Secondary minerals in the leucogabbro/anorthosite are, in addition to those already mentioned, cummingtonite-grunerite and chlorite.

Very coarse-grained (centimetre- to decimetre-size crystals) pegmatoid bodies occur within the leucogabbro/anorthosite. Most of them are similar to those found in the gabbro. A particularly noteworthy occurrence of a different type of ”anorthosite pegmatite” is found at Mjösand in the eastern leucogabbro/anorthosite (excursion locality 5:6). It consists of up to 5 dm long crystals of clinopyroxene, in part uralitized, with lamellae of orthopyroxene. Other constituents are up to 4 cm long prisms of apatite, titanomagnetite, pyrrhotite, olivine, K-feldspar and quartz. For analyses, see excursion locality description.

The chemical composition of the leucogabbro/anorthosite resembles that of the gabbro. This account is based on 98 major element analyses, whereas the number of trace element analyses varies with element. When all the basic rocks (all 232 chemical analyses) are displayed together (cf. Fig. 26), the bimodal variation is very pronounced. This means that the leucogabbroic/anorthositic part of the rock sequence normally is very well separated from the gabbro. Striking is the generally parallel variation displayed by the leucogabbro/anorthosite and the gabbro in most variation diagrams. No specific point in the rock evolution exists at which the plagioclase-enriched rocks seem to have been separated from the gabbro magma. The Mg# number in the leucogabbro/anorthosite is between 0.094 and 0.442. This overlaps the gabbro variation range but is slightly displaced towards higher values. The molar ratio Ca/(Ca+Na) in the gabbro varies between 0.60 and 0.85 and in the leucogabbro/anorthosite between 0.59 and 0.77. The normative anorthite content in the leucogabbro/anorthosite is all the same higher than in the gabbro due to the fact that much Ca in the gabbro occupies the M2 position in clinopyroxene. However, the normative anorthite content in the gabbro overlaps that in the leucogabbro/anorthosite.

The REE patterns of the leucogabbro/anorthosite have a gentle negative slope with an Eu-anomaly that varies from zero to strongly positive. The contents of the rare earth elements are usually low.

2.3.3.2 Nordingrå granite

The Nordingrå granite is the areally dominating plutonic rock of the Nordingrå massif. It was intruded later than the leucogabbro/anorthosite, as xenoliths of the latter are found in the granite. Also the gabbro seems to be largely older than the granite, but the relations between these two rocks are more complicated. Gradual transitions in the form of monzonitic, hybrid(?) rocks are found at the gabbro-granite contact, e.g. on Omneberget in the southernmost parts of the granite area. In addition, breccias similar to the one at excursion locality 5:10 close to Salsåker contain angular xenoliths of gabbro in granite, but also gabbro enclaves with more gradual (hybridic) contacts to the matrix granite. The latter feature suggests mingling and limited mixing of the two

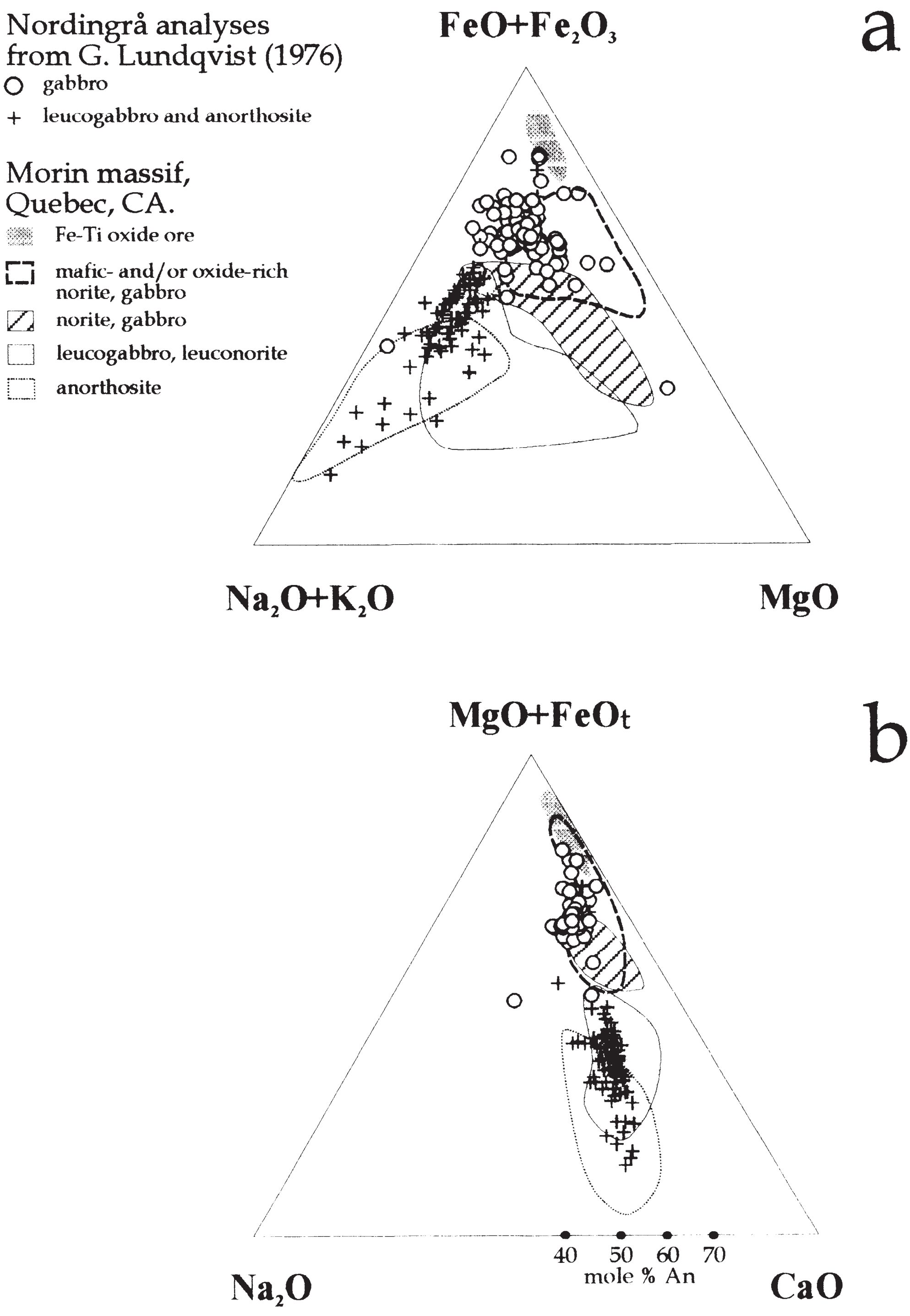


Fig. 27. Triangular compositional diagram (wt. %) for comparison of Nordingrå gabbro and leucogabbro/anorthosite with the Morin massif in Quebec, Canada (cf. Ashwal 1993 and references therein). Low to intermediate Mg# and intermediate plagioclase composition are conspicuous traits of Proterozoic massif-type anorthosites. (a) AFM diagram in which the compositional range and spread of gabbro and leucogabbro/anorthosite show enrichment in Fe as well as a plagioclase accumulation trend towards the alkali apex. (b) NMC diagram where the plagioclase accumulation trend towards An$_{50}$ is notable.

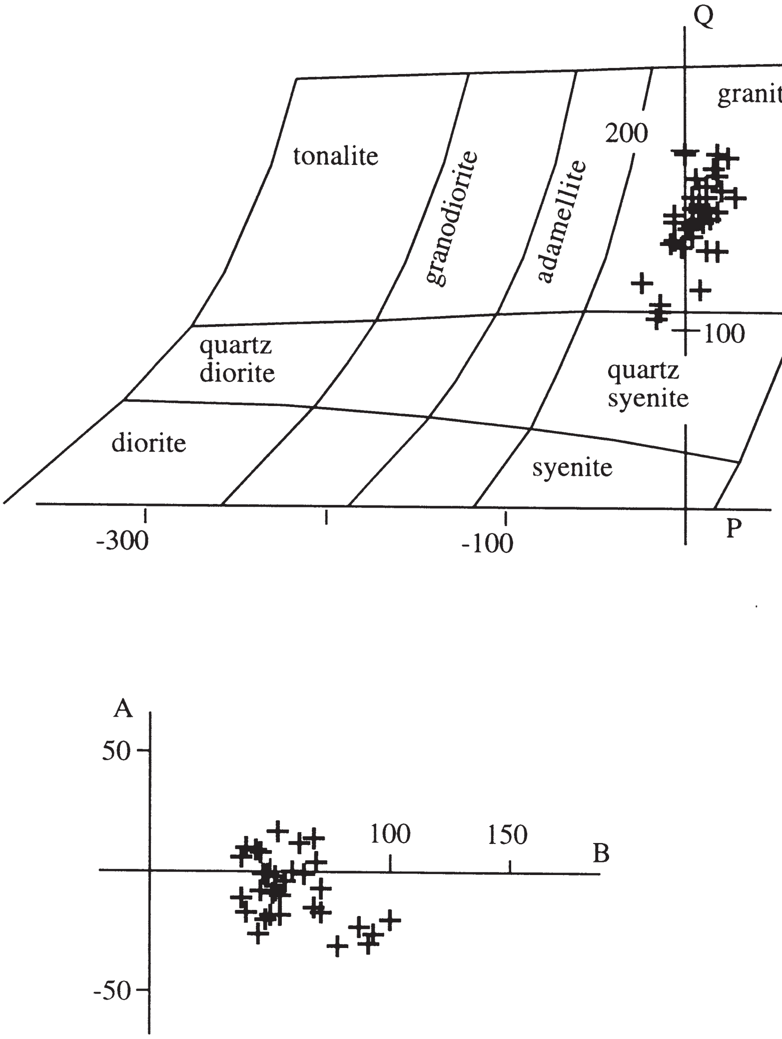


Fig. 28. The Nordingrå felsic rocks are almost totally restricted to the granite field of Debon & Le Fort (1982). They are metaluminous and straddle the line A = 0.

magmas.

Pegmatite and aplite are uncommon in the Nordingrå granite. The peculiar pegmatites occurring in what is probably the roof of the granite have already been mentioned (see ”General geology”). Miarolitic cavities in the Nordingrå granite, filled with quartz, perthitic K-feldspar, chlorite, calcite etc., are found at several localities, e.g. in the Norrfällsviken area.

The Nordingrå granite is red or greyish red, rarely grey (in the matrix of wall-rock breccias). The most common type is characterized by tabular, c. 0.5–2 cm long feldspar phenocrysts embedded in a fine-grained or finely medium-grained matrix. Because of the varying grain size of the matrix the porphyritic texture may be more or less prominent. In part the matrix is granophyric, displaying a fine intergrowth between quartz and K-feldspar. The feldspar is mostly a strongly perthitic K-feldspar, structurally intermediate between orthoclase and microcline (Lundqvist 1973). The K-feldspar phenocrysts seldom show albite mantling. In the matrix, K-feldspar and quartz dominate. Plagioclase (usually oligoclase or albite, rarely with cores of andesine) occurs in the matrix. It is generally stained with sericite.

Mafic minerals in the Nordingrå granite form c. 1–15% of the rock volume. Granites with differing contents of dark minerals are seen in sharp contact with each other at some localities. Common hornblende is the predominating mafic mineral, followed by clinopyroxene (ferrohedenbergite), biotite, oxide minerals (magnetite), sometimes also by fayalite and orthopyroxene. Among the accessory minerals zircon and fluorite are prominent, but also titanite, apatite and allanite occur. Secondary minerals include chlorite, grunerite, sericite, prehnite and epidote, sometimes also pumpellyite.

The chemical composition (based on 35 analyses) corresponds to dominating granite and minor quartz syenite according to the classification scheme designed by Debon & Le Fort (1982; Fig. 28). The SiO_2 content varies between 65.7 and 76.5%. The content of MgO (0.07–0.5%) and the

Mg# value (0.10–0.02) are extremely low. The ratio $K_2O/(K_2O+Na_2O)$ is fairly constant. It varies between 0.62 and 0.69. It appears unrelated to the magnesium-iron ratio. The Rb/Ba and Rb/Sr ratios suggest a magmatic evolution of the rock group. The variation is, however, small compared to that of most other rapakivi granite massifs. No strongly evolved rocks exist in the present set of analyses. The granite is a typical A-granite with high Ga/Al and (Zr+Nb+Ce+Y); cf. Whalen et al. (1987). The REE patterns are gently negatively sloping with pronounced but not very deep negative Eu-anomalies. The normalized La/Lu ratio varies between 4.2 and 7.6.

2.3.3.3 Nd isotopes

Initial ε_{Nd} values for the Nordingrå granites range from -3.1 to -2.5, and for the gabbro/anorthosites between -3.2 and 1.5 (Andersson 1994, Fröjdö et al. 1996, Lindh & Johansson 1996, Lindh et al. in prep.). There is thus a complete overlap between the mafic and felsic rocks in the complex, a feature which is also typical for other rapakivi complexes in central Sweden (Andersson & Neymark 1994, Andersson 1997a, b, Persson 1996), and the Salmi batholith (Neymark et al. 1994). The other complexes, however, have significantly lower initial ε_{Nd} values (-10.1 to -4.8), compared to Nordingrå (see chapters 2.1.7.1**,** 2.4.5 and 2.5.5.2).

The time-integrated ε_{Nd} evolution of the Nordingrå rocks is totally encompassed by the evolution of the early Svecofennian (c. 1.89–1.86 Ga) metaigneous rocks (Fig. 18). This makes a derivation of the Nordingrå granite from such early Svecofennian sources viable, similarly to what has been proposed for the rapakivi granitoids in SE Finland (Rämö 1991). An origin by mixing between fractionated juvenile, mantle-derived magmas and Archaean sources (including perhaps also Svecofennian components) can, however, not be dismissed, especially since an Archaean basement is indicated to be present in the lower crust below central Sweden (Andersson 1997a, b, Andersson & Neymark 1994).

Crustal sources are, however, not tenable for the associated mafic rocks. An enriched mantle source or a major crustal input has to be invoked to explain their low initial ε_{Nd} values. The latter model gains support in the petrographical and geochemical characteristics presented above. A model where crustal refractory material (dominated by plagioclase and pyroxene) left behind after the rapakivi granite melting, is assimilated in the mantle magma may be adequate (Emslie & Hegner 1993, Emslie et al. 1994). The assimilation may also include components of less refractory material, as indicated by e.g. the high K_2O contents noted above. Since this problem is fundamental in the rapakivi province of central Sweden, it is discussed in more detail in chapter 2.1 above.

2.4 The Rödö rapakivi complex

U.B. Andersson

2.4.1 INTRODUCTION

Early works discussing the Rödö complex include Högbom (1893, 1909, 1910) and Lundbohm (1893, 1899), but most thoroughly Holmquist (1899). The latter author described in detail the petrographic relations of the granite and many of the associated dyke rocks, as well as discussed the major element geochemistry. Already both Högbom (1893) and Holmquist (1899) suggested the operation of magma mixing processes between a silicic crystal-bearing and basic magmas in some of the Rödö porphyries, although Holmquist concluded that also the surrounding country rock gneiss had participated in this mixing. Later von Eckermann (1938, 1944, 1945, 1946a, b, 1947) has studied the Rödö dykes petrographically and geochemically. He proposed e.g. (von Eckermann 1938) that a dyke rock from the islet of Känningen (south of Rödön, Fig. 29) represented a natural example of an anorthositic melt (a rock which he termed kenningite), based on two chemical analyses which showed strong chemical resemblance with anorthositic rocks. Later investigations have not been able to confirm this (Lundqvist 1975). The most recent account of the rocks in the Rödö area is presented by Andersson (1997b).

2.4.2. GEOLOGICAL SETTING

2.4.2.1 Country rocks

The country rocks in the Rödö area consist of strongly migmatized ortho- and paragneisses. The paragneisses are dominantly metagreywackes belonging to the early Svecofennian successions of the Bothnian Basin (Lundqvist 1987, Lundqvist et al. 1990). The orthogneisses are also of early Svecofennian origin. Similar metagranitoids elsewhere in the basin have recently been dated to 1.88–1.87 Ga (Welin et al. 1993, Claesson & Lundqvist 1995), except for a very high age in one sample (2.03 Ga; Welin et al. 1993), which may be caused by inherited components. Especially in the paragneisses the intense migmatization has led to voluminous melting and formation of palingenic granites, which is characteristic of the country rocks around the Rödö intrusion. This ultrametamorphism and granite formation is probably similar in age to the widespread S-type Härnö granites in the Bothnian Basin (c. 1.82 Ga; Claesson & Lundqvist 1995). Numerous tourmaline-bearing pegmatites cut all the Svecofennian rocks.

2.4.2.2 The rocks of the Rödö complex

The *Rödö granite* itself is a coarse porphyritic, red granite (SiO_2=68.2–74.7%; Stops 6:1 and 6:2). The megacrysts are large (≤3 cm) ovoidal K-feldspars, and rounded (≤1 cm), drop-like quartz grains. K-feldspars are both mantled and unmantled by plagioclase, but mantled grains usually predominate. The mantles can be difficult to see in places, since they commonly also are brick red in colour. The thickness of these mantles varies, but is usually a couple of millimetres. The predominance of this mantled ovoid texture (rapakivi texture) makes the Rödö granite a wiborgite according to Finnish rapakivi terminology (e.g. Vorma 1976), in fact the only one in Sweden. K-feldspar and quartz also dominate the groundmass, and thus appear in two generations, which is typical for rapakivi granites. The granite is strongly miarolitic, and the vugs contain crystals of feldspar, quartz, calcite, and sometimes fluorite. The size of the vugs is up to about 15 cm. Similar cavities occur also in many of the dyke rocks, both mafic and felsic, but are usually smaller, a couple of centimetres at the most.

The areal extension of the granite intrusion is poorly known, since large parts of the area are water-covered. A possible outline has been sketched in Fig. 29, suggesting an area of at least 20 km^2. Recent aeromagnetic data (Geol. Survey of Sweden 1997) suggests an almost circular form of the granite intrusion, extending somewhat further south than indicated on Fig. 29.

Aplitic dykes, a few centimetres to about two decimetres, cross-cut the granite (Stop 6:1). They are grey or red and very fine-grained. They often thin out and dissappear into the granite, suggesting a formation as late liquids sqeezed out of the granite crystal mush. They are rich in F (up to 3820 ppm) and fluorite.

Dark schlieren structures are common in the Rödö granite on the southern coast of Rödön (Stop 6:1). They are stretched out, arc-like structures and consist mostly of altered Fe-Mg silicates (mica, chlorite etc.), presumably after primary amphibole or pyroxene. Other minerals with enhanced abundances compared to the granite are oxides, zircon, and apatite, whereas quartz and feldspar occur in smaller amounts. The schlieren are often associated with vugs and aplitic dykes.

Pillows of *granite porphyry* (Stop 6:1), from a decimetre to about a metre in size, are distributed throughout the granite. These have a finely medium-grained groundmass (coarser than the QFPs), but contain otherwise the same type of megacrysts as the granite. This type of granite porphyry also occurs as larger irregular enclaves in the granite, from a few metres to several hundreds of metres in size. This is especially common in the higher areas of central Rödön. The granite porphyry has essentially the same mineralogy and geochemistry as the granite, and it is interpreted as a chilled marginal facies which has been disrupted and distributed in the granite magma as semisolid enclaves of variable size.

Apophyses of granite porphyry can be observed to emanate from the Rödö granite into the country rocks at one locality on central Rödön. A set of similar subparallel dykes also occurs in the sedimentary gneiss at the southwestern shore of Rödön (Stop 6:2). These dykes can, however, not be followed into the granite due to lack of exposure. They are 1 dm to 1 m wide, and are also suggested to be apophyses from the granite.

Country rock xenoliths are very scarce in the Rödö granite. At one locality close to the contact on SW Rödön, a few such xenoliths occur (Stop 6:2). They are dark angular micaceous metasedimentary pieces. No hornfels contact metamorphic assemblage is preserved in them, but they are retrograded and very chloritic. This holds for the whole contact area. No contact aureole has been found. The country rocks at the contact have been thoroughly retrogressed (or are unaffected by the intrusion?).

The Rödö complex is perhaps most well-known for the numerous dyke rocks of various types that are associated with the granite (e.g. Holmquist 1899, Lundqvist et al. 1990, Andersson 1997b). More than 100 dyke localities have been documented (Andersson 1997b) in a relatively small area. Many of these, however, record the continuation of the same system, but at least 45 different dykes are present. The Rödö dykes are spread out in an area of c. 11.5 x 7.5 km around the granite intrusion, of which the major part is water-covered. Presumably many more dykes are present under water. Those farthest away are about 6.5 km SW of Rödön.

The dykes can be divided into three main categories: i) quartz-feldspar porphyries (QFPs), which contain phenocrysts of quartz, K-feldspar, and more seldom plagioclase in varying amounts and sizes (Fig. 29), ii) dolerites, which are more or less contaminated by felsic material, usually quartz and feldspar xenocrysts and iii) hybrid porphyries (HPFs), which are magmatic mixtures of the two previous in different proportions. Some of these occurrences are quite spectacular.

A few localities with *composite dykes* occur, of which one is described in Stop 6:2. One occurs on the tip of Åstholms udde east of Rödön. This dyke is at least 3 m wide, but only one side is exposed. It consists of a slightly hybridized 0.5 m wide black marginal zone (SiO_2 = 67.9%), and a several metres wide central QFP-zone (SiO_2 = 74.4%). Both contain megacrysts of K-feldspar, plagioclase and quartz up to a size of 2 cm. The K-feldspars are sometimes resorbed and mantled by skeletal plagioclase. The QFP contains numerous dark rounded enclaves from some decimetres and downwards in size. Also these contain the megacrysts described above.

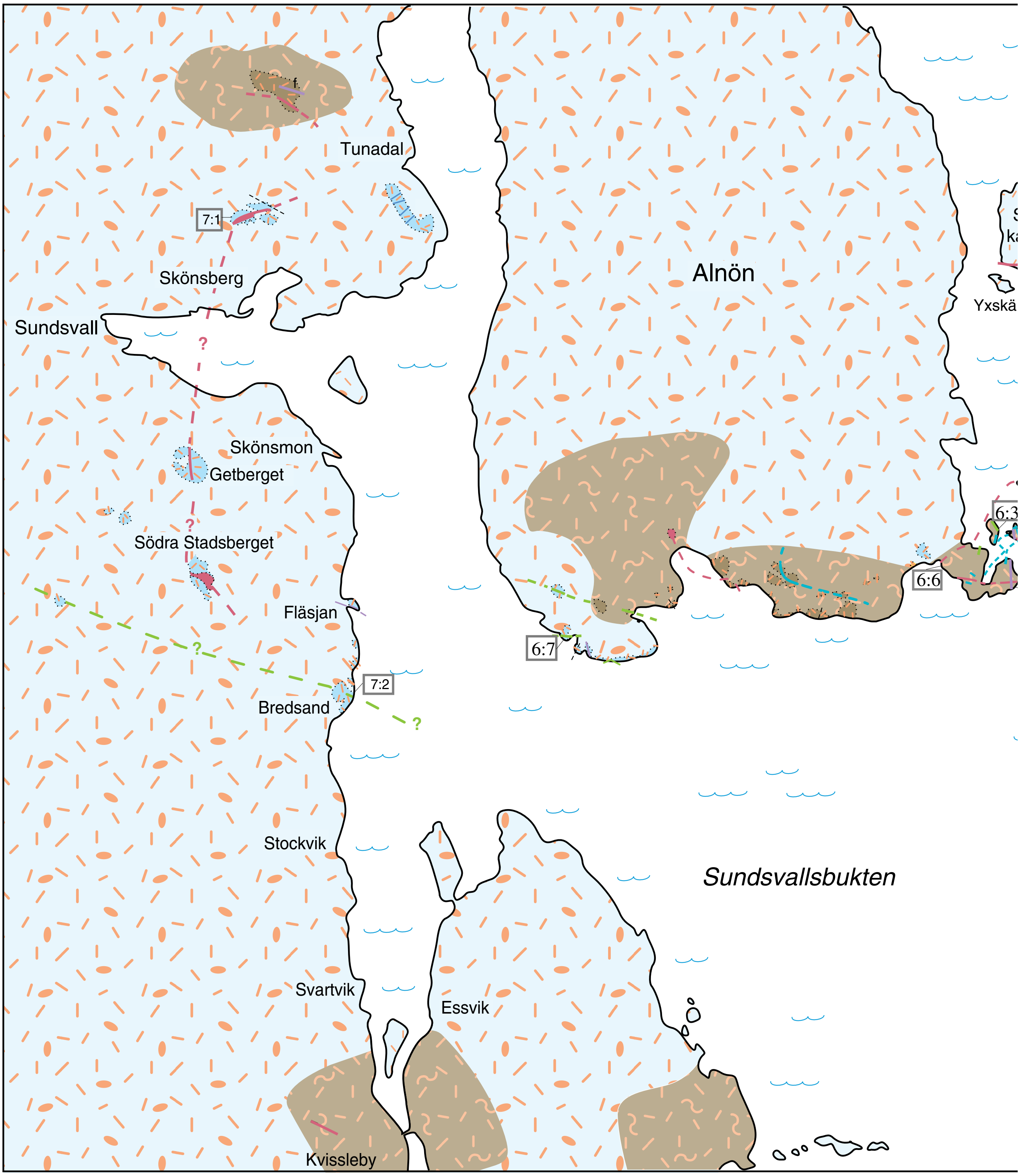


Fig. 29. Geological sketch map of the Rödö area. The Rödö granite intrusion is indicated as an oval delineated in red. Blue, brown and orange illustrate different country rocks (para- and orthogneisses, and palingenic granites, respectively). The Rödö dykes are indicated

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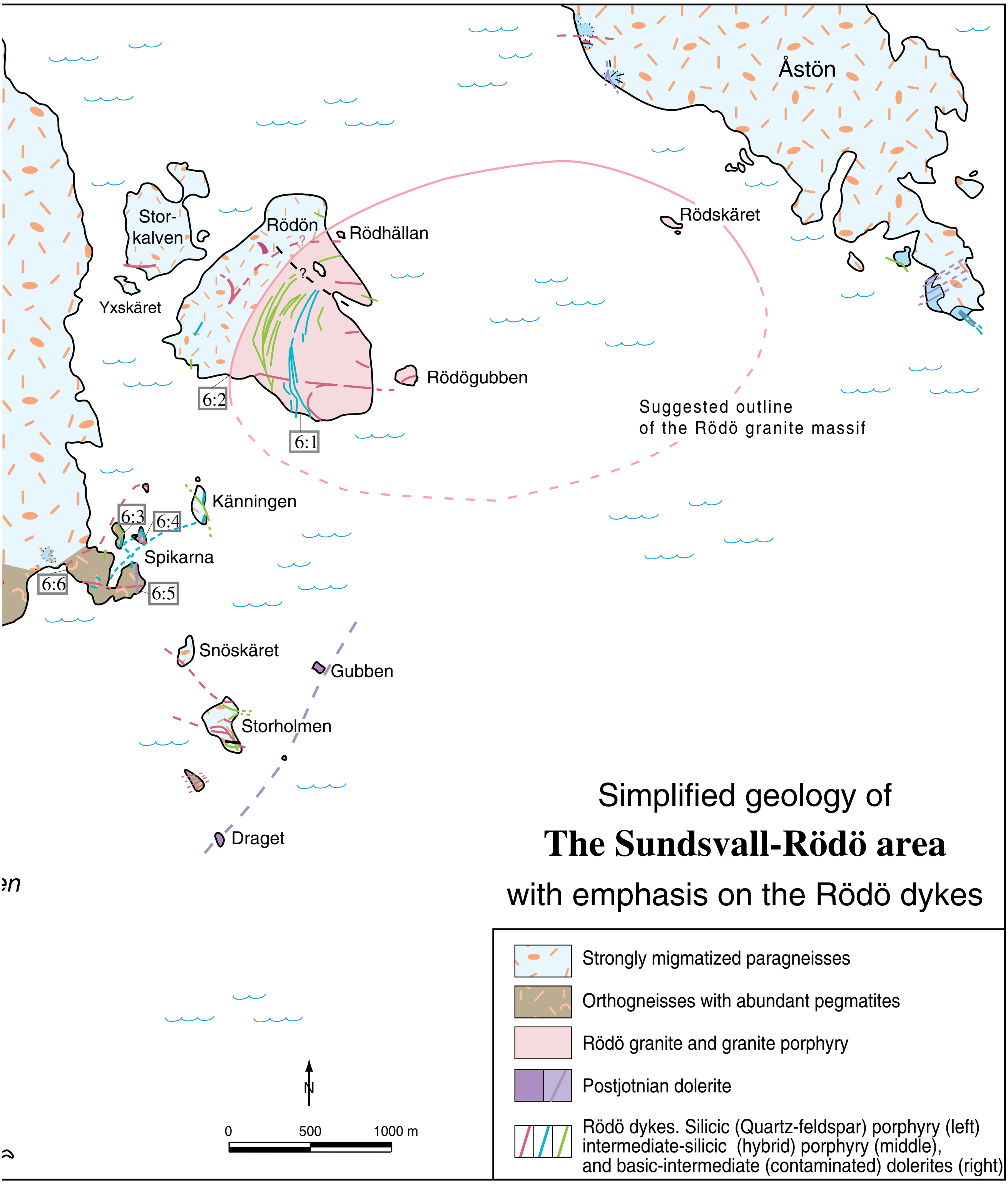

Fig. 29 (continued)
as quartz-feldspar porphyries (QFPs; red), dolerites (greenish), and hybrid porphyries (HPFs; greenish with red dots). Excursion stops are indicated. More detailed maps are presented in Andersson (1997b).

The QFPs occur in several modifications. There are three main types:

i) one which is coarse-porphyritic, with big crystals of K-feldspar, skeletal plagioclase and quartz, similar to the Rödö granite itself, but with finer grained matrix. This type also contains numerous rounded mafic-hybrid enclaves and is closely associated with the coarse-porphyritic hybrids described below (Stop 6:4).

ii) The second type has phenocrysts of slightly smaller size: up to c. 1 cm crystals of quartz and K-feldspar. Most Rödö QFPs belong to this group, which is generally little evolved and similar geochemically to the Rödö granite itself ($SiO_2 = 69.5–76.6\%$). Hybrid, quartz and K-feldspar xenocryst-rich enclaves, some centimetres to a decimetre in size, occur in some instances (Stop 6:10).

iii) The last type has the smallest phenocrysts, generally less than 0.5 cm, usually only a couple of millimetres, but usually including albitic plagioclase. These are also the most fractionated parts of the silicic Rödö magmatism (see the geochemistry below). One example is described in Stop 6:5 on eastern Skorven. A few others occur on Storholmsfläsjan, south of Rödön (the most extremely evolved, see geochemistry below), on Storkalven NW of Rödön and on Rödön itself ($SiO_2 = 71.1–77.2\%$). Mafic/hybrid enclaves occur only in the one at Skorven (Stop 6:5).

The dolerites are usually black and very fine-grained. They are commonly very homogeneous in size, 1–3 m. Almost ubiquitously they contain some felsic xenocrysts, such as quartz or K-feldspar, more or less resorbed and coated with mafic minerals or plagioclase. Sometimes a more general "monzonitization" of the dolerite into a violet-red rock of hybrid character is observed (e.g. on Långfläsjan, Stop 6:3). Composite dolerite-hybrid dolerite dykes occur in some instances, characterized by a lateral zoning pattern. One such dyke on southern Rödön is described in Stop 6:2.

The *hybrid porphyries* occur in two major types:

i) a dark, coarse-porphyritic type, with large (around 3 cm) crystals of K-feldspar, more or less intergrown with or overgrown by plagioclase, quartz (≤1 cm), and large skeletal plagioclases. They are geochemically rather silicic ($SiO_2 = 66.5–69.3\%$), and very different from the other main group of hybrids. This type occurs in some spectacular occurrences on Långfläsjan (Stop 6:3), Gråfläsjan (Stop 6:4), Skorven (Stop 6:5), Spikarö and Känningen. These occurrences probably form an interconnected system of flat-lying dykes. These hybrid porphyries also contain hybrid enclaves, with more sparsely distributed megacrysts of the same type as in the surrounding hybrid porphyries. These enclaves are, however, much more basic in nature ($SiO_2 = 56.6–59.1\%$).

ii) The second group of hybrid porphyries is more basic in character ($SiO_2 = 61.5–64.3\%$), and usually contains smaller resorbed K-feldspar and quartz xenocrysts. These dykes occur more widely distributed, e.g. in some dykes of the cone-sheet intrusion (see below) in the Rödö granite, on western Rödön, on Storholmen, and on southern Alnön. The distinction between xenocrystic dolerites and basic hybrid porphyries is unsharp, but has been subjectively put at around 60% SiO_2, based on petrographic and geochemical similarities.

Within the Rödö granite massif a number of xenocryst-bearing dolerites and hybrid porphyries form so-called *cone-sheet intrusions*. These dykes bend around and follow the shape of the outer contact of the granite intrusion in the western part of the granite and the immidiate country rocks, with increasingly steep dips towards the center of the granite intrusion (from 10° at the contact to the country rocks to 55°–80° further inwards). These cone-sheets of mafic-hybrid dykes show that the associated basic magma was still active after major parts of the granite were solidified, sometimes mixing with remaining silicic magmas. This cone-sheet pattern is cross-cut by at least one dyke of QFP (Fig. 29).

Generally the Rödö dyke rocks are 1 to 5 m in width (exceptionally up to 150 m), often with a slightly irregular intrusion pattern; bending, bulging, or zig-zaging, especially the silicic ones. This contrasts with e.g. the Postjotnian dykes which are usually narrower than 1 m, and cut the country rocks with straight contacts.

2.4.3 GEOCHEMISTRY

2.4.3.1 Characterization and classification

The rocks of the Rödö complex have been plotted in the classification diagram of De la Roche et al. (1980) in Fig. 13b. All the silicic rocks classify as monzo- or syenogranites, whereas the basic-intermediate rocks spread from gabbro to syenite. There is, however, a general tendency towards a monzonitic trend, similar to that for the Åland rapakivi complex and the associated dykes of the Åland-Åboland dyke swarm. A number of HPFs and "contaminated" dolerites fall in the syenofields. These are the HPFs derived by mixing of the most evolved end members, as will be shown below.

No peralkaline rocks have been encountered in the Rödö suite, but the granites are metaluminous to slightly peraluminous (Fig. 16a). Alumina saturation increases markedly with fractionation in the QFPs.

Trace element classification diagrams generally indicate A-type geochemistry for the silicic Rödö rocks (Fig. 16b–c). Some of the QFPs and aplites, however, have low contents of especially Ce (LREE) and Zr, placing these rocks in the fields of orogenic granites. With regard to the Rb-Nb+Y diagram of Pearce et al. (1984), the Rödö rocks are transitional. Most of the granites actually plot in the volcanic-arc granite field, whereas most of the QFPs plot in the within-plate granite field. The Rödö rocks are therefore not as distinctly within-plate as e.g. the Suomenniemi rocks (cf. Rämö 1991). Some QFPs even fall in the syn-collision granite field due to an increased Rb content during fractionation. In Fig. 14a the composition of average Rödö granite is normalized to bulk crust (Taylor & McLennan 1985), and compared to averages for similar rocks. The Rödö granite is e.g. closely similar in chemistry to some other Swedish rapakivi granites, but tends to have the highest LREE contents. Compared to the average Finnish subalkaline rapakivi granites (Rämö & Haapala 1995) the Rödö granite is lower in most HFS and LIL elements.

The Rödö dolerites show a relatively distinct geochemical character in the trace element classification diagrams (Fig. 17). According to the classification of Pearce & Cann (1973; see Fig. 17a), they are within-plate basalts partly trending out of the classification fields towards the Zr-corner. This trend is partly due to contamination from the associated rapakivi magmas. In Fig. 17b (Meschede 1986) they classify as within-plate alkali basalts, and in Fig. 17c they generally fall in the field of continental basalts. The Rödö dolerites are much more distinct in continental within-plate character compared with the dolerites of the Suomenniemi swarm (Rämö 1991). However, comparing many elements in the MORB-normalized diagram of Fig. 14c, a general similarity in pattern is apparent for different rapakivi-associated basic rocks. The Rödö dolerites are most akin to the Strömsbro dolerites and slightly less so to the Mårdsjö gabbro, except for Th and U, which are clearly higher in the Rödö rocks. The Suomenniemi dolerites are generally higher in the HFS elements, and markedly similar to continental flood basalts, except for the LIL elements. The Postjotnian dolerites are generally lower in all HFS and LIL elements, except Nb.

2.4.3.2 Variation diagrams

The geochemical systematics of the Rödö suite rocks are displayed in selected Harker diagrams in Figs. 30–31. Postjotnian dolerites from the Rödö area and rocks from the Suomenniemi complex (Rämö 1991) have been included for comparison. The analyses of the dark schlieren segregations clearly fall off the trend of the rest of the samples of the rapakivi complex, showing high abundances of e.g. TiO_2, Fe_2O_3*, Zr, Y, Zn, Li, Th, REE except Eu, and low abundances of e.g. Al_2O_3, Na_2O, and K_2O (not all shown).

The silicic parts of the Rödö suite are characterized by a large variation in certain elements. The granites, granite porphyries, and the majority of the QFPs, however, show the typical rapakivi chemistry with low contents of e.g. MgO, CaO, P_2O_5, Al_2O_3 and Sr, but high contents of K_2O (generally between 5 and 6%), Rb, F, Ga, Zr, Hf, Th, U and the REEs (cf. e.g. Rämö 1991, Vorma 1976, Rämö & Haapala 1995). The strong variation in the silicic suite is manifested e.g. by increased contents of Al_2O_3 (up to 15.4%) in some QFPs, Na_2O (especially in the aplites, up to 5.08%), Rb (up to 2080 ppm), Cs (17 ppm), Nb (659 ppm), Ga (79), Y (193 ppm), Pb (55 ppm), U (75.2 ppm), Th (240 ppm), Li (226 ppm, especially the aplites), Be (10.2 ppm), the HREEs (Yb 21.4 ppm), and F (3820 ppm, Fig. 30).

Elements that show depletion in certain parts of the suite comprise: K_2O (down to 4.24%), Ba (39 ppm), Zr (18 ppm), Y (6.1 ppm), Be (1.1 ppm), the LREEs (La 8 ppm), the MREEs (Sm 1.6 ppm), Eu (0.2 ppm or less), and F (85 ppm). The total alkali content is generally high (c. 8–9%; Fig. 31), but decreases partly in the most silicic samples). The iron /magnesium ratio is generally high (FeO*/(FeO*+Mg) > 0.85; Fig. 31), which is typical for ra-pakivi rocks. In some of the QFPs, however, the iron-enrichment decreases to 0.69.

The Rödö dolerites (including those presumably contaminated and the mafic/hybrid enclaves) show a relatively large spread in composition, not least for SiO_2 (45.0 to more than 60%), where the limit towards the hybrid porphyries is gradual and overlapping. The limit has been set somewhat arbitrary to around 60% SiO_2, whereas the limit between dolerites and "contaminated" dolerites likewise has been set at about 55% SiO_2. Most elements show a considerable variation, e.g. K_2O (0.69–5.66%), MgO (0.58–7.79%), Ba (88–1280 ppm), Cr (<1–197 ppm), and Eu (0.7–3.4 ppm). Generally the Rödö dolerites are low in elements like TiO_2, Cr, V, Ni and Sc, whereas they are high in Na_2O, K_2O, Ba, Cs, and Eu. The high contents of alkali elements, especially in the "contaminated" dolerites (up to almost 10%), make them plot in the alkaline field in Fig. 31. Regarding the iron/magnesium ratio, this is generally substantially lower than in the silicic Rödö rocks, around FeO*/(FeO*+MgO) = 0.6–0.7, but some samples extend to higher values (0.93).

The hybrid porphyries generally have a composition intermediate between the dolerites and the silicic rocks. The petrological delimitation towards what could be called contaminated or hybridized dolerites, is as mentioned above somewhat arbitrary. Within the suite of hybrid porphyries two distinct groups can be separated with characteristic geochemistry: i) one group with markedly silicic composition (SiO_2 65.0–69.3%), somewhat overlapping with granites and QFPs, and ii) one group with more typical intermediate composition (SiO_2 c. 60–65%). These groups differ by showing divergent trends for many elements. The more silicic group e.g. exhibits a separate MgO-trend at higher contents (Fig. 30), whereas the intermediate group shows high

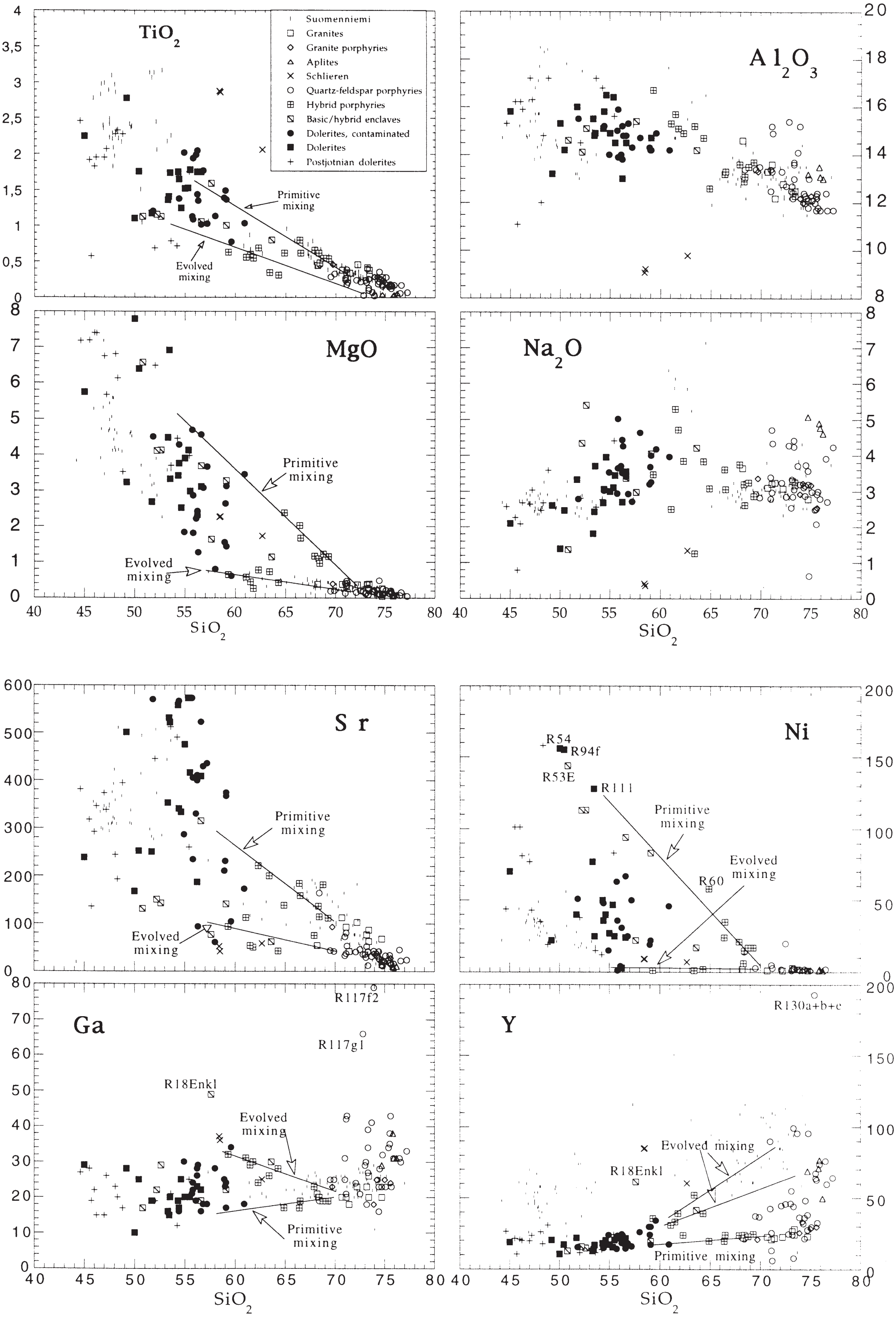
TiO2
Al2O3
MgO
Na2O
Sr
Ni
Ga
Y
SiO2
Suomenniemi
Granites
Granite porphyries
Aplites
Schlieren
Quartz-feldspar porphyries
Hybrid porphyries
Basic/hybrid enclaves
Dolerites, contaminated
Dolerites
Postjotnian dolerites
Primitive mixing
Evolved mixing
R54
R94f
R53E
R111
R60
R117f2
R117g1
R18Enkl
R130a+b+c
40
45
50
55
60
65
70
75
80

Fig. 30. Harker variation diagrams of selected major and trace elements for the rocks of the Rödö complex (Andersson 1997b). Rocks from the Suomenniemi complex (Rämö 1991) and Postjotnian dolerites (from the Rödö area) are included for comparison. The primitive and evolved mixing trends displayed by the two groups of HPFs are indicated (see text). Certain sample numbers are included.

alkali contents (Fig. 31). Also with regard to Al_2O_3, MnO, Cs, Zr, Nb, Ga, Y, Zn, Be, and REE, the intermediate group show trends at higher abundances, whereas the silicic group is higher in Sr, V, Ni, and Li (Figs. 30–31; not all shown). The intermediate group of hybrid porphyries is also strongly enriched in Fe compared to Mg, but the opposite is true for the silicic hybrid porphyries (Fig. 31).

The rocks of the Suomenniemi suite differ from the Rödö suite by having higher abundances of Fe_2O_3*, MnO, CaO, Ba, Y, Sc, Yb, and F in the silicic end of the suite. In the basic rocks of the suites a tendency for higher contents of Fe_2O_3*, Zr, Y, P_2O_5, Sc, and REE is observed for the Suomenniemi rocks (only partly shown). The latter are also clearly subalkaline in Fig. 31, and a tendency for higher FeO*/(FeO*+MgO) can be traced.

2.4.3.3 REE-patterns

Chondrite-normalized plots of selected rock groups in the Rödö suite and Postjotnian dolerites are shown in the diagrams of Fig. 32. The Rödö granites are enriched in the LREEs (La_N/Yb_N=25.6–39.4), with a distinct negative Eu-anomaly (Sm_N/Eu_N=4.6–9.9). The rocks of the dark schlieren structures are strongly enriched in the REEs (e.g. La up to 217 ppm and Yb up to 7.3 ppm), except Eu, and thus have deeper negative Eu-anomalies (Sm_N/Eu_N=22.7–26.6) than

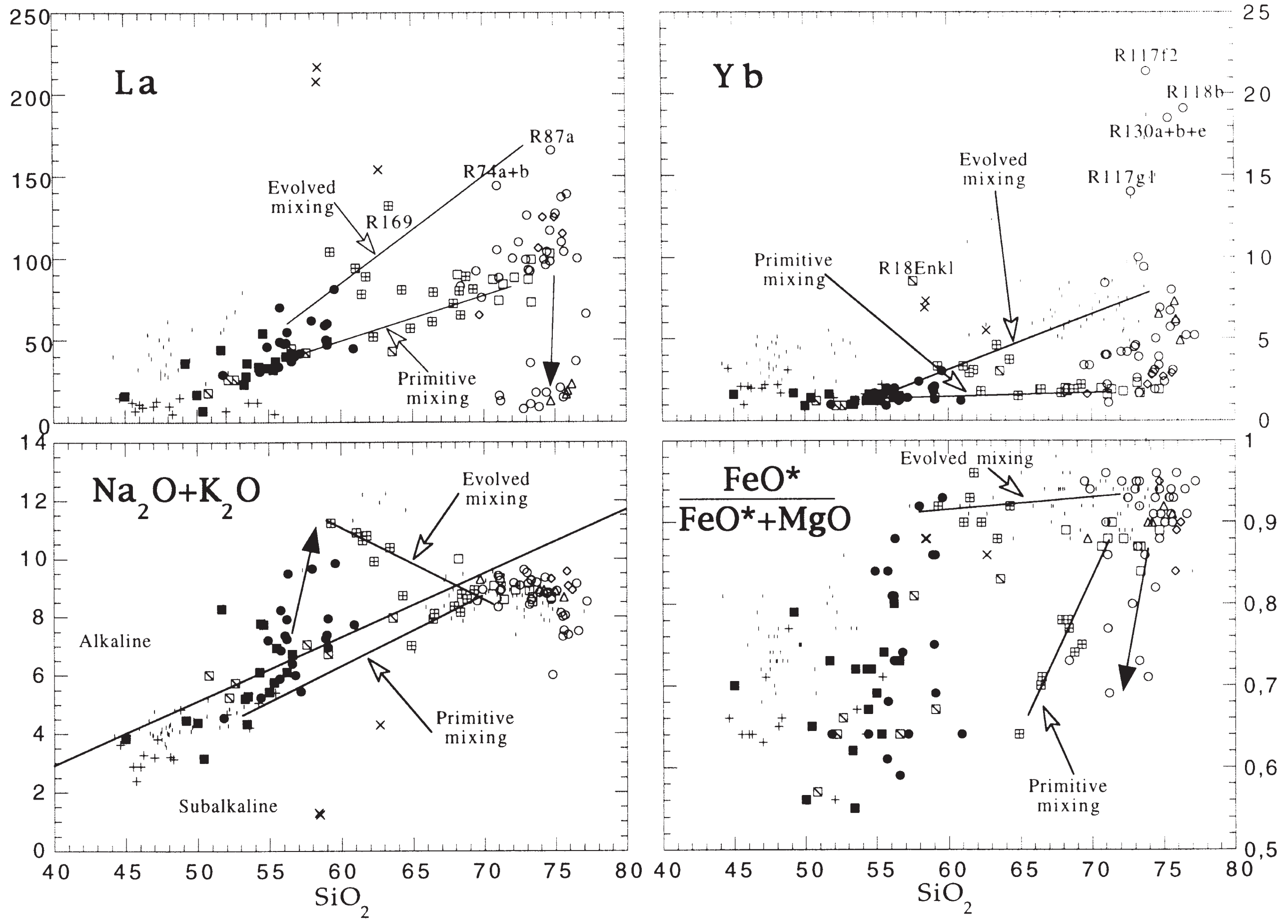

Fig. 31. Harker variation diagrams for selected REEs, total alkalies, and iron/magnesium ratios. Primitive and evolved mixing trends are indicated, as well as some fractionation trends (solid arrows). Some sample numbers are included. Legend as in Fig. 30.

the granites in which they occur. Otherwise their patterns are parallel to that of the granites. The majority of the QFPs have patterns very similar to that of the granites, however, they are generally slightly less enriched in the LREEs ($La_N/Yb_N=11.6–20.9$). The Eu-anomalies are partly deeper for the QFPs ($Sm_N/Eu_N=2.8–27.2$), compared to the granites. Another small group of QFPs has very different patterns, with strongly negative Eu-anomalies ($Sm_N/Eu_N=5.4– 20.1$) and enrichment of the HREEs instead of the LREEs ($La_N/Yb_N=0.39–6.4$). The absolute abundancies of the LREEs are sometimes very low (e.g. La down to 8 ppm), and very high for the HREEs (Yb up to 21.4 ppm). The aplites exhibit flat REE-patterns ($La_N/Yb_N=2.1–3.2$), with significant Eu-anomalies ($Sm_N/Eu_N=6.3–11.5$).

A majority of the Rödö dolerites have LREE-enriched patterns lacking an Eu-anomaly (Fig. 32). The patterns are slightly flatter than those of the granites ($La_N/Yb_N=14.3–22.8$). A number of "contaminated" dolerites have patterns with similar LREE-enrichments ($La_N/Yb_N=18.0–25.7$), but with a weakly negative Eu-anomaly ($Sm_N/Eu_N=1.6–4.0$; not shown.

The silicic group of hybrid porphyries has REE-patterns very similar to the granites, whereas the intermediate group has slightly weaker Eu-anomalies ($Sm_N/Eu_N=2.5–5.0$), and higher contents of HREEs ($La_N/Yb_N=14.8–19.4$). The basic/hybrid enclaves exhibit considerable similarity in REE-pattern to the xenocrystic ("contaminated") dolerites ($La_N/Yb_N=3.4$; not shown).

The Postjotnian dolerites have flat REE-patterns ($La_N/Yb_N=1.5–6.2$), compared to the Rödö dolerites, with in particular low abundancies of the LREEs (Fig. 32). Only weak tendencies for Eu-anomalies exist, negative or positive.

2.4.3.4 Interpretation

The geochemical characteristics presented above show that the silicic Rödö rocks belong to a metaluminous to peraluminous rapakivi suite, with an A-type signature (Fig. 16). The documented chemical spread in the silicic Rödö suite shows that strong fractionation has operated in the silicic part of the magma system. This fractionation partly follows typical rapakivi trends with e.g. increasing Na_2O, and Na/K (especially in the aplites). The trace elements that behave most incompatibly with high abundances in certain samples are Cs, Rb, Nb, Ga, Y, Pb, U, Th, Li, Be, F, and the HREE. Compatible are, except for the "mafic" elements, P_2O_5, Ba, Zr, LREE, MREE, and Eu, to some degree also F, Y, Be, and Li. Some of the QFPs and the aplites exhibit extreme differentiation with very high contents of incompatible elements, meaning that no minerals with high mineral/melt partition coefficients for these elements have crystallized. This means e.g. that biotite (Rb, Cs), columbite (Nb, Ta), or xenotime (HREE) are not part of the fractionating assemblage. The two latter minerals have, however, been encountered as minute grains in the most evolved QFPs. On the other hand, quartz, K-feldspar (K_2O, Ba) and plagioclase (Sr, Eu) are the major fractionating phases as evidenced by their ubiquitous occurrence as phenocrysts. Zircon (Zr, Hf, HREE, Y) has only preciptitated in certain parts of the system affecting some of the most evolved dykes but not others. The partly high F content in the magma may have increased the solubility of zircon and HFSE-oxides, e.g. columbite, $(Fe,Mn)(Nb,Ta)_2O_3$, in accordance with the experiments by Keppler (1993). Amphibole (Y, HREE), or perhaps clinopyroxene, may have fractionated in minor amounts in the early stages, but cannot have been a major fractionating phase in the advanced stages because of the strong increase in Y and HREE in the most evolved magmas.

During search for possible phases that could explain the strong depletion in LREE (and concomitant enrichment in HREE) in the most evolved rocks, relatively abundant grains of a reddish brown phase, often associated with fluorite, was encountered. Qualitative compositional data obtained on this material showed that it contained Ca-LREE (La, Ce, Pr, and Nd in varying proportions)-F as major elements, but no trace of HREE. The relative proportion of Ca and LREE was variable, and the grains were easily burnt under the electron beam of the microprobe. These qualititive results indicate minerals of the bastnäsite group (bastnäsite $LREE(CO_3)F$, parisite $CaLREE_2(CO_3)_3F2$, röntgenite $Ca_2LREE_3(CO_3)_5F_3$, synchysite $CaLREE(CO_3)2_F$; Burt 1989). This is consistent with the relatively high contents of both F and CO_2 in these rocks, seen in the abundance of fluorite and calcite. Bastnäsite minerals have been reported previously from the small Fjälskär rapakivi intrusion in SW Finland (Lahti & Suominen 1988). The fractionation of these fluorocarbonates can readily explain the depletion in LREE and incompatible nature of the HREE (Figs. 31–33). The studied grains are not found associated with the miarolitic cavities but as individual anhedral grains in the groundmass of schlieren, little evolved QFPs, but most frequent in some of the more evolved QFPs.

F is strongly partitioned into the melt phase as compared with the fluid phase (e.g. Webster 1990, Carroll & Webster 1994, Johannes & Holtz 1996) in peraluminous magmas, whereas CO_2 is much less soluble (Blank & Brooker 1994, and references therein). F, however, appears to be slightly more soluble in CO_2-containing magmas (Webster 1990). Experimental data and textural examination indicate that the LREE-fluorocarbonates in the silicic Rödö rocks may have precipitated directly from the F-rich rapakivi melts, but precipitation from a late exsolved fluid phase rich in CO_2 and F, where LREE and Ca are extracted from the melt and car-

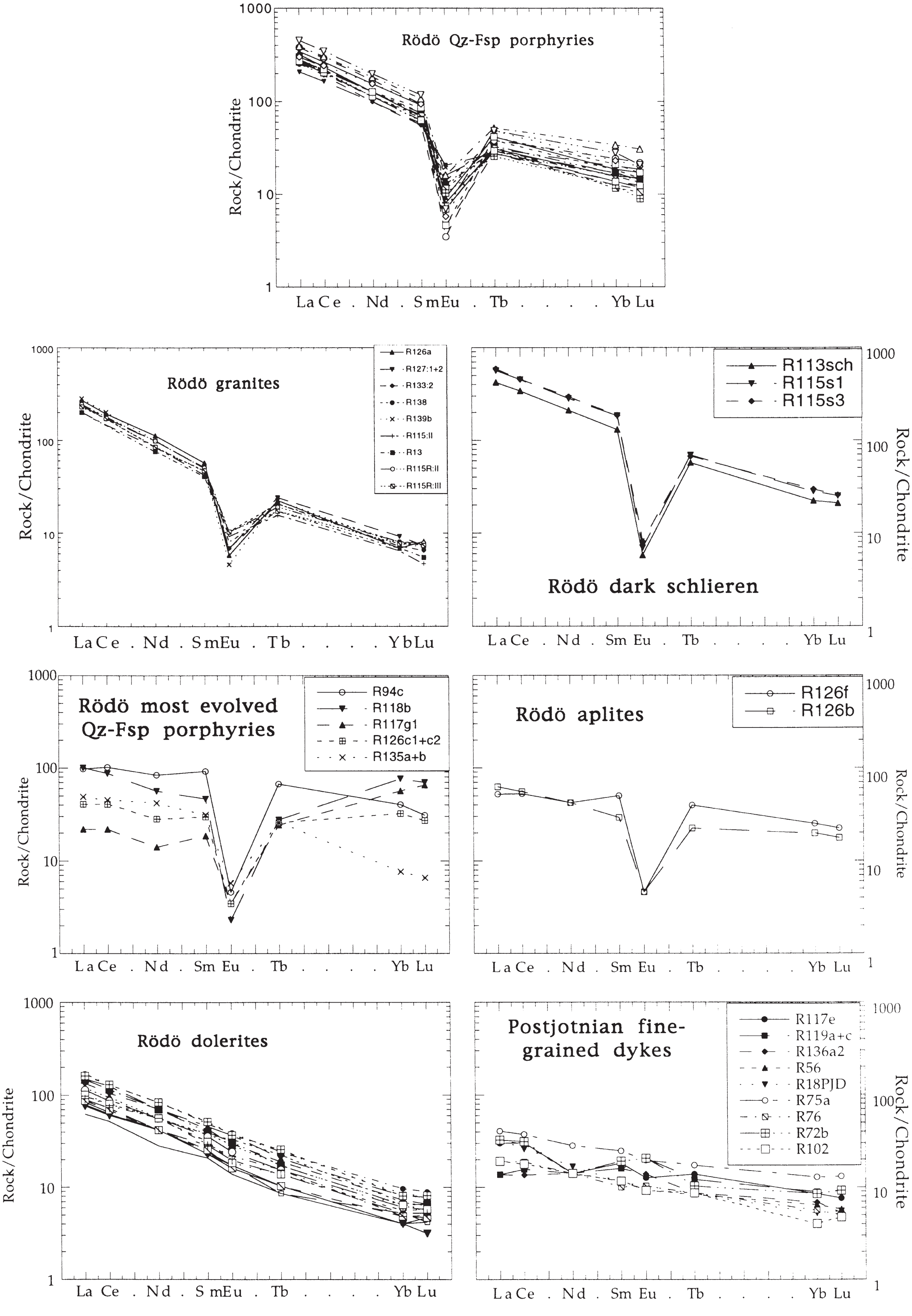

Fig. 32. Chondrite-normalized REE-diagrams of selected Rödö rocks (Andersson 1997b).

ried as carbonate or fluoride (or perhaps fluorocarbonate) complexes (e.g. Kosterin 1959, McLennan & Taylor 1979, Wendlandt & Harrison 1979), is also possible. Ekambaram et al. (1986) have discussed LREE-depletion in parisite-bearing magmatic-hydrothermal fluorite-carbonate desposits and ascribed it to complexing in a CO_2-F-rich fluid phase. The fluorite in the Rödö rocks does not contain any REEs. The extraction of fluorite together with the fluorocarbonates can account also for the sharp drop in the F content of the evolved rocks, down to 104 ppm (Fig. 33). Fig. 33 illustrates the effects of the accessory phases on the trace element geochemistry of the silicic Rödö rocks.

The dark schlieren structures are rich in Fe_2O_3*, TiO_2, Zr, Nb, Y, P_2O_5, Zn, and Li, but also REE (except Eu), and Th. These structures most probably mark channelways for the late fluid flow in the crystallizing granite, leaching out certain minerals (e.g. feldspars), and precipitating others (e.g. chlorite, zircon, apatite etc.).

The Rödö granites are assumed to represent the most primitive part of the silicic Rödö suite (the parental magma). If so, the negative Eu anomaly of the REE patterns of the granites indicates that plagioclase remains in the source. The LREE enrichment character of the patterns indicates the presence of one or more HREE-retaining phases in the unmelted source residue. Clinopyroxene, amphibole, garnet or zircon may contribute to this. A protolith giving these REE characteristics to a partial melt could very well be an orthogneiss, similar to the early Svecofennian country rocks. Crystal fractionation of this parental rapakivi magma commences with early quartz and K-feldspar in a lower/middle crustal magma chamber, followed by plagioclase during/after emplacement in response to decreasing pressure (cf. e.g. Nekvasil 1991, Eklund et al. 1996a; decreasing Eu and Ba, increasing REE), and minor apatite, amphibole, Fe-Ti oxides (decreasing P, Fe, Ti, Mg, Ca etc.), and partly zircon. In the most evolved stages extraction of LREE-fluorocarbonates and fluorite caused the depletion in LREE and F.

The basic to intermediate dykes are characterized by large variability in geochemistry (Fig. 30). The alkali-rich character of the more contaminated dykes is clearly displayed in the Na_2O+K_2O diagram (Fig. 31). Partly the chemical spread can be ascribed to the contamination by the

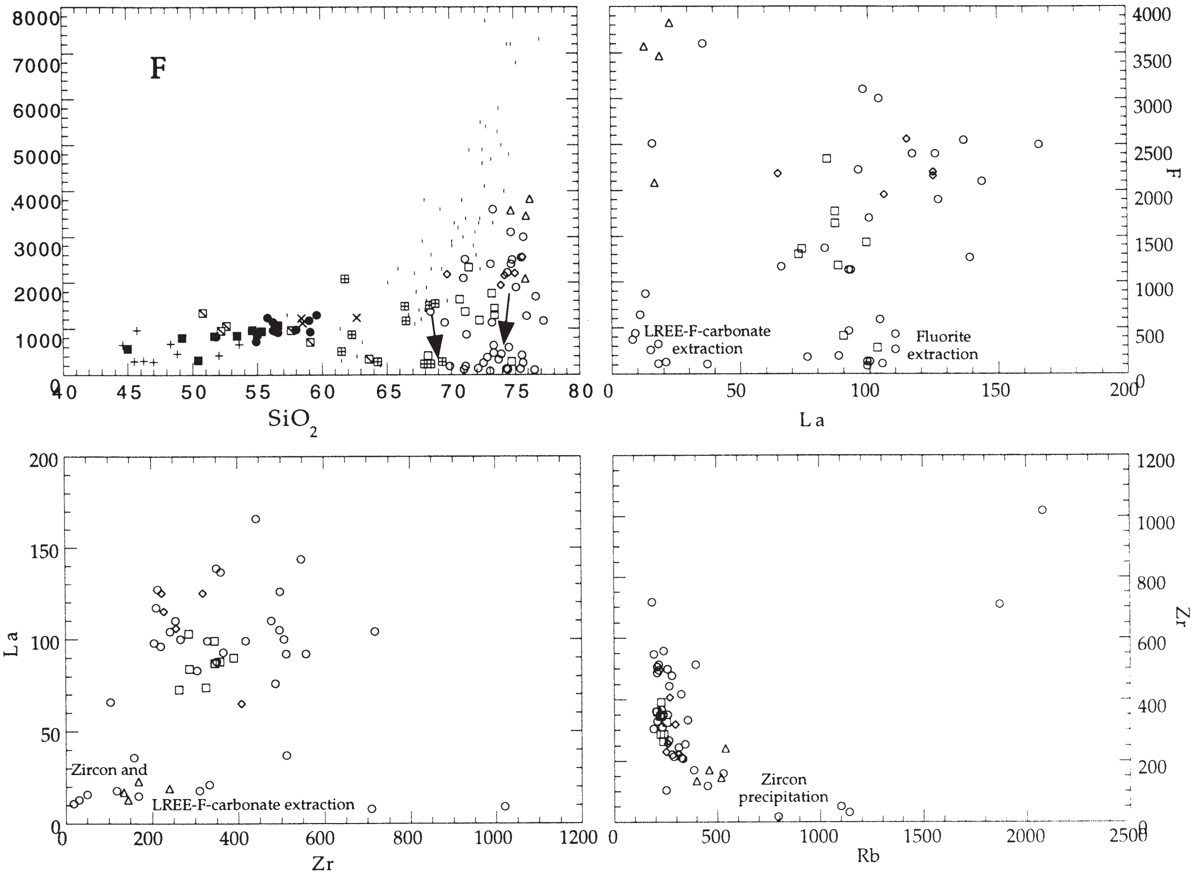

Fig. 33. Variation diagrams for certain elements selected to illustrate the influence of accessory phases in the geochemical evolution of the silicic Rödö suite. Solid arrows indicate F extraction (by fluorite+LREE-fluorocarbonates). Legend as in Fig. 30. See text for discussion.

associated silicic magmas, which is manifested by xenocrysts of K-feldspar and quartz, but partly this enrichment may be related to fractionation of plagioclase, Fe-Mg silicates and Fe-Ti oxides within the basic suite.

The marked LREE enrichment of the Rödö dolerites, usually without any Eu anomaly, seems to be a primary feature, which distinguishes them from the Postjotnian dolerites which are only very slightly LREE-enriched. A relatively low percentage of melting of a mantle source containing pyroxene but not plagioclase can give a REE pattern like that of the Rödö dolerites. The Postjotnian dolerites, on the other hand, seem to have been generated by a larger degree of melting of a similar source, giving a lower LREE enrichment. The reason may also be that the mantle sources were different, having different degrees of enrichment or depletion. Tendencies for both positive and negative Eu anaomalies can be detected for the Postjotnian dolerites, and can be interpreted as resulting from incipient plagioclase precipitation. The more xenocrystic/hybridized of the Rödö dolerites usually show a distinct negative Eu anomaly, but not as pronounced as the silicic rocks. Free plagioclase phenocrysts occur relatively abundantly in the dolerites and may partly have fractionated out and contributed to the anomaly. Another explanation is that the hybridization with the silicic magmas may have affected also the Eu characteristics of the hybridized dolerites. This latter explanation is also supported by the fact that the dolerites with these anomalies generally seem to be more mixed with the silicic magmas.

The most silicic hybrid porphyries have REE patterns very similar to the granites (Fig. 32). This is not surprising since their chemistry as a whole is close to that of the granites. The HREE content of the intermediate hybrid porphyries tends to be higher than in the silicic hybrid porphyries, and thus resembles the QFPs more. These two types of hybrid porphyries differ geochemically in several other respects. This means that they do not belong to the same mixing series between the same end member magmas, which is also supported by the textural differences. The silicic hybrid porphyries have large megacrysts of feldspar (≤3 cm) and quartz (≤1 cm), which closely resemble those of the Rödö granite. The megacrysts of the intermediate hybrid porphyries are generally smaller (≤1 cm) and more akin to those encountered in many QFPs.

The diverging trends between the two types of hybrid porphyries are most clearly seen for MgO, Al_2O_3, Sr, Zr, Ga, Y, V, Ni, and the REEs (Figs. 30–31). The silicic hybrid porphyries are thus the result of mixing between a silicic end member corresponding to the Rödö granite and a basic end member corresponding to some of the least evolved (more primitive, with e.g. higher MgO contents etc.) parts of the dolerite suite. The other hybrid porphyries have more evolved end members: a fractionated (but not strongly fractionated) QFP magma as the silicic end member mixed with some of the most evolved parts of the basic suite. The most fractionated QFPs and the aplites do not have any matching hybrid porphyries, intermediate to the dolerites, suggesting that the fractionation in the silicic magma continued after the mixing processes had ceased.

It is also clear that the mixing between the granite and the primitive dolerites must have occurred before that beween the QFPs and the evolved dolerites, which also must mean that there is a corresponding succession in age between the different types of dykes. This type of age relation has only been possible to verify in very few instances in the field, since Rödö dykes crosscutting each other are very rarely exposed. At one locality on Rödön, however, a strongly evolved QFP can be seen to cut a dolerite. Another, not completely exposed, seems to indicate that a highly evolved QFP cuts the silicic (early) hybrid porphyry on Spikarö. The geochemical trends can thus be used to infer the relative geologic age of the dykes even if no contacts are exposed.

The basic/hybridized enclaves generally follow the trend of the basic suite, at relatively primitive compositions seen e.g. from the relatively high Ni and Cr contents. Most of the analysed enclaves occur in the silicic hybrid porphyries of the early mixing episode, and should thus be rather primitive. One of the analysed enclaves, however, differs markedly. This one occurs in one of the most evolved QFPs (on Skorven, Stop 6:5 below), and has anomalously high contents of Rb, Nb, Ga, Y, U, and Yb (Figa. 30–31), while having especially low contents of the "mafic" elements. This shows that this enclave represents a blob of magma from the most evolved dolerites, mixed with a strongly evolved QFP.

2.4.4 AGE

Nine fractions of zircons of different types and sizes were handpicked. Two of these were air-abraded. The zircons were of two different types, one long prismatic with a length:breadth ratio around 4:1, and one shortprismatic with a length:breadth ratio around 1:1. The former were generally brown and turbid, but with well developed crystal forms. The latter were clear, slightly yellow, also with sharp crystal forms. All the 9 fractions give a poor discordia with an upper intercept age of 1500±26 Ma (MSWD=22). The relatively large MSWD value indicates a relatively large scatter among the fractions, more than can be accounted for by analytical errors. The two abraded fractions (R9 and R10) are the most concordant. They yield $^{207}Pb/^{206}Pb$ ages of 1490 and 1503 Ma, respectively. One fraction is above the concordia curve (R4). If this fraction together with those that are slightly displaced to the right of the discordia (R1, R2, R6) are omitted, the statistically best constrained age is calculated (1497±6 Ma, MSWD=1.3; Fig. 34).

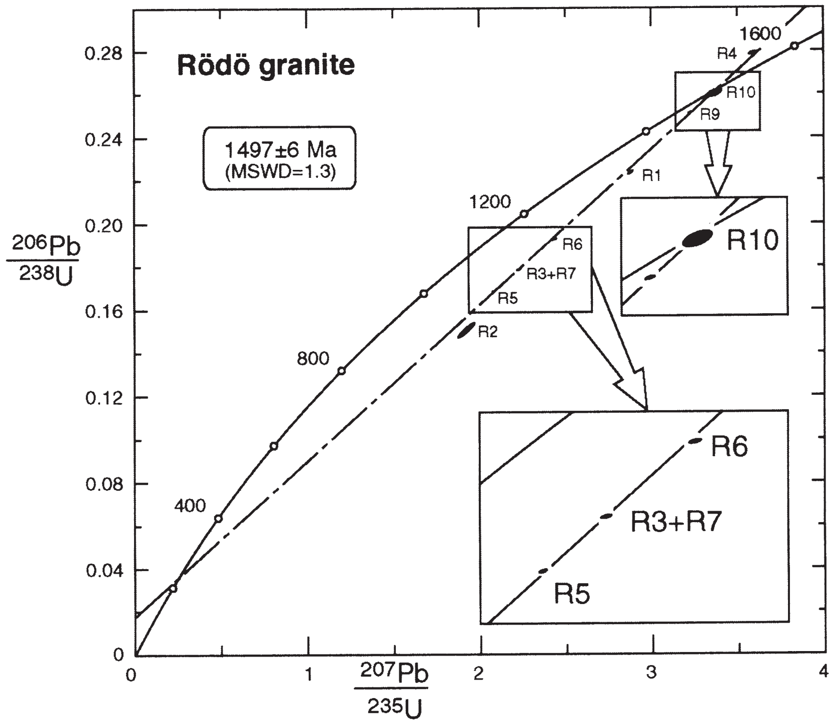

Fig. 34. Concordia diagram for the Rödö granite. Fractions R1, R2, R4, and R6 have been omitted in the calculation of the preferred age of 1497±6 Ma. See text for discussion.

Welin (1994) has previously determined a U-Pb zircon age from 4 zircon fractions to 1513±5 Ma. The analytical quality of the data points is, however, not stated. The scatter obtained in the U-Pb data of this study significantly exceeds the analytical errors (MSWD values >>1), suggesting involvement of geological factors, such as e.g. remnants of older cores. The analysed fractions plotting slightly to the right of the discordia may contain an older component. Such a component is either minor in volume and much older, or relatively large in volume but only slightly older, since the points are still close to the discordia. The former alternative is more likely in the light of the low ε_{Nd} values for the Rödö granites and associated rocks (chapter 2.4.5), suggesting a major Archaean input to the magmas. Thus a small amount of zircon material of possibly Archaean age is suggested by the data, even though no specific inherited type of zircons has been identified, such as in the case of the Nordsjö monzonite (Andersson 1997b, Claesson et al 1997). The fraction plotting above the concordia (R4) has most likely experienced U loss due to incomplete digestion of the crystals, where some of the bounded U (but not the more loosely bound Pb) was lost. Thus, 1497±6 Ma is the preferred age estimate, as it probably reflects only a minimum influence of older components. This age is slightly but possibly significantly lower than the 1513±5 Ma age obtained by Welin (1994). Based on these results one may argue that the age reported by Welin (1994), calculated from only 4 fractions, may also contain unidentified older components, giving a slightly too old intrusion age.

A Sm-Nd whole-rock isochron was calculated from the data on the silicic Rödö rocks (Andersson 1997b). This gives an age of 1608±45 Ma (MSWD=0.53), which is an isochron of acceptable quality. The basic and intermediate rocks do not give any meaningful age results. All but one sample fall within analytical error on the isochron line. This leads to an about 110 Ma too old age compared to the U-Pb age suggested above. There is a large spread in the ^{147}Sm/^{144}Nd ratios, but only a few samples exist with very high ratios. These samples therefore have the largest impact on the isochron calculation, and small errors in their determined values will have relatively large effects on the determined age. Any difference in the initial ^{143}Nd/^{144}Nd ratios in the system would make the isochron unreliable. If the 1497 Ma U-Pb age is accepted as the true intrusion age, the calculated initial ε_{Nd} values of the whole rocks show a significant spread, where the samples with the highest Sm-Nd ratios have the highest ε_{Nd} values. This means that those samples which have the largest impact on the isochron calculation probably had higher initial ^{143}Nd/^{144}Nd values compared to the others, giving a too high age estimate. The reason for this remains unclear since the geochemistry (above) indicates that they have evolved in the same silicic magma system as the other samples, and the spread in space is also restricted. No specific evidence indicates that just these rocks have a different age or suffered a later change in their Sm/Nd ratios.

2.4.5 ISOTOPIC DATA

The intial (at 1.50 Ga) ε_{Nd} ratios for the silicic Rödö rocks are between -7.4 and -4.8, and for the basic-intermediate rocks between -8.9 and -6.9. There is thus a tendency for somewhat lower values in the associated basic rocks. The most evolved silicic rocks have the highest initial values and very high $^{147}Sm/^{144}Nd$ ratios (0.1454–0.2204), suggesting LREE-fractionation (see geochemistry section). The Rödö granites, on the other hand, have low $^{147}Sm/^{144}Nd$ ratios (0.0928–0.0960). The low ε_{Nd} values strongly suggest Archaean components in both the Rödö silicic and basic magmas. These characteristics are closely similar to those of rocks from the Ragunda (Persson 1996) and other complexes in Jämtland and Ångermanland (Andersson & Neymark 1994, Andersson 1997b). The generally slightly lower initial ε_{Nd}-values for the associated basic rocks indicate that these have been crustally contaminated (assuming a depleted mantle origin) with material containing a higher proportion of Archaean components compared to the crustal sources of the rapakivi granite magma.

The Sr isotopic system is severely disturbed in the Rödö rocks, and gives reasonable initial values only for a few basic-intermediate rocks. It will not be discussed further here. Limited Pb-Pb WR data from the silicic Rödö rocks (Andersson 1994, 1997b) are in accordance with the Nd isotopes and suggest involvment of Archaean lower crustal sources. The interpretation of the isotopic data is discussed in more detail in chapter 2.1.7 above.

2.5 The Strömsbro Complex

U. B. Andersson

2.5.1 BACKGROUND

The Strömsbro granite and its Subjotnian nature have been known for more than 100 years. It is e.g. noted by Högbom (1893) that "the insignificant cliffs of red granite by Strömsbro near Gefle are closely connected petrographically to the closest parts of the rapakivi province, namely the Nystad (Laitila/Vehmaa) and Åland massifs" (translation by the author). However, since the massif is very small (c. 8 x 1.5 km; cf. Fig. 35) and only few outcrops occur (seven localities are known to the present author), it has been little studied. The Strömsbro granite was briefly touched upon by e.g. Blomberg (1895), Högbom (1910) and Lundegårdh (1967), but was more thoroughly described by Asklund (1930, 1939). Modern geochemical and isotopic approaches have not been applied until recently (Andersson 1997a).

The massif is truncated in the south by the Gävle graben filled with Jotnian sedimentary rocks. The latter have been intruded by Postjotnian dolerite dykes and sills (Törnebohm 1877, Asklund 1939, Gorbatschev 1967). In the basal parts of the Jotnian sandstone sequence conglomerates containing Strömsbro granite clasts have been found, although the actual contact has not been observed (Högbom 1910, Asklund 1930, Gorbatschev 1967). In these conglomerates boulders of rapakivi-type quartz-feldspar porphyries occur abundantly. This type of porphyry has not been observed in outcrop, but it appears likely that it is a part of the basement of the Jotnian graben successions in this area. Furthermore, it occurs especially as abundant boulders on the shores of some of the islands in the southern part of the Gävlebukten Bay (Asklund 1939). Thus, the rapakivi rocks in this area may have a considerably wider extent in the basement of the sandstone within the graben structure. The Subjotnian label for the Strömsbro rapakivi is therefore especially adequate.

2.5.2 GRANITOIDS

Since the granite in no place has been observed in contact with the surrounding early Svecofennian ortho- and paragneisses, its post-Svecofennian nature has been inferred by petrographical and structural similarities with other massifs (e.g. Högbom 1910, Asklund 1939). It is totally isotropic with no structural or metamorphic overprint, and similar in colour (brick red) and petrographical characteristics to other rapakivi granites.

The granite contains megacrysts of strongly perthitic K-feldspar. The megacrysts are somewhat elongated (usually c. 2 x 1 cm) and rounded, often irregular. They are never overgrown by plagioclase, and according to the texture the rock thus classify as somewhere in between pyterlitic and porphyritic rapakivi, according to Finnish terminology (e.g. Vorma 1976). The granite is similar to the Jämtland and Nordingrå rapakivi granites, but is generally somewhat more coarsely porphyritic. Larger (<0.5 cm) quartz grains are sometimes roughly rounded, but not as distinctly as in e.g. the Rödö granite. In some varieties the K-feldspar shows microcline twinning, in others not. The groundmass is usually granular, containing quartz, K-feldspar, plagioclase, and chlorite. Here and there quartz and K-feldspar form micrographic intergrowths. The K-feldspar is strongly pigmented, and brown in thin section. Chlorite in pseudomorphs, presumably mostly after biotite, is the only mafic mineral. Secondary opaque phases are associated with the chlorite, as are relatively abundant apatite and zircon crystals. At locality 10 the rock is also especially rich in fluorite.

A finer grained granite porphyry type occurs at one local-

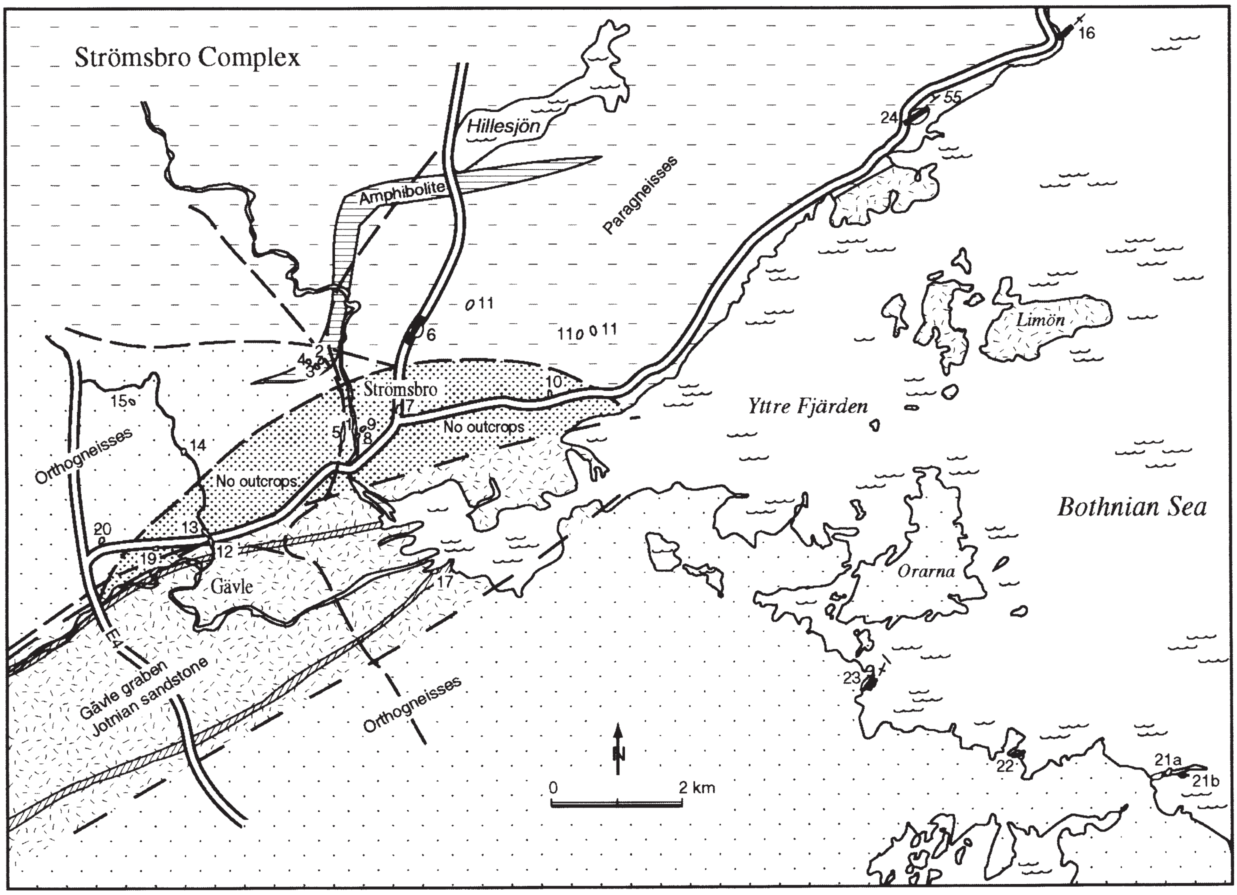

Fig. 35. Simplified geology of the Strömsbro area (after Asklund 1939). Suggested outline of the intrusion based on the few localities, marked by dense stipples. The Strömsbro rocks most likely extends southwards beneath the Jotnian cover in the graben. The stop will be at the locality labelled 1 (and possibly 5). Rocks marked by ruling in the sandstone are Postjotnian dolerites. Rapakivi-associated dolerites are marked by thick black lines.

ity (9). A specific type of an even more strongly altered dark, brick red rock occurs at locality 13. This type contains no mafic minerals but abundant opaqes, and calcite in spots.

2.5.3 ASSOCIATED DOLERITES

A few dolerite dykes have been suggested to be related to the Strömsbro granite. Six occurrences were mentioned by Asklund (1939), of which one crosscuts the granite. Four of these have been documented by the present author (Fig. 35; Andersson 1997b). The one crosscutting the granite unfortunately appears to have been blasted away. The four dykes were all emplaced relatively far away from the granite outcrops, but not necessarily far from Strömsbro rocks beneath the Jotnian cover, east of the exposed massif (Fig. 35). Two of the dykes occur south of the graben and two north of it. They all strike NE with steep dips, and are less than 5 m wide. They are distinguished macroscopically from the Postjotnian dykes primarily by lacking the ophitic texture, being brownish black and very fine-grained, and in some instances containing plagioclase phenocrysts up to 2 cm in size (locality 22).

The groundmass contains laths of strongly sericitized plagioclase. In between these laths, usually fine-grained secondary mafic minerals occur (presumably mostly chlorite and/or amphibole) together with opaques, and abundant calcite. In some cases primary clinopyroxene has survived relatively well.

2.5.4 GEOCHEMISTRY

2.5.4.1 Silicic rocks

The silicic rocks are metaluminous and generally plot in the field of monzo- and syenogranites of De la Roche et al. (1980; see Figs. 13 and 16). They show typical A-type and within-plate characteristics in the trace element classification schemes of Whalen et al. (1987) and Pearce et al. (1984). See Fig. 16. In these diagrams the Strömsbro rocks seem to be most akin to the Rödö rocks. In the spider plot in

Fig. 14, the average Strömsbro granite has similar trends as other Fennoscandian rapakivi granites. The Strömsbro granite, however, differs by having lower Cs and Li contents, but higher Th, U, and HREE, compared to other Swedish rapakivi granites. With respect to the high Th, U, and HREE contents it approaches the average Finnish subalkaline rapakivi granite of Rämö & Haapala (1995).

These higher HREE contents (10–40 times average chondrite) compared with the Rödö and Jämtland granites, which are all lower than 10 times chondrite, effectively preclude garnet and zircon as residual phases after extraction of the Strömsbro magma, probably also clinopyroxene. Residual plagioclase is indicated by the pronouncedly negative Eu-anomalies and may be accompanied by orthopyroxene. The most evolved of the Strömsbro granites (sample/locality 10) is slightly enriched in all REEs (except Eu, Fig. 14a) relative to the other granites, indicating that no REE containing phase (such as zircon, apatite, clinopyroxene) have been separated during this evolution.

2.5.4.2 Dolerites

The dolerite dykes plot in the gabbro to monzodiorite fields of De la Roche et al. (1980). In the trace element classification diagrams of Fig. 17, the Strömsbro dolerites differ from the rest of the Swedish rapakivi-related dolerites by having relatively higher Y and Nb contents. They show transitional characters between the Suomenniemi dykes (Rämö 1991) and Postjotnian dolerites (Andersson 1997a). This may indicate that some of them have been misinterpreted as Subjotnian dykes and actually are Postjotnian. In the Zr-Ti/100-3 x Y-diagram of Pearce & Cann (1973) they are transitional into the calc-alkali basalt field (together with the Suomenniemi dykes), whereas in the Zr/4-2 x Nb-Y-diagram of Meschede (1986) they appear to trend towards a tholeiitic volcanic-arc character, and in the La/10-Y/15-Nb/8-diagram of Cabanis & Lecolle (1989) they extend across the fields of continental basalts and alkali basalts from intercontinental rifts. The reason for these divergences are presently not known.

In the spiderplot of Fig. 14 the dykes show a relatively strong resemblance with other Fennoscandian rapakivi-related basic rocks, although discrepancies involving Nb and Y are observed also here. A significant similarity with the continental flood basalt average (Thompson et al. 1983) is noted, as well as the enriched character relative to MORB for all “incompatible” elements. Some kind of enrichment in these elements must have occurred, either in the mantle or by assimilation in the lower crust.

2.5.5 ISOTOPIC DATA

2.5.5.1 U-Pb geochronology

Recently obtained U-Pb isotopic data from zircons indicate an age of 1500±19 (MSWD=1.7) Ma for the Strömsbro granite (Andersson 1997a). The granite is very rich in zircons of a homogeneous type. These were unfortunately dominantly brown and turbid, and thus markedly discordant. Five out of eight fractions are included in the discordia calculation. The other three lie off this discordia to the right. Two of them are the most discordant and trend towards origo. They may be affected by recent lead loss, while the third has a large analytical uncertainty. Although not very well constrained, the age obtained falls in the same range as other rapakivi granites in Sweden (1526–1496 Ma, except Nordingrå, which is 1578 Ma), confirming that the Strömsbro complex belongs to this youngest group of westerly complexes in the shield (see chapter 2.1).

2.5.5.2 Nd isotopes

Samples of Strömsbro granite and one Strömsbro dolerite (loc. 16) have been analysed for Nd isotopes (Andersson 1997a). Initial (1.50 Ga) ε_{Nd} values range between -5.7 to -4.6 for the Subjotnian rocks. The values for the Strömsbro rocks are encompassed by the time-integrated evolution of the early Svecofennian metaigneous rocks (Fig. 18), similarly to other rapakivi complexes in the shield (Nordingrå, Åland, and SE Finland; Rämö 1991, Andersson 1994, Lindh & Johansson 1996, Andersson, Fröjdö & Eklund in prep.), although they fall in its most negative part. A derivation of the silicic Strömsbro magmas from lower crustal sources composed dominantly of such material thus appears as an attractive model (cf. e.g. Rämö 1991, Andersson 1997a, and chapter 2.1). Archaean source material may, however, be important also in this area, as is indicated by the equally low initial value recorded for the associated dolerite. Unless enriched mantle sources are invoked, the dolerite magma must have assimilated a significant portion of Archaean source material to obtain this low value. Svecofennian material having $\varepsilon_{Nd(1.50)}$ as low as -6.0 will have to be assimilated in proportions of 70–90% to give ε_{Nd} = -5.2 for the mixture, which is highly unrealistic. Archaean material therefore probably contributed significantly to the silicic Strömsbro magmas as well, since the latter presumably were generated spatially close to the place where the basic magmas were contaminated.

3. EXCURSION ROUTE

This excursion route was used in 1996.
The coordinates are in the Swedish national grid system.

Day 1. Wednesday, July 17th

“LATE SVECOFENNIAN” A-TYPE GRANITES IN BERGSLAGEN AND THE “POST-SVECOFENNIAN” SMÅLAND–VÄRMLAND I-TYPE GRANITOIDS

1:1 The Bispberg granite

a. Bispberg: Svecofennian volcanic rocks (669340/ 149860)

Fine-grained pink felsic metavolcanic rock belonging to the 1.9 Ga supracrustal sequence of Bergslagen. The rock displays only weak foliation and shows occasional phenocrysts. It forms part of the host rock sequence to the BIF-type iron ores, which were mined at a number of sites in Bergslagen.

b. Bispbergs klack: “Late Svecofennian” anorogenic granite (669320/150055)

Slightly porphyric granite with K-feldspar, biotite, quartz. Fractures and joints in a number of directions are common in the granite. Some of the fractures are filled with cm-wide veins of quartz. The main fracture zone runs in N–S direction and forms a major fault zone with downward movement of the eastern block. Two sets of dolerite dykes can also be distinguished at Bispberg, both post-dating the granite.

The site is also of cultural interest because of the Royal inscriptions of Carl, Oscar and Gustaf who visited this place in the 19th century.

c. The Mo deposit at Bispbergs klack (669335/150075)

Significant molybdenite deposit, which was mined during World War II. Cronstedt and Scheele investigated molybdenite and scheelite from this place in the 18th century, which led to the discovery of tungsten and molybdenum. Recent investigations of molybdenite by means of the Re-Os method has led to the first reliable age determination of the Bispbergs Klack deposit yielding ages between 1780 and 1800 Ma (Sundblad et al. 1996).

1:2 The Högberget granite and the Wigström mine

a. The Högberget granite (665040/145465).
b. Veins of the Högberget granite in Svecofennian supracrustal rocks (665045/145460).
c. The Wigström skarn deposit (665050/145450).

1:3 The Skålhöjden granite (663775/142225)

Intensely red granitic rock in the central part of the Skålhöjden pluton.

1:4 Filipstad: undeformed Värmland granitoid (662290/140915)

Coarse-grained Värmland granitoid belonging to the Transscandinavian Igneous Belt. Locally occurring wiborgitic textures are worth noting, but are not typical of the Filipstad granitoid. A U-Pb determination of zircon has been carried out at this site yielding 1783±10 Ma (Jarl & Johansson 1988), which is in agreement with other ages of TIB in most parts of the Småland–Värmland belt (cf. Mansfeld 1991).

Day 2. Thursday, July 18th

THE DALA GRANITOIDS AND PORPHYRIES AND THE RÄTAN GRANITOIDS

Excursion localities are shown on the map, Fig. 4.

2:1 Vantjärnsboren: Järna granitoid (671440/140980)

Small fresh road cut with brick red microcline-porphyric Järna granitoid. At this locality the typical texture of the porphyric type of Järna granite is displayed. Occasional rapakivi textures appear in local boulders. The granite contains different types of inclusions, occurring as small (2–4 cm) black and white enclaves and aggregates of mafic minerals.

2:2 Eldberget: Siljan granite and greisen veins (672555/140825)

In the early eighties a major prospecting operation was made at this place. The forest was harvested, a number of prospecting trenches were dug and a number of drill-holes were made. The place was abandoned in connection with the tin market collapse in 1985. Today, the vegetation is wild and the trenches are refilled.

a) Two large outcrops of brick-red Siljan granite occur near the top of the hill. In one of these a sample for U-Pb dating was collected, yielding an age of 1681±16 Ma. Geochemical data are presented as sample MA 90077 in Table 3.

b) A hundred metres downhill and some thirty metres through heavy vegetation, remnants of the exploration trenches are found. Greisen veins are exposed in a number of local boulders.

2:3 Oxberg: Garberg granite (678180/141116)

Red, feldspar- and quartz-porphyritic Garberg granite, forming a high-level intrusion in the surrounding Dala volcanites and the ”Digerberg formations”. The chemical composition is shown in Table 4, no. 12, and in a REE plot in Fig. 8. This type of granite grades into more syenitic varieties. The U-Pb zircon age of Garberg granite from this locality is 1706+15/-13 Ma (Th. Lundqvist & P.-O. Persson in prep.).

2:4 Blyberget: Dala porphyry (678385/141175)

A short walk uphill brings us to the old Blyberget porphyry quarries. The Blyberget porphyry was the most extensively used raw material for ornamental stone in the old Älvdalen factories. For instance the grave monument of Carl von Linné in the cathedral of Uppsala, and the big obelisk near this cathedral were made of the Blyberget porphyry.

The porphyry at Blyberget is an ignimbritic, dark brown, aphanitic rhyolite with grey or pink, millimetre-size phenocrysts of perthitic K-feldspar and albite. Pink ignimbrite flames mark a subhorizontal structure. Epidote schlieren occur.

2:5 Älvdalen: Porphyry museum (679190/140408)

The museum at Älvdalen shows geological maps of the area and various porphyry types which have been used as ornamental stones. Examples of vases, urns and other products from the old Älvdalen porphyry factories are also shown. The history of the porphyry works at Älvdalen is also illustrated. In many cases stones were selected for use among moraine boulders or among the cobbles and pebbles of the rivers of the region. A few, like the Blyberget quarry which we have just seen, were quarried from the bedrock. Also the Garberg granite, of the type shown by the first locality, was used, especially for bigger products like the sarcophagus of King Carl XIV Johan (Riddarholmskyrkan church, Stockholm), and large vases. The reason for this is that the granites generally display more widely spaced fractures than the porphyries.

2:6 Tandhem: Phenocryst-rich Dala porphyry (684140/144470)

This Dala porphyry is a quartz-trachytic variety rich in centimetre-size feldspar phenocrysts, which occur in a microcrystalline groundmass of mainly quartz and feldspar. The phenocrysts are perthitic alkali feldspar and plagioclase (andesine-oligoclase). Perthite mantles are seen on the plagioclase. The composition has been interpreted to be a consequence of cumulative enrichment in feldspar (Lundqvist 1968). Porphyries of this type are also enriched in zircon, apatite and dark minerals, and have more An-rich plagioclase in comparison with porphyries with smaller and fewer feldspar phenocrysts, like the Blyberget porphyry of locality 2:4. They also show a greater frequency of (Svecofennian) xenoliths, in the case of this locality consisting of quartzite/arkose, meta-argillite, metabasalt etc. There are also dykes or inclusions of granite porphyry, the character of which is uncertain due to insufficient exposure. The porphyry at Tandhem was earlier interpreted as a volcanic rock (Lundqvist 1968), but later mapping (Sjöblom & Aaro 1987a) showed that it is in fact intrusive (subvolcanic). The Tandhem porphyry is cut by two dykes of granophyre belonging to the Dala granites.

2:7 St. Halvar–Jonsberget: Rätan granitoid (686455/143785)

At this locality the Rätan granitoids are exposed in large road cuts displaying a rather syenitic variety (Table 2, sample number MA 94629). Both gray and red granite varieties can be seen. The texture is very characteristic for the porphyric type of the Rätan granitoids. Small black and white enclaves as well as mafic schlieren occur in the granitoid. The porphyric variety of the Rätan granitoid is cut by irregular, fine-grained, red aplitic granite veins, which show a dm-wide contact zone between the granitoid and the aplite. Furthermore, an enclave of a dark fine-grained rock is seen with K-feldspar porphyroblasts at the border between the porphyric Rätan and the fine -grained aplitic part.

2:8 Sålnberget: Deeply weathered Rätan granitoid (676960/142795)

At this site a strongly weathered outcrop of the Rätan granitoids can be examined. The weathering has been so intense that the site is used commercially for gravel. This phenomenom can be compared with what locally can be seen in the rapakivi plutons in southern Finland (rapakivi = rotten rock in Finnish language). The weathering is probably of Precambrian age and is interpreted to have been preserved by an earlier cover of Cambrian sedimentary strata and Caledonian nappes.

Day 3. Friday, July 19th

THE REVSUND GRANITOIDS AND THE RAGUNDA COMPLEX

3:1 Österböle: Revsund granitoid (699040/145625)

Road section on highway E14. Revsund granitoid with classical coarse -grained porphyritic texture; several centimetres big feldspar phenocrysts. Chemical composition given by sample T9209.

THE RAGUNDA COMPLEX

The excursion stops in the Ragunda area are shown in Fig.19.

3:2 Gesunden (700360/151010)

This locality consists of an almost 550 m long road cutting situated in the westernmost part of the Ragunda complex at the shore of Lake Gesunden, which is actually a reservoir belonging to the Krångede hydropower station. Variations in the Ragunda (quartz) syenite are found at this locality. Approximately 200 m to the west, the nearest outcrop of the country rock is found. In the syenite, a lot of xenoliths of the country rocks are found. A distinct sheeting is visible in the syenite.

The only observed sharp contact between Ragunda syenite and Ragunda granite is found here. The contact strikes approximately N–S and dips c. 45° to the west. The granite shows inclusions of syenite and gabbro approximately 15 m to the east of the contact. In the easternmost part of this outcrop occurs gabbro penetrated and brecciated by Ragunda granite (biotite granite).

The youngest magmatic activity exposed at this locality is a 1.5 m wide diabase dyke cutting the syenite in the westernmost part of the outcrop. The dyke, which has a weak columnar jointing, strikes E–W and dips c. 60° N.

3:3 Krångede (700380/151460)

This locality with well exposed outcrops in the river bed (often dry) is situated 1 km east of the hydropower station at Krångede. Here, you find an amphibole-bearing granite of type A (see p. 51). It is medium- to coarse-grained and greyish green. The mineralogy is similar to that of the syenite, however, the quartz content in this rock is very high, sometimes up to 40%. At this outcrop, it is possible to find irregular pegmatite spots and miarolitic cavities with large quartz and fluorite crystals.

The amphibole-bearing granite is cut by a set of diabase dykes, which trends NW–SE and dips gently to the south. The gently dipping diabase, which shows columnar jointing, is possible to follow, and one of the dykes decreases from 3 m to a few centimetres in width over a distance of 30 m. It then finally pinches out. At this locality, also a vertical diabase dyke occurs.

3:4 Storrisberget (700120/151250)

This locality is an almost 500 m long road cut at the NE foot of the hill Storrisberget. The outcrop is dominated by a fine-grained gabbro which is cut by a large number of acid dykes and one diabase dyke. The dykes trend between E–W and NW–SE and dip vertically or steeply to N–NE. Within the fine-grained gabbro, a few xenoliths of a phenocryst-bearing gabbro occur.

Eight acid dykes are found within a distance of c. 400 m. Four of them are bluish grey, quartz-feldspar porphyry dykes, two are red, granitic dykes and two are aplite dykes. None of the dykes is wider than 2 m. The quartz-feldspar porphyries show sharp and slightly sinuous contacts towards the gabbro. The sinuous contact may be interpreted to suggest only a short time interval between the emplacement of the gabbro and the later quartz-feldspar porphyries.

The contact to the syenite is situated only 15 m east of the road. The gabbro is found as xenoliths in the syenite.

3:5 Döviken (700450/151900)

At this stop you will see Ragunda syenite which is cut by a phenocryst-free acid dyke, c. 3 m wide. Within the syenite there are strongly weathered horizontal bands.

3:6 Över-Böle resp. Böle (700295/151525 resp. 700395/152075) (optional)

Short stop at two small road cuts: 1) medium- to coarse-grained, reddish brown amphibole-bearing granite of type A and 2) medium-grained, red biotite granite.

3:7 Hammarstrand slalom slope (700035/152540)

Medium- to coarse-grained, flesh-red biotite granite with miarolitic cavities in which crystals of fluorite and quartz are found. At the foot of the slalom slope (under the lift) you can see biotite granite with large, well-rounded quartz crystals, measuring up to 7 x 7 mm.

Day 4. Saturday, July 20th

THE RAGUNDA COMPLEX (CONTINUED)

4:1 Ragunda old railway station “Stationsberget” (699350/153035)

This locality is situated just south of the old railway station in the village of Ragunda. A large number of old, very small quarries occur in the Ragunda granite. A small road leads up over the hill ”Stationsberget” and at the road side a contact between the Ragunda granite and the postorogenic Revsund granite is found.

Almost all old buildings in the villages of Ragunda and Hammarstrand are built on Ragunda granite foundations. Most of the quarries around the village of Ragunda were probably operated around the end of the 19th century. A lot of the quarried Ragunda granite was used in the rebuilding of the city of Sundsvall, which was totally destroyed by fire in 1888. During a walk on the streets of Sundsvall, you will find the Ragunda granite in many house foundations.

Topics of interest: The occurrence of medium- to coarse-grained, light-red to red amphibole-bearing granite of type B (see p. 51). A U-Pb zircon dating of the granite har yielded an upper intercept age of 1513±9 (2σ) Ma. The granite occasionally contains more or less rounded, dark xenoliths of a more basic rock. These xenoliths probably represent remnants of Ragunda gabbro.

The contact relations between the Ragunda granite and the Revsund granite: The contact is very sharp, with Ragunda granite cutting the K-feldspar megacrysts of the Revsund granite. There is also a very narrow (2 cm) apophysis from the Ragunda granite cutting the Revsund granite. The amphibole-bearing granite is fine-grained and pale red in a 20 cm wide contact zone. There is a zone of fine-grained, light red, amphibole-bearing granite crowded with small (0.5–20 cm) inclusions of gabbro 20 cm from the contact. About 4 m from the contact, in the Ragunda granite, there is an inclusion of Revsund granite.

In one of the small quarries, two types of narrow dykes occur. The first type is a red aplite dyke (1–3 cm wide). The second type is very narrow (1 cm wide) (Fig. 36). It consists mainly of K-feldspar, quartz, fluorite and molybdenite.

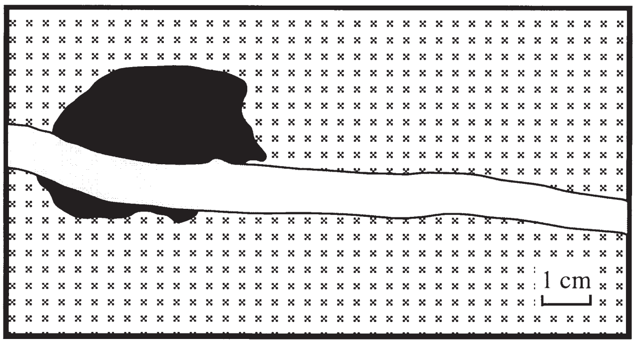

Fig. 36. Narrow dyke (light grey) containing fluorite and molybdenite cutting amphibole-bearing granite (type-B) (crosses) with a small basic xenolith (black).

4:2 Prästberget (699920/152880)

This locality consists of a 175 m long roadcutting, c. 1 km SSE of the village of Hammarstrand. At this locality, typical magma mingling structures are found (Fig. 37). Field evidence shows that mingling must be due to the coexistence of granitic and gabbroic magmas. The gabbro shows chilled and crenulated margins against the granite. Some observations, e.g. apophyses of granite in gabbro and angular gabbro and hybrid fragments brecciated by granite, suggest that some of the mafic rocks were partly consolidated when invaded by silicic magma. Incomplete mixing of magmas has occurred on scales ranging from the formation of metre-size pillows through centrimetre-size inclusions, to complete dispersion with incorporation of xenocrysts into the silicic magma. The contrasted liquidus and solidus temperatures, and various cooling rates of individual pillows are reflected in a diversity of structures and textures in the roadcut at "Prästberget".

Fig. 37. The contrasted liquidus and solidus temperatures and various cooling rates of individual pillows are reflected in the diversity of structures in a road cut at ”Prästberget”, c. 1 km SSE of the village Hammarstrand. The gabbro is beautifully netveined by granite. The large gabbro pillow in the central part measures c. 9.5 m across. To the right of the large gabbro pillow some angular gabbro and hybrid (light grey) fragments occur in the granite, suggesting that some of the mafic rocks were partly consolidated when invaded by silicic magma. The arrow points to a gabbro enclave which is proposed to have a downward sinking structure (smooth curved lower part and a rough upper part penetrated by granite).

4:3 Hammarforsen (700050/152785) (optional stop)

This locality is situated at the foot of the reservoir of the hydropower station at the village of Hammarstrand. This is a more or less horizontal cross-section of the same rock features as seen at Prästberget (locality 4:2).

4:4 Flakamyran (699805/154375)

This locality is a newly opened aggregate stone quarry. In the quarry the largest dyke of the Ragunda complex is found. It trends more or less E–W and dips 45° N. The dyke is a 12 m wide composite dyke. It is composed of 2 m wide, basic, bluish grey margins and an 8 m wide, central, brownish red quartz-feldspar porphyry. The contact between the bluish grey margin and the brownish red central part is sharp. The dyke cuts the Ragunda gabbro. The latter is intensely penetrated by Ragunda granite. Typical magma mingling structures and textures (quartz ocelli mantled by amphibole) are found.

4:5 Uthammarsberget, Västby (701545/154850) (optional stop)

At this locality, a five metres wide composite dyke occurs. A grey fine-grained plagioclase-porphyritic rock intruded first. This intrusion has an aphanitic contact towards the country rock. It was followed by a later intrusion of fine-grained, greyish red quartz porphyry, which brecciated the first dyke.

4:6 Holmstrand (701870/154845)

You will find this locality just NE of the shooting-range at Holmstrand. Here, medium-grained, pale-red amphibole-bearing granite of type B (see p. 51) is found. In this outcrop there are areas of strong weathering. Such areas are particularly found on the Ärtriksklippen hill, 2.5 km northeast of this stop.

4:7 Gagnet (701730/154940)

A small isolated outcrop consisting of a gabbro variety, which macroscopically differs from the normal Ragunda gabbro by its larger grain-size (plagioclase grains are normally over 1 cm in length) and its higher plagioclase content (c. 65–75% of the rock).

Day 5. Sunday, July 21st

THE NORDINGRÅ MASSIF

Excursion localities are shown on the map, Fig. 25.

5:1 Järesta (698335/162460)

Medium-grained Nordingrå gabbro. The main dark minerals are clino- and orthopyroxene, and fayalitic olivine. Looking east, the Ringkallen hill is seen, where a Postjotnian dolerite sill caps red, Jotnian sandstone, in turn resting on gabbro/leucogabbro/anorthosite.

5:2 Omnesjön (698490/162705)

Layered and laminated Nordingrå gabbro. The dip is towards the NW.

5:3 Vågsfjärden (698140/162670)

Leucogabbro/anorthosite and Nordingrå gabbro, the latter forming dykes in the former. Two types of the former are seen: anorthosite proper (white) and leucogabbro/anorthosite. Labradorizing plagioclases may be found.

5:4 Bönhamn (697715/163415)

Leucogabbro/anorthosite of the eastern massif (east of the dolerite intrusion). Big plagioclase crystals occur. Gabbro schlieren and granitoid dykes are also seen.

5:5 South of Bönhamn (697585/163415)

Leucogabbro/anorthosite, in part relatively rich in K-feldspar and with altered plagioclase, intruded and brecciated by Nordingrå gabbro. A very coarse-grained, grey to bluish grey variety of anorthosite is in contact with the normal leucogabbro/anorthosite. Dykes and schlieren of hornblende- and K-feldspar-rich granitic or monzonitic rocks occur as well as fine-grained quartz-albite dykes. A dyke of Postjotnian dolerite cuts the gabbro.

5:6 Mjösand (697590/163260)

Pegmatitic segregation in leucogabbro/anorthosite, with big crystals of clinopyroxene (with orthopyroxene lamellae), Ti-magnetite, olivine and apatite. The clinopyroxene contains 53% of the Mg end member, the orthopyroxene 39% en and the olivine 18% fo.

5:7 Mjällom (698875/163410)

Feldspar-porphyritic Nordingrå granite.

5:8 East of Norrfällsviken (698740/163915)

Nordingrå granite with miarolitic cavities filled with quartz, feldspar, chlorite and calcite.

5:9 Överveda (698710/162420)

Contact zone between the country rock metagreywackes and the rapakivi gabbro. The contact is characterized by numerous, mostly angular fragments of metagreywacke in a gabbroic matrix.

5:10 Salsåker (698950/162600)

Nordingrå granite with xenoliths of Nordingrå gabbro. In some cases mingling and mixing between the gabbro and granite magmas are suggested by diffuse (hybrid) boundaries of the inclusions. Small pits in the surface of the granite were probably formed by weathering of altered xenocrysts (chlorite, magnetite etc.) of dark gabbro minerals.

Day 6. Monday, July 22nd

THE RÖDÖ MASSIF

Excursion localities are shown on the map, Fig. 29.
A more detailed map is presented in Andersson (1997b).

6:1 Southern Rödön (691990/159150)

Rödö granite. The granite contains numerous up to c. 5 cm wide miarolitic cavities unfilled or filled with calcite, quartz, and sometimes fluorite. The light brick-red granite becomes dark brick-red in zones of brittle deformation and fluid flow associated with Alnö intrusion. The ovoids are usually plagioclase-mantled, but this can be hard to see as the mantles also have turned brick-red during alteration.

Decimetre- to metre-size pillows and larger areas of granite porphyry occur within the granite, as well as thin red to grey aplite veins. Dark, often arc-formed schlieren structures are well developed in the granite. Larger vugs and aplitic material is often associated with these.

Two complex dykes cut the granite on a promontory close by. They are composite dolerite-hybrid dolerite dykes characterized by a lateral zoning pattern. One is a c. 5 m wide dyke with a 1–2 m brown marginal zone. The latter is slightly more felsic (SiO_2=59.1%) compared to the grey-green central zone (SiO_2=56.6%). The transition is gradual, and both facies contain scattered xenocrysts of quartz (≤1 cm), K-feldspar (≤3 cm), and large megacrysts of skeletal plagioclase. The other dyke is thinner (c. 2 m). In this case the central part is browner (SiO_2=66.4%; silicic hybrid porphyry) and the c. 0.5 wide margins darker (SiO_2=55.8%). Numerous small dark rounded enclaves of the margin can be found in the brown central zone. Megacrysts similar to those found in the first dyke are met with. Both dykes form part of the suggested system of cone-sheet intrusions in the granite.

6:2 SW Rödön (692035/159080)

Area of contact between the Rödö granite and the country rocks. The contact is, however, covered with rubble. The Rödö granite here contains a few xenoliths of the metasedimentary country rocks. No hornfels assemblages have been found neither in the xenoliths, nor in the country rocks anywhere along the contact. Chloritization is abundant in these rocks.

A composite dyke cuts through the Rödö granite close to the contact. It is about 5 m wide and consists of a marginal facies, c. 1 m wide, of a black dolerite, which relatively sharply turns into a 30 cm wide hybrid zone. The latter transform over a decimetre into the central, almost 2 m wide QFP. Both the QFP and the hybrid zone contain pillows (enclaves) of fine-grained mafic material similar to the margins, but they are smaller in the QFP. K-feldspar phenocrysts of the QFP also occur in the hybrid where they have more clearly developed plagioclase mantles. Also skeletal plagioclases can be found in the hybrid zone.

A set of subparallel granite porphyry dykes occurs in the sedimentary gneiss close to the contact. These dykes are 1 dm to 1 m wide, and are suggested to be apophyses from the granite, since a dyke of similar material can be followed from the granite into the country rocks on central Rödön. They can, however, not be followed here into the granite due to lack of exposure. A c. 1 dm wide carbonatitic dyke belonging to the c. 0.56 Ga old Alnö alkaline complex (Lundqvist et al. 1990), cuts through both the gneisses and the granite porphyries.

6:3 Långfläsjan (691840/158930)

Spectacular structures in a dark, coarse-porphyritic hybrid porphyry (HPF) can be observed on the SE part of the islet. The HPF dips c. 45° the east and contains numerous up to metre-sized rounded xenocryst-bearing mafic (SiO_2= 56.6%) magmatic enclaves (MMEs). The xenocrysts are K-feldspars and quartz of the same type as in the surrounding hybrid porphyry, but more sparsely distributed. The MMEs often contain a core of slightly coarser, more mafic material with calcite-filled cavities. The upper parts of the HPF are reddish in colour, but have identical composition with the dark facies (SiO_2=68.4%). This HPF belongs to the group of more silicic HPFs which have formed from primitive end members (see text section). Two other small occurrences of HPFs occur along the eastern shore. One of these is slightly more basic (SiO_2=64.9%), small, porphyritic, containing also small skeletal plagioclase megacrysts.

Along the northern part of the eastern shore a large sheet of Rödö dolerite is exposed. A couple of apophyses from this sheet can be followed on the islet. The dolerite sheet strikes NNW and dips about 30°E. It is at least 10 m thick, but only one contact is exposed. The central part is a reddish monzodolerite (SiO_2=59.0%), whereas the margins are more basic and black (SiO_2=56.6%). The dolerite carries sparse gneissic xenoliths, K-feldspar and quartz xenocrysts, and occasional quartz lumps, where the feldspar component appears to have been selectively dissolved (cf. Eklund & Lindberg 1992). The country rock is here an orthogneiss.

6:4 Gråfläsjan (691830/158960)

The northern point of this islet is crosscut by the same type of dark, coarse, silicic (SiO_2=69.3%) hybrid porphyry as on Långfläsjan. Feldspar textures are nicely exposed. They are dominated by large (up to 3 cm), euhedral to rounded K-feldspar megacrysts. Partially or wholly plagioclase-mantled as well as unmantled K-feldspars occur side by side.

Thick plagioclase mantles are often coarsely skeletal, and skeletal plagioclases also occur without a K-feldspar core. Centimetre-sized droplets of quartz are abundant. They are not coated with amphibole or pyroxene. Closest to the contact to the orthogneiss small megacrysts predominate, suggesting that the larger crystals were sorted out during transport. Also here MMEs occur with cores of cavity-rich material (SiO_2=52.2%). The hybrid porphyry swings around the islet on the eastern side and follows it more or less along the surface of the water, apparently forming a subhorizontal sheet through the islet. A relatively steeply eastward dipping dolerite cuts the HPF on the eastern side. A c. metre-wide carbonatite dyke cuts all the other rocks also along the eastern shore.

The HPF can be followed to the SE point of the islet where it appears to have diffuse contacts to a QFP (SiO_2=71.1%), which here forms a large (at least 20 m wide) dyke. It is brick-red and coarse-porphyritic, with megacrysts closely similar to the HPF above. It also contains abundant dark hybrid magmatic enclaves (SiO_2= 59.1%). The enclaves are rounded, millimetre-sized to less than 0.5 m, and contain xenocrysts of exactly the same type as the megacrysts in the surrounding QFP. Here and there megacrysts can be seen to protrude from the QFP into the enclave. Apparently the megacrysts formed in the QFP magma have been mechanically engulfed in the enclaves during a dynamic magma mingling event.

A c. 1 m wide ophitic Postjotnian (c. 1.26 Ga; Suominen 1991) dolerite dyke cuts through the gneiss in a NNW direction on the southern shore. On the westernmost tip of the islet (closest to Långfläsjan) the typical coarse HPF appears again, winding but generally gently dipping to the east. Similar coarse silicic HPFs occur also further east on the island of Känningen, and to the south on Skorven and Spikarö. It seems clear that they form an interconnected nework of flat-lying dykes in this area.

6:5 Skorven (691775/158960)

Walk around the islet of Skorven, starting on the southern shore. The grey orthogneisses present here contain very large K-feldspar megacrysts or glomerocrysts (up to 15 cm). Gently eastward dipping lineation. A network of centimetre- to decimetre-sized pegmatites crosscuts the gneisses. They contain abundant black tourmaline. Mobilization and magmatic structures can be observed within the gneisses, as well as scattered metasedimentary enclaves.

On the eastern side of the islet a minor area of biotite-rich metasediments and a large red pegmatite occur. These rocks are crosscut by a c. 5 m wide QFP dyke running E–W with vertical dip. About halfway up the shore the dyke is faulted left-laterally c. 10 m, after which it continues straight up across the islet. Its continuation can be followed c. 500 m further west on Spikarö. The dyke is extremely fine-grained and greenish close to the contact. It contains small (a couple of millimetres) megacrysts of feldspar and quartz, and abundant rounded small green MMEs These are from a few millimetres up to c. 1 dm in size and contain identical megacrysts as the QFP. Some of the bigger enclaves are less well rounded, darker and contain bigger megacrysts, as well as numerous calcite-filled cavities. This may indicate that the QFP has been involved in two subsequent mingling events, or alternatively that the bigger enclaves were picked up by the QFP magma as fragments from an associated hybrid porphyry.

Near the fault a Postjotnian dolerite (PJD) appears to have crosscut the QFP. The actual contact is, however, not exposed. The PJD strikes NNW all along the steep slope on the east side of the islet. A c. 1/2 m wide alnöite dyke cuts the QFP higher up on the shore. This QFP dyke belongs to the group of most evolved silicic Rödö rocks (SiO_2 73.3%, Rb 797 ppm, Li 94, Ga 39, Nb 86, Ta 20, and Pb 43 ppm). Low contents of Zr (18 ppm), Y (7.8 ppm) and the REE suggest that zircon is an important fractionating phase. This dyke is the only example where zircon is inferred to be important for the geochemical evolution (see text above). The geochemistry of this QFP indicates that it represents a relatively highly evolved residual granitic magma, though not the most evolved in the area (see text above).

On the northern part of the islet a hybrid porphyry (SiO_2=66.5%), of the same type as described above (stops 6:3 and 6:4), cuts the orthogneiss. Undoubtedly it belongs to the same dyke system.

6:6 Western Spikarö peninsula (691790/158870)

At this locality a quartz-feldspar porphyry (SiO_2=71.0%) containing relatively abundant mafic/hybrid MMEs occurs. The porphyry contains K-feldspar phenocrysts, up to 2 cm in size, but virtually no quartz phenocrysts. It is loaded with black spots, associated with small cavities containing calcite in the middle and chlorite in the margins. The enclaves carry the same megacrysts as the QFP, but usually has larger vugs. This QFP continues northward to northern Spikarö and probably further north to the little islet Lergrundet, where an identical dyke is present. It belongs to the most primitive (i.e. least evolved) type of QFPs, which are also most common and similar to the Rödö granite geochemically.

6:7 SW Alnön, Vindhem (691700/158385)

A c. 0.5 m wide rapakivi dolerite (SiO_2=51.7%) cuts trough the gneisses in a NW direction. It contains numerous calcite-filled vugs, chlorite-calcite pseudomorphs after pyroxene, skeletal plagioclases and sparse large K-feldspar xenocrysts, set in a heavily altered groundmass of plagioclase, Fe-Mg silicates and oxides. The K-feldspar xenocrysts seem to be of a type more akin to those occurring in the country rocks than of rapakivi type, and the plagioclase megacrysts are albitic, suggesting some assimilation in the basic magma.

Day 7. Tuesday, July 23rd

7:1 Ortviksberget (692220/157975)

Minor quarry in the Sundsvall quartz-feldspar porphyry. This is a yellowish red QFP, which carries phenocrysts of quartz droplets (< c. 0.5 cm) and euhedral to rounded K-feldspar (< c. 1 cm), in a groundmass dominated also by K-feldspar and quartz, together with minor amounts of oxides and fluorite. The relatively fluorite-rich nature is also evident in the high contents of fluorine in this rock (2400–3600 ppm). Otherwise this porphyry is little evolved and close to the Rödö granite in geochemistry. Close to the contact it is greenish and extremely fine-grained. The dyke is here about 150 m wide and continues over Ortviksberget, where it turns to the east and narrows to <50 m. It is highly probable that the three known occurrences of Sundsvall porphyry, this one and the two south of Sundsvall, are part of the same dyke or parallel dykes in the same system. This conclusion is based on strong similarites in petrography, geochemistry, and geographical arrangement of the dykes. The QFP dyke at Gärdeberget c. 1 km north of Ortviksberget, may also be connected to this dyke system, based on geochemical and petrographical similarities.

7:2 Bredsand (691625/158120)

A c. 7 m wide "contaminated" Rödö dolerite (SiO_2=56.3%) striking WNW and dipping vertically. This dyke may have its continuation at a locality in a northwesterly direction. It is brownish black in colour and contains K-feldspar xenocrysts, elongated plagioclase phenocrysts, and scattered gneissic xenoliths, in a relatively well-preserved matrix containing plagioclase, clinopyroxene, biotite, and oxides. Most of the Rödö dolerites are "contaminated" in the sense that they contain scattered K-feldspar and quartz xenocrysts. This particular dyke has a syenitic composition and Na-rich pyroxenes (Andersson 1997b), suggesting that it belongs to the most highly evolved parts of the basic Rödö suite.

THE STRÖMSBRO GRANITE

7:3 Strömsbro (673205/157390)

The Strömsbro stop will be by the stream in Testeboån in the municipality of Strömsbro, nowadays a suburb of Gävle. Outcrops of the typical coarse Strömsbro granite are present in the stream and closeby localities, including a granite porphyry variant. The granite is uniform with little variation.

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