

Geological Survey of Finland, Special Paper 37

**The Transscandinavian Igneous Belt (TIB) in Sweden:
a review of its character and evolution**

edited by

Karin Högdahl, Ulf B. Andersson and Olav Eklund

with contributions by Ulf B. Andersson, Karin Högdahl, Roland Gorbatshev,
Jan-Olov Nyström, Anders Wikström, Håkan Sjöström, Stefan Bergman,
Martin Ahl, Joakim Mansfeld, Carl-Henric Wahlgren, Michael B. Stephens,
Dick T. Claeson, Olav Eklund, Thomas Lundqvist, Björn Öhlander,
Sten-Anders Smeds, Krister Sundblad

Geological Survey of Finland
Espoo 2004

Högdahl, K., Andersson, U.B. & Eklund, O. (eds.), Andersson, U.B. et al. 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evaluation. Geological Survey of Finland, Special Paper 37, 123 pages, 73 figures and one table.

The Transscandinavian Igneous Belt (TIB) comprises a giant elongated array of batholiths extending c. 1400 km across the Scandinavian Peninsula from southeasternmost Sweden to northwestern Norway. The TIB is traditionally divided into four main units based on tectonic and lithological criteria: i) the Småland-Värmland belt in the south and west, ii) the Dala Province and iii) the Rätan Batholith in the centre, and iv) the Revsund granitoid suite in the north. The rocks of TIB dominantly consist of coarse (porphyritic) monzodiorites to granites of alkali-calcic chemistry, with transitions to calc-alkaline or alkaline rocks. Mafic rocks (with destructive plate margin affinity) are abundant in many areas, and mingling/mixing structures common. Associated volcanic rocks are widespread in the southern Småland-Värmland Belt, but dominating in the down-faulted Dala Province. Intrusive ages cover the whole range 1.85 to 1.65 Ga, where the oldest tend to occur in vicinity of the margin to the older Svecofennian Domain. The major part of magmatism in Småland-Värmland Belt and the Revsund granitoid suite occurred during 1.81–1.76 Ga, while the youngest phase (1.72–1.65 Ga) dominates the Dala Province and Rätan Batholith, as well as the western margin of SVB where it becomes increasingly overprinted by Sveconorwegian (1.1–0.9 Ga) deformation westwards. Isotopic data has revealed no Archaean components, and the TIB has dominantly formed by reworking of the juvenile (2.1–1.87 Ga) Svecofennian crust, supplemented by mantle additions in a continental-arc setting.

Key words (GeoRef Thesaurus, AGI): intracontinental belts, igneous rocks, granites, volcanic rocks, geochemistry, magmatism, shear zones, Proterozoic, Sweden.

Karin Högdahl, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; E-mail: karin.hogdahl@geol.lu.se

Ulf B. Andersson, Swedish Museum of Natural History, Box 50007, SE-104 05 Stockholm, Sweden and Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden; E-mail: ulf.andersson@nrm.se

Olav Eklund, Department of Geology, University of Turku, FI-20014 Turku, Finland; E-mail: olav.eklund@utu.fi

ISBN 951-690-889-6
ISSN 0782-8535

FOREWORD

The present volume grew out as an extension of a ‘preliminary’ guidebook produced for the workshop and excursion ‘TIB-2001’. This was an arrangement within the NorFA-sponsored Nordic network “Transition from Orogenic to Anorogenic Magmatism in the Fennoscandian Shield” held in Stockholm 2001-08-13, and followed by an excursion to the central parts of the Transscandinavian Igneous Belt (TIB) 2001-08-14–19, which was attended by 60 (workshop) and 42 (excursion) persons, respectively (Högdahl et al. 2001a). In connection with the excursion and later, interests were expressed to collect the up-to-date knowledge about the TIB in a rewritten more formally published review volume. The Geological Survey of Finland (GTK) kindly offered to sponsor such a publication and space in an issue of their Special Paper series. NorFA (Nordisk Forskerutdanningsakademi) kindly covered the remaining of the printing costs.

The TIB has been a key issue of Swedish and Fennoscandian geology since the beginning of regional geological investigations, and hypotheses concerning its formation and position in relation to surrounding rock units have been the focus of shifting ideas. The amount of data and information gathered about the TIB has previously perhaps not accumulated to such an extent that a comprehensive review was meaningful. However, we feel that this is now possible by a combination of data collected from variable angles of regional studies; geochemistry, isotopic data, geophysics and structural geology. This book is intended to offer such first review collection as a base for further studies, and the future will determine if the TIB concept will endure.

A complementary web-page with outcrop pictures from the areas presented in this book is found at:

<http://www.utu.fi/ml/geologia/norfa/kehyssivut/aloitussivu.html>

A note on nomenclature

A comment on nomenclature concerning the use of the terms Svecofennian and Svecokarelian in the text is requisite. Note that different authors have used the terms in slightly different ways, following their own preference, however, consistently in the respective sections. This was allowed by the editors, as there is at present no consensus on how to use these terms. Both terms have a long prehistory, which will not be reiterated here. However, during the last two decades the rapid development in the understanding of the Proterozoic evolution of the Fennoscandian shield, not least in the light of application of modern plate-tectonic models, has provoked some conflicting use of terminology. Gaál & Gorbatshev (1987) proposed that Svecokarelian should be

abandoned and substituted by Svecofennian orogeny. The reason being that the >2.0 Ga Karelian formations represent intracratonic cover and passive continental margin sequences on the Archaean craton, while the Svecofennian formations to the southwest essentially represent new orogenic crust younger than 2.0 Ga, formed and accreted to the craton margin 1.88–1.86 Ga and subsequently strongly reworked during the late Svecofennian period 1.85–1.78 Ga.

However, Wahlgren et al. (1996a) revived the term Svecokarelian orogen as representing the entire area affected by its youngest orogeny in the time span 2.0–1.65 Ga, including also the Karelian craton margin. They emphasised that orogeny is related to deformation, metamorphism and plutonism, and the Svecokarelian orogeny reached its culmination c. (1.90-) 1.85–1.80 Ga. However, in their ‘extended’ definition they also included rocks that were formed prior to (e.g. subduction-related rocks formed before accretion-collision) or after (e.g. rocks formed during post-collisional extensional collapse) the orogenic culmination.

This concept has been advocated mainly by geologists of the Geological Survey of Sweden (SGU) and has not been embraced by all scientists working in the Fennoscandian shield. For example, the recent developments in the understanding of the consecutive events in the assembly and reworking of the Svecofennian Domain in Finland (e.g. Lahtinen 1994, Lahtinen & Huhma 1997, Nironen 1997, Korsman et al. 1999, Väisänen 2002) has not promoted the use of Svecokarelian instead of Svecofennian. In southern Finland three different ‘Svecofennian’ arc complexes have been identified with individual histories. The two northern ones have recorded only ‘early’ Svecofennian processes ending with peak metamorphism around 1.88 Ga, while the southern complex reached maximum reworking later, c. 1.83 Ga ago. In Sweden, regions that preserve only ‘early’ metamorphism are not yet known. In fact, ‘early’ metamorphism is barely recognised as a whole in the Swedish Svecofennian.

At present, some authors seem to prefer to use Svecokarelian only for ‘late Svecofennian’ (c. 1.85–1.80 Ga) deformational, metamorphic, and plutonic (‘orogenic’) processes (orogenic culmination). According to Wahlgren et al. (1996a), however, also rocks formed in island-arcs prior to orogenic culmination or just after it, should be called pre-orogenic or post-orogenic Svecokarelian, respectively. In this definition, most of TIB is late- to post-orogenic Svecokarelian. Only pre-1.87 Ga supracrustal rocks are in this terminology Svecofennian.

Nevertheless, it is important to remember that most of the continental crust in the Svecofennian Domain was formed in several arc systems, probably starting already slightly before 2.0 Ga (Claesson et al. 1993, Lahtinen & Huhma 1997, Lahtinen et al. 2002), and were accreted to the cratonic nucleus by 1.88–1.86 Ga. This is the period of Svecofennian crustal growth. Almost only indirect evidence of magmatism exists for the earliest ‘proto-Svecofennian’ period, 2.1–1.95 Ga. After 1.86 Ga, processes turned more distinctly to reworking of the juvenile crust by strong deformation, regional metamorphism and extensive remelting, including the Karelian Domain and TIB (although central Svecofennian regions in Finland appear to have escaped this stage). This may then be called the Svecokarelian stage or late Svecofennian crustal reworking stage. However, juvenile crust appears to have been produced in some regions simultaneously with reworking of Svecofennian crust in other regions.

Ulf B. Andersson

Karin Högdahl

Olav Eklund

Acknowledgements

We would like to thank all authors of this volume for their efforts, including reviewing other chapters. Special thanks go to Gabor Gaál, Pekka Nurmi and Mikko Nironen of the Geological Survey of Finland (GTK), who offered to publish this volume as a survey monograph. Sini Autio at GTK handled the final layout of the volume. Thanks also go to Andreas Hendrich (GFZ, Potsdam) for help with figures in Chapter 2. The review of Mikko Nironen improved the manuscript considerably. Karl-Inge Åhäll is thanked for comments on the final manuscript.

CONTENTS

Foreword, <i>Ulf B. Andersson, Karin Högdahl & Olav Eklund</i>	3
1. The Transscandinavian Igneous Belt – introduction and background, <i>Roland Gorbatshev</i>	9
1.1. Essentials of the Transscandinavian Belt	9
1.2. Age patterns and regional variation	10
1.3. The concept of a Transscandinavian Igneous Belt, previous interpretations and current discussion	13
2. The Småland-Värmland belt	16
2.1. Overview, <i>Ulf B. Andersson & Anders Wikström</i>	16
2.2. The Småland-Värmland belt in southeastern Sweden, <i>Joakim Mansfeld</i>	20
2.3. Geological features of the Småland-Värmland belt along the Svecofennian margin, part I: from the Loftahammar to the Tiveden- Askersund areas, <i>Anders Wikström & Ulf B. Andersson</i>	22
2.3.1. Introduction	22
2.3.2. The Loftahammar area	26
2.3.3. Augen gneisses in the area between Loftahammar and Norrköping	29
2.3.4. The Linköping area	29
2.3.5. The Graversfors intrusion	30
2.3.6. The Stavsjö-Jönåker intrusions	32
2.3.7. The Finspång massif	32
2.3.8. The Kårtorp complex	34
2.3.9. The Tjällmo-Vättern zone	37
2.3.10. The Askersund area	38
2.3.11. The Tiveden area	38
2.4. Geological features of the Småland-Värmland belt along the Svecofennian margin, part II: the Nygård, Karlskoga and Filipstad areas, <i>Ulf B. Andersson, Dick T. Claeson, Karin Högdahl & Håkan Sjöström</i>	39
2.4.1. The Nygård norite pluton and its surroundings	39
2.4.2. The Karlskoga area	41
2.4.3. The Filipstad area	42
2.4.3.1. General features	42
2.4.3.2. The Eriksberg gabbro	44
2.4.3.3. The Gåsborn pluton	45
2.5. Geochemical character of the mafic-hybrid magmatism in the Småland- Värmland Belt, <i>Ulf B. Andersson, Olav Eklund & Dick T. Claeson</i>	47
2.6. Tectonometamorphic reworking of TIB rocks during the Sveconorwegian orogeny, south-central Sweden, <i>Carl-Henric Wahlgren & Michael B. Stephens</i>	56

3. The Dala Province	58
3.1. Dala volcanism, sedimentation and structural setting, <i>Jan-Olov Nyström</i>	58
3.1.1. Geology and petrography	58
3.1.2. Geochemistry	63
3.1.3. The origin of the Dala volcanites	69
3.2. The Dala granitoids, <i>Martin Ahl, Ulf B. Andersson, Thomas Lundqvist & Krister Sundblad</i>	70
3.2.1. Introduction	70
3.2.2. The Dala granitoids	72
3.2.3. Geochemical characteristics of the Dala granitoids	72
3.2.4. Source of granitoid magmas	74
4. The Rätan batholith and the Nordkölen rocks	75
4.1. The Rätan batholith, <i>Martin Ahl, Roland Gorbatshev & Krister Sundblad</i>	75
4.2. The Nordkölen quartz monzodiorite and associated rocks, <i>Roland Gorbatshev</i>	76
5. The Revsund granite and related rocks in Jämtland	78
5.1. Precambrian crustal provinces and their relationships with Revsund-type granitoids, <i>Roland Gorbatshev</i>	78
5.2. The Revsund massifs, <i>Roland Gorbatshev</i>	80
5.3. The Grötingen granite, <i>Roland Gorbatshev, Ulf B. Andersson & Sten-Anders Smeds</i>	83
5.4. Granite ages and some problems of rock classification, <i>Karin Högdahl & Martin Ahl</i>	86
5.4.1. Geochronology	86
5.4.2. K-feldspar megacryst-bearing granites (KFM granites) in the western part of the South Jämtland massif	87
5.4.3. Geochemical characteristics of the KFM granites in the Transition Belt	88
5.4.4. Origin of the KFM granites in the Transition Belt	89
6. Shear zones in the Rätan and southern Revsund areas, <i>Stefan Bergman, Karin Högdahl & Håkan Sjöström</i>	89
6.1. The Storsjön-Edsbyn Deformation Zone	89
6.1.1. Southern and central part	91
6.1.2. Northern part (Svenstavik-Hackås)	93
6.1.3. Tectonic significance and relation to the Rätan batholith	94
6.2. Plastic shear zones in the southern Revsund Transition Belt	95
6.2.1. The Forsaån Zone	95
6.2.2. Plastic deformation zones in the Lockne-, Näkten- and Pån areas	98
6.2.3. Regional correlation	101
7. The Ljusdal batholith and late Svecofennian magmatism	101
7.1. The Ljusdal batholith, <i>Håkan Sjöström & Karin Högdahl</i>	101
7.2. The late Svecofennian magmatism, <i>Ulf B. Andersson & Björn Öhlander</i>	102
8. The Transscandinavian Igneous Belt, evolutionary models, <i>Ulf B. Andersson, Håkan Sjöström, Karin Högdahl & Olav Eklund</i>	104
9. References	113

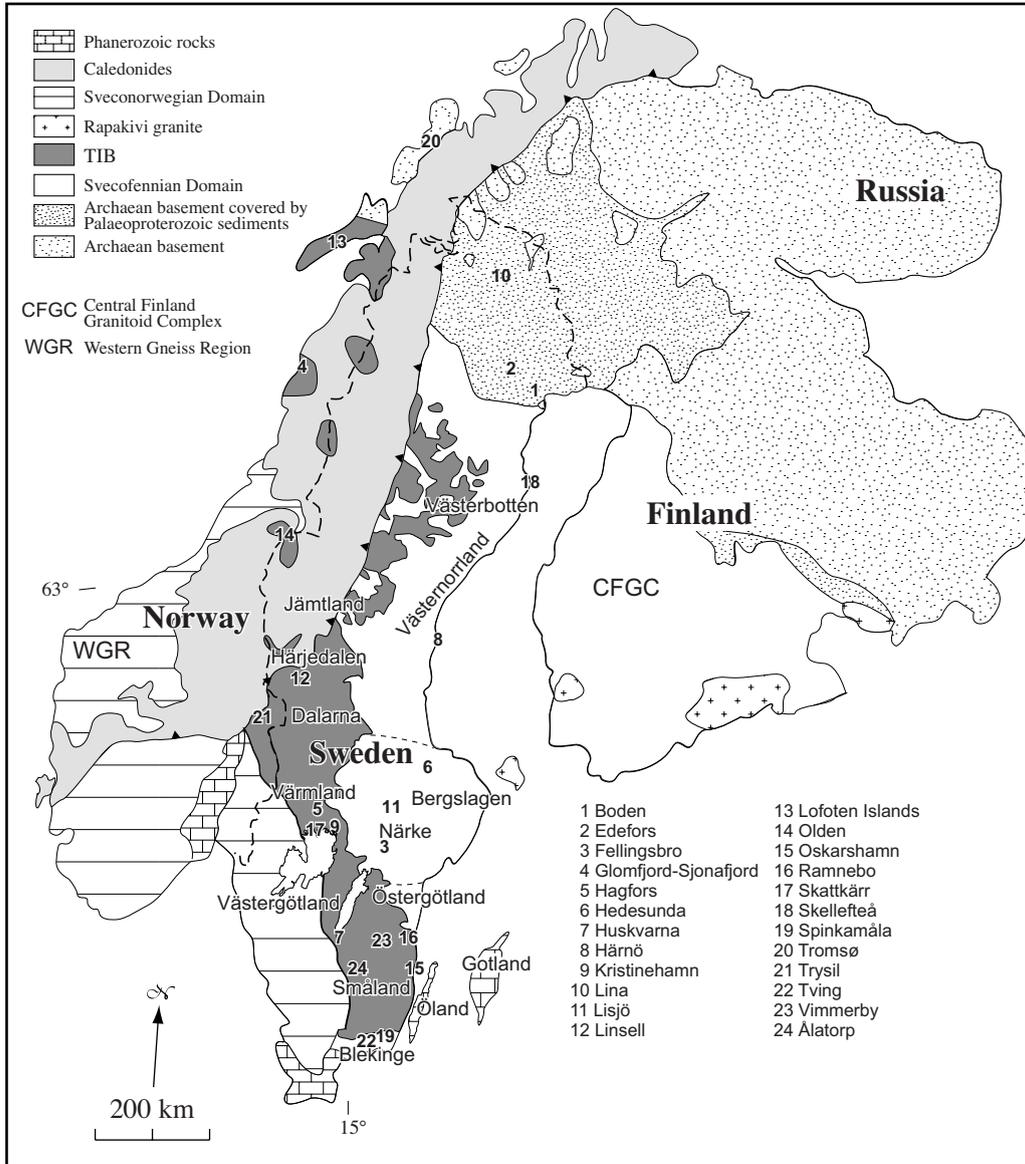


Fig. 1. Generalised geological map over the Fennoscandian shield including provinces, and other localities mentioned in the text.

1. THE TRANSSCANDINAVIAN IGNEOUS BELT – INTRODUCTION AND BACKGROUND

Roland Gorbatshev

1.1. Essentials of the Transscandinavian Belt

The Transscandinavian Igneous Belt (TIB, Fig. 1) is a giant array of large massifs of granitoid rocks and associated mafic intrusions. The ages range between c. 1.85 and 1.67 Ga, but the different age groups all feature a pronounced general tendency towards monzogranitoid, alkali-rich lithologies (cf. Ahl et al. 1999). The chemical compositions are commonly alkali-calcic and of the I and A types, or transitional between these two. The geochemical surveying of the TIB is still far from complete, but major deviations from the alkali-rich, alkali-calcic trend do not appear to be very numerous. One instance is the South Jämtland massif of Revsund granite, where the rocks, albeit highly potassic, tend to be calc-alkalic (cf. Chapter 5.2). Other, regionally even more important exceptions occur in the WNW-ESE to W-E trending, partly gneissic, 1.77–1.81 Ga TIB terrains in the Småland-Blekinge region of SE Sweden (cf. Chapter 1.2).

On the whole, however, the TIB intrusions are markedly different from the TTG-type (tonalite-trondhjemite-granodiorite-) subduction-related late Palaeoproterozoic to Mesoproterozoic plutonic rocks in Scandinavia. They also differ substantially from the partly coeval, compositionally less varied, mostly S-type granitic rocks formed by the remelting of tectonised and metamorphosed pre-existing continental crust without manifest participation of underplating mafic melts. The latter rocks typically appear to be products of various within-crust processes, while the TIB

tends to associate with one-time active continental margins.

The most common appearances of the granitic/(quartz-) monzogranitic to monzodioritic TIB plutonic rocks are more or less massive to flow-textured, coarse- to coarsely medium-grained, mostly with numerous up to several centimetres large megacrysts of potassic feldspar with or without plagioclase mantles. Amphiboles and biotite are the standard dark silicates but pyroxenes are by no means absent. Fayalite together with quartz is found in extremely ferrous rock varieties like the Sörvik granite in Jämtland (Chapter 5.2).

In the north-south direction, the TIB extends for more than 1200 km, with similar coeval rocks also occurring within the Labrador Belt in Canada. In Scandinavia, the northernmost occurrences of granites coeval with and resembling those of the TIB are on the Norwegian coast near Tromsø (Andresen 1980, Romer et al. 1992), while at the southern extreme, most of the province of Blekinge on the southern coast of Sweden is essentially built up of TIB granitoids (Kornfält 1996).

In northern Scandinavia, however, interpretation is complicated by the presence in the Lofoten-Islands region of a huge mass of gabbroic, anorthositic, mangeritic and charnockitic (AMCG) rocks (Griffin et al. 1978) with ages between c. 1.76 and 1.80 Ga (e.g. Corfu 2000, Rehnström 2003). Because AMCG complexes usually mark post-collisional, within-plate environments, the

presence of such a complex may be at variance with a TIB classification of the 1791 ± 10 Ma rocks described by Romer et al. (1992) from an area only c. 70 km away.

In general, the TIB tends to follow the western and southwestern margins of the c. 1.92–1.86 Ga continental crust formed during the Svecofennian orogeny.

Particularly in the southern and south-central

parts of the Belt, the plutonic rocks of the TIB commonly coexist with nearly simultaneously formed, predominantly felsic volcanic rocks. In the north, in contrast, associated volcanic rocks are scarce if present at all. Similarly to the TIB plutonics, the volcanic TIB rocks comprise at least two different age groups (cf. Lundqvist & Persson 1999).

1.2. Age patterns and regional variation

While there has been awareness for a long time that the rocks at present grouped within the TIB belong to at least two different generations (e.g. Hjelmqvist 1966), the work of Larson and Berglund (1992) was the first to propose a consistent age subdivision based on U-Pb zircon data mainly from the southern half of Scandinavia. These authors distinguished a TIB-1 group of 1.76–1.81, a TIB-2 group of 1.69–1.71, and a TIB-3 group of 1.65–1.67 Ga age.

Despite a need of some adjustment of the proposed age delimitations and the discovery of still older, c. 1.84–1.86 Ga, granitoid massifs more or less fitting the characteristics of TIB rocks (Persson & Wikström 1993, Wikström 1996, Andersson et al. 2004, Högdahl 2000a, Högdahl & Sjöström 2001), the TIB-1/TIB-2 age subdivision by Larson and Berglund has proved extremely viable. By the work of Romer et al. (1992), it was extended also to northern Scandinavia. Hitherto, only one major TIB massif, the 1.74–1.75 Ga Grötingen granite in Jämtland, has yielded an age markedly outside the indicated group limits (see Chapter 5.3).

As different from the well established TIB-1 and TIB-2 groups, the definition of the TIB-3 group is conjectural. Amongst the eight age determinations employed in Larson and Berglund's paper of 1992, six derive from the Western Gneiss Region (WGR) of Norway, while the age of the Hagshult granite in Småland has recently been recalculated to 1673 ± 19 Ma (Jarl 2002). The error limits of that dating overlap the c. 1.69-Ga age of the neighbouring TIB-2 Barnarp granite (Gorbatshev, Söderlund & Persson, in preparation, cf. Fig. 2).

From the WGR, Tucker et al. (1991) obtained ages ranging between 1686 and 1650 Ma, which

falls into the time span of the TIB. That region has therefore occasionally been described as a TIB area (e.g. Lutro et al. 1997). However, the TIB concept was intended to describe a particular region of rather specific rocks, not to be part of a time terminology (cf. Chapter 1.3). In regard to rock types, the WGR largely contains tonalitic to granitic rocks belonging to the TTG type rather than to the monzogranitoid, frequently alkali-calcic TIB family.

Already Larson and Berglund (1992) considered that the TIB-2 and TIB-3 events may represent one single continuous episode, while the difficulty to define separate TIB-2 and TIB-3 belts is notorious in southern Sweden (cf. Andersson & Wikström 2001). Amongst the five ages below c. 1675 Ma quoted in Åhäll and Larson (2000) and Andersson and Wikström (2001), the Hagshult age has been changed since (cf. above). Two of the other four derive from the border region of the Eastern Segment of SW Sweden, while a third is an age from Blekinge with a MSWD value of 110. Also the Skattkärr dating of Söderlund et al. (1999) includes a substantial error (1661 ± 27 Ma). For these reasons, it would appear most appropriate to change the lower age limit of the TIB-2 group from 1.69 to 1.67 Ga and altogether discard the concept of a separate TIB-3 group.

The TIB-1 as well as the TIB-2 rocks extend all the way from southern Sweden into the basement of the Caledonides in Norway. The trends of the TIB as a whole and the TIB-1 and TIB-2 sub-belts are therefore N-S to NNW. The TIB-2 rocks generally occur to the west of their TIB-1 counterparts. However there are several exceptions to these rules. Thus, for instance, the c. 1.7-Ga TIB-2 Råtan granite in Jämtland (Fig. 3) mostly bor-

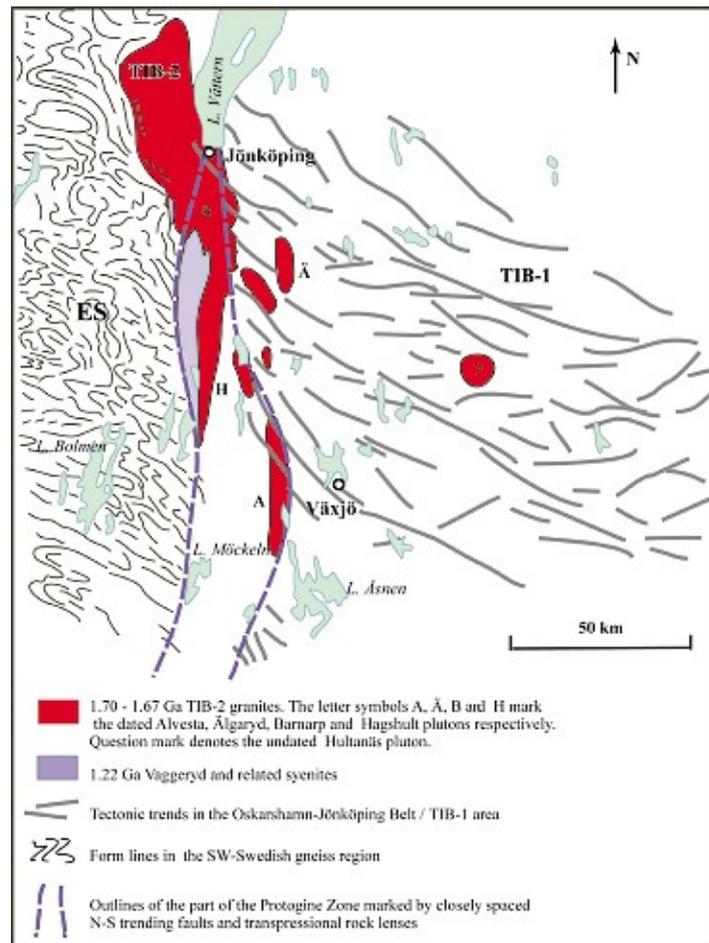


Fig. 2. The relationships between TIB-1, TIB-2, and “Eastern Segment” (ES) rocks and domains in the part of Sweden to the south of Lake Vättern. The ages and sources for the dated TIB-2 intrusions are: Barnarp – 1.69–1.70 Ga (Gorbatshev, Söderlund & Persson in prep.), Hagsbult – 1673±19 Ma (Jarl 2002) and 1690±5 Ma (Welin 1994), Alvesta – 1713+2/-3 Ma (Johansson 1990) and Älgaryd – 1701±3 Ma (single-grain evaporation, Söderlund & Rodhe 1998). These ages are quoted as given in the original publications, i.e. without recalculation.

ders directly on Svecofennian rocks in the east, while substantial deviations of the TIB-1 belt from consistent N-S to NNW trends occur particularly in southeastern Sweden and to some extent also in the Central Svecofennian Province (the so-called Bothnian Basin).

In southern Sweden, recent work (Mansfeld 1996, Beunk et al. 1996, Sundblad et al. 1997, Beunk & Page 2001) has confirmed previous indications (Gorbatshev 1980) of dominantly WNW to W-E tectonic trends. In the southeast, these trends mark the shapes of the individual TIB-1 intrusions as well as the orientation of the dominant gneissose foliation. The tonalitic to granodioritic orogenic rocks of the Oskarshamn-Jönköping Belt (OJB), dated by Mansfeld (1996) and later Åhäll et al.

(2002) at 1.84–1.82 Ga, also strike in the same direction (in Fig. 3, the OJB is marked in yellow in the area to the southeast of Lake Vättern).

Despite the still low numbers of precise age and geochemical data there exist indications that the TIB-1 terrains in Småland and farther north may feature age zoning, with c. 1.81–1.80 Ga rocks mostly in the north and 1.79–1.77 Ga rocks more often in the south. Similarly, the existing data appear to suggest relatively more pronounced alkali-calcic characteristics to the north of the OJB and more calc-alkalic to its south, particularly in the extreme south, in Blekinge. Whether there exists one single or several somewhat different age groups of TIB-1 related volcanic rocks is still unclear.

In conjunction with recent deep seismic surveys, which demonstrate N- to NNE-dipping crustal and mantle reflectors, and stepwise thickening of the crust in the same direction (BABEL Working Group 1993, Lund et al. 2001), the new geological findings suggest that virtually the entire territory to the south of the 1.90–1.86 Ga South Svecofennian Province (the Bergslagen area), including also the TIB-1 intrusions, is built up of southwards younging belts of late Palaeoproterozoic crust (cf. Mansfeld 1996, Beunk & Page 2001).

Recent EUROBRIDGE data and new mapping results suggest that the TIB extends eastwards to the basement beneath the island of Gotland (Sundblad et al. 1998) and into western Lithuania (cf. Bogdanova et al. 2001).

In the area to the south of Lake Vättern, TIB-1 rocks may conceivably continue westwards across the Protogine Zone tectonic boundary (PZ in Fig. 3) into or beneath the Eastern Segment of SW Sweden. The tectonic grain in the two domains trends similarly, but no granitic rocks with protolith U-Pb zircon ages above c. 1.71 Ga (Söderlund et al. 2002) have been identified in the west. As indicated in Fig. 3, the E-W strikes in the TIB-1 region of SE Sweden tend to turn NNW in the western part of that region and farther north, thus in an arc-like manner curving around the southwestern edge of the Svecofennian Domain.

In the Bothnian Basin area, the intrusions of Revsund granite largely form isometric or NW/WNW-trending, partly domal batholiths. The shapes of these massifs appear to be related to the long-lasting deformation of that region (cf. Lundqvist et al. 1998), rather than directly to east-directed subduction. The TIB-1 massifs in the Bothnian Basin tend to have relatively low initial ϵ_{Nd} values, indicating substantial involvement of metasedimentary materials with Archaean detrital components (Patchett et al. 1987, Claesson & Lundqvist 1995, Andersson et al. 2002).

The occurrence area of TIB-2 granitoid rocks reaches its greatest exposed width in the counties of Värmland, Dalarna and southern Jämtland. Within that region, two major belts of plutonic rocks and an intervening area largely occupied by TIB-2 volcanics can be distinguished. However, age determinations are still not numerous enough

to decide whether septa of TIB-1 or other older rocks intervene between the various TIB-2 sub-areas.

One of the belts of TIB-2 granites comprises the Rätan granite marked in Fig 3. From that area towards the north-northwest, positive magnetic anomalies indicate that this granite continues beneath a cover of Palaeozoic sediments and a pile of Caledonide nappes, ultimately to join up with the TIB-2 granite in the Olden basement culmination within the Scandinavian mountain belt. Extrapolating that trend farther northwards, this TIB-2 belt would be expected to reach the Atlantic coast of Norway somewhere close to Glomsfjord and Sjonafjord, but it is not clear whether the TIB-type granites in that area are strictly autochthonous.

The other nearly coherent belt of TIB-2 granites extends from the Caledonide Front in Norway south-southeastwards across the Trysil area into central and eastern Värmland, and farther along the eastern coast of Lake Vänern to the southern tip of Lake Vättern. South of that point there is an almost continuous series of large, nearly NS-trending TIB-2 granite massifs outlining the Protogine-Zone (PZ) boundary between SE and SW Sweden and sharply truncating the nearly west-northwestern tectonic trends of the TIB-1 terrain in the eastern part of that area (Fig. 2). Actually, the incidence of TIB-2 granites along the PZ is probably larger than shown in that map, but only dated rock massifs and a few other bodies confidently attributed to the TIB-2 group were plotted.

In regard to the c. 1.84–1.86 Ga TIB-type rocks, the distribution of the hitherto dated occurrences may suggest affiliation with major crustal province boundaries, in southern Sweden the boundary between the c. 1.9–1.87 Ga South Svecofennian Province (Bergslagen volcanic area) and a domain of later rims of crustal growth farther to the south (cf. Mansfeld 1996), and in central Sweden the boundary between that volcanic province and the Central Svecofennian Province (the Bothnian Basin). These boundaries probably represented rheological discontinuities and possibly also zones of early transpressional and trans-tensional deformation allowing the ascent of mantle melts which interacted with the continen-

tal crust some time before the main mass of TIB rocks began to form.

As a rule, the contacts of the TIB granites with older rocks are clearly intrusive. Single massifs of TIB rocks (mostly TIB-1) occur in the Svecofennian orogenic domain, while isolated intrusions of TIB-2 plutonic rocks are found in

the TIB-1 areas, for instance the one depicted in Fig 2. Even if we, in broad outline, can still speak of TIB-1 and TIB-2 sub-regions and belts, their boundaries are highly irregular in places. The various TIB domains thus represent igneous provinces rather than coherent tectonic terranes or orogens.

1.3. The concept of a Transscandinavian Igneous Belt, previous interpretations and current discussion

The concept of an igneous belt extending obliquely across Scandinavia was developed as work in the basement of the Scandinavian Caledonides indicated that rocks similar to those in the “Småland-Värmland Granite-Porphyr Belt” (SVB, cf. Chapter 2) were exposed in many of the basement “windows” in that mountain range and along its eastern margin (Gorbatshev 1980, 1985). Simultaneously, chemical study demonstrated that these and other rocks subsequently referred to the TIB differ in composition from both the TTG-type subduction-related calc-alkalic plutonics and the S-type leucogranites, generated by the melting of thickened continental crust.

Contributing reasons to introduce the TIB concept were to provide a genetically and chronologically neutral term as a roof for future discussion and modelling and, apart from that, simply to describe a previously unknown major accumulation of igneous rocks trending towards alkali-calcic, A- and I-type compositions.

The term used to describe the TIB was initially “Transscandinavian Granite-Porphyr Belt” (e.g. Gorbatshev 1985), later changed to “Transscandinavian Igneous Belt” (e.g. in Patchett et al. 1987).

The Småland, Värmland, Dalarna, Rätan, Revsund, etc. granitoids have, of course, been known “for ages” and so named at least since the nineteenth century. When the concept of (geosynclinal-) orogenic cycles was adopted in the 1930’s, these rocks were related to various stages of such orogenies. Thus the Småland and Värmland rocks were first classified as “primorogenic (=early orogenic) Gothian” and later as “post-orogenic Svecofennian”. The latter was also the term used in many other cases. The

Revsund granites, however, were discussed in regard as to whether they were “serorogenic” (=late orogenic) or post-orogenic. Similarities with the Finnish rapakivis were also considered (Persson 1978).

With the advent of plate-tectonic modelling, both before and after the introduction of the “Transscandinavian” term in 1980, two groups of hypotheses came to dominate the interpretations. Both took account of the location of the Transscandinavian (and/or Småland-Värmland-) Belt close to a one-time margin of the Proterozoic Fennoscandian proto-craton. One set of interpretations emphasised the effects of active-margin orogeny, explaining the configurations as well as the chemical and structural specifics of the TIB rocks in terms of gentle dips and shallow depths of the subduction zone and/or interaction with pre-existing continental crust during Andinotype orogeny. The other group of interpretations instead focused on interaction of the crust with mantle materials concomitantly with crustal extension. The mechanisms could have been either detachment of the lowermost crust associated with upwelling of the asthenosphere, or back-arc crustal thinning, or gravitational collapse/extensional delamination of previously (over-)thickened lithosphere.

While the present introduction is not intended to consider the particulars and pros-cons of the various interpretations, and there is not even space to do so, the papers by Nyström (1982), Wilson (1982) and, lately, Åhäll and Larson (2000) can be named as instances of the first-named group of hypotheses, while those by Wilson et al. (1985), Johansson (1988), Zuber and Öhlander (1990), Korja et al. (1993), Beunk et al.

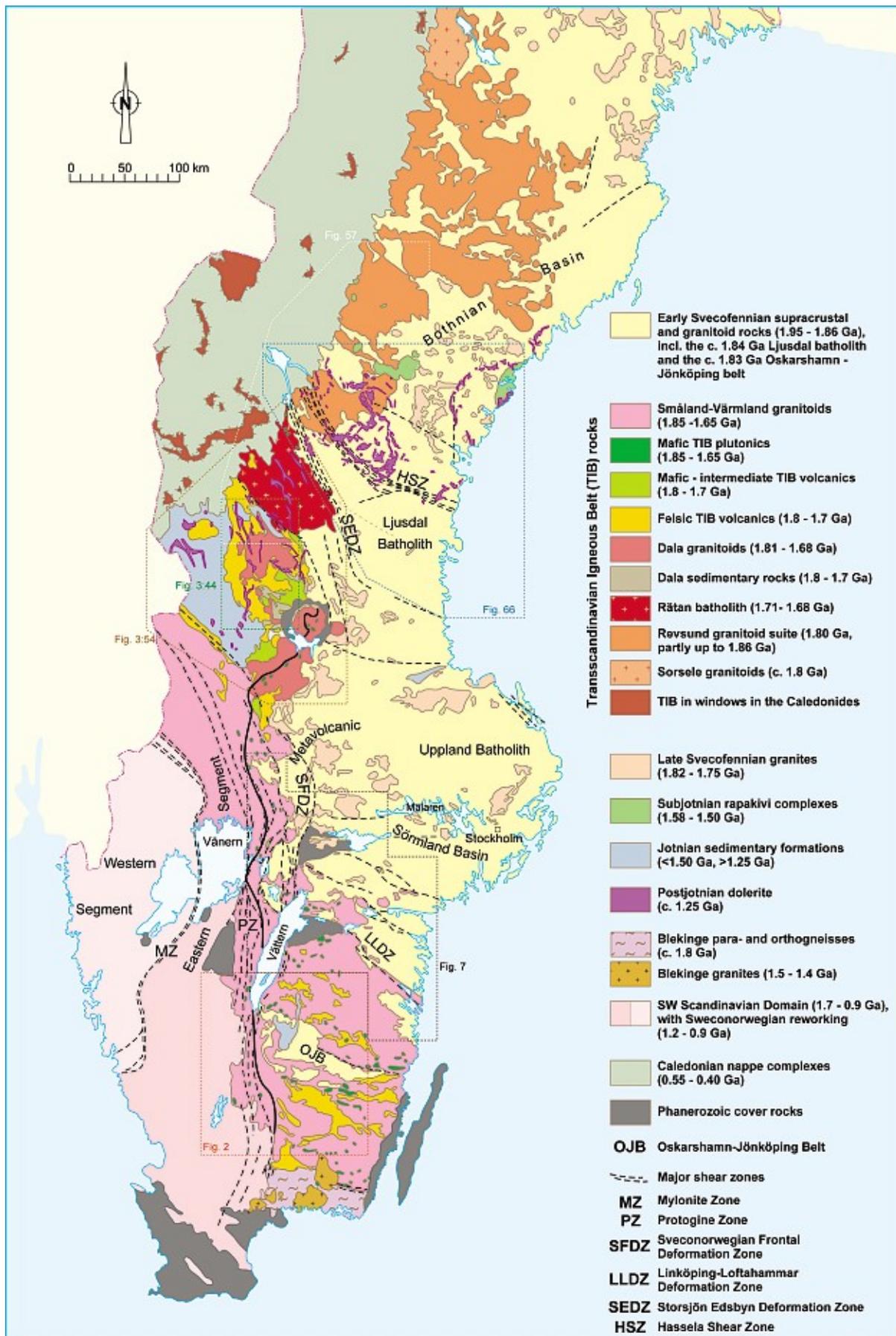


Fig. 3. Geological overview map of TIB in central and southern Sweden, with subdivisions. Modified from Lundqvist et al. (1994) and Koistinen et al. (2001). The frames outline areas of subsequent maps. Solid black line along the Protogine zone marks the approximate border between TIB-0,1 (east) and TIB-2,3 (west) rocks (from Koistinen et al. 2001).

(1996) and Andersson (1997a) are among those emphasising various aspects of the other. In view of the great extent of the TIB rocks in space and time, and the variation of the two principal sub-belts in character, width and, in places, also orientation, it would appear presumptuous to necessarily envisage one single genetic mechanism. A combination of mechanisms covered by the two groups of genetic hypotheses appears possible.

An integrated approach considering aspects of interaction between compression and extension, lower-crust delamination, and a succession of Svecokarelian tectonic and magmatic regimes was proposed by Stephens and Wahlgren (1995).

Recently, isotopic dating in the eastern part of southwestern Sweden and in the Western Gneiss Region of Norway has begun to create a basis for the correlation of the formation of the TIB-2 sub-

belt along the edge of the Svecofennian proto-craton with the creation of a new crustal domain somewhat farther towards the present west.

Against this background, the TIB concept emphasises the importance of large-scale geodynamic study rather than local modeling. However, the idea is not to lump together rocks with similar age ranges, petrography, and geochemistry in order to suggest a single mode of formation. Despite occasional recent use to the contrary, the Transscandinavian-Belt denomination is not either conceived to be the name of an orogeny plus an orogen, a phase of tectonisation or magmatism, or any other event. Still much less is it part of a time terminology covering all rocks of a certain age disregarding place and composition. Even within the Belt, the rocks are late Palaeoproterozoic, not "Transscandinavian" in age.

2. THE SMÅLAND-VÄRMLAND BELT

2.1. Overview

Ulf B. Andersson & Anders Wikström

The Småland-Värmland Belt (SVB) occupies the southern and southwestern parts of the TIB. It consists of plutonic rocks of gabbroic/noritic to granitic compositions and, particularly in Småland, of associated felsic volcanic rocks (Fig. 3), often showing well-preserved volcanic textures (e.g. Persson 1974, 1985). From Blekinge in the south-east, it extends towards the north-northeast where its magmas have intruded and partly tectonically interacted with the Svecofennian rocks along its eastern margin (cf. Chapters 2.3 and 2.4) between c. 1.85 and 1.80 Ga ago. Further northwards, the boundary with the Dala Province in the northeast is poorly known but is presumably dominantly of tectonic nature. The SVB in that area appears to have moved up relative to the dominantly volcanic Dala Province in the east (Magnor et al. 1996). Still further northwards in Norway, the SVB disappears beneath the Caledonide nappes, but is exposed in basement windows (Fig. 3; Gorbatshev 1985, Rehnström 2003).

The age distribution pattern within the SVB is

complex and unknown in many areas. The ages encompass the entire range 1.86–1.65 Ga, where the oldest rocks (1.86–1.83 Ga) generally occur close to or within the Svecofennian marginal rocks. In the field, boundaries between these older and younger SVB granitoids are mostly difficult to define, especially where the older generation is without visible Svecokarelian deformation structures. Petrographic and geochemical characteristics are also indistinguishable between the age groups (cf. Fig. 5, and Andersson & Wikström 2001). This group of oldest SVB rocks has recently been referred to as 'TIB-0' (Ahl et al. 2001).

According to Åhäll and Larson (2000) and Åhäll et al. (2002) TIB-0 (or c. 1.85 Ga 'Askersund suite') are better kept separate from SVB (TIB) as these rocks experienced an early deformation episode and formed prior to the 1.84–1.82 Ga Oskarshamn-Jönköping Belt (OJB), which in turn predates the TIB-1 rocks (below, and Chapter 2.2). However, as pointed out by Andersson

and Wikström (2001), there is no field (except for the more obvious “TIB-0”, conformably folded augen gneisses), petrographical or geochemical evidence to make this distinction. In fact, in several instances (e.g. in the Askersund and Graversfors areas) TIB-0 rocks show post-tectonic relations to the Svecofennian margin rocks (Wikström et al. 1980, Persson & Wikström 1993, Wikström et al. 1997, see Chapter 2.3). Instead, we suggest a more or less continuous magma generation and emplacement of the same type over a long time, where the earliest c. 1.85 Ga rocks mark the beginning of a shift from collision to postcollisional (extensional) regimes. This scenario is compatible with the general TIB-0 to TIB-1 petrographical character and the granitoid subdivision based on tectonic setting devised by Barbarin (1990) (cf. Persson & Wikström 1993).

Most of the rocks in the SVB, however, fall in the age range 1.81–1.76 Ga, traditionally referred to as ‘TIB-1’ (cf. Larson & Berglund 1992), including all volcanic and plutonic rocks of east central Småland (cf. Mansfeld 1996). The volcanic rocks associated with this generation, “the Småland porphyries”, are predominantly felsic and constitute substantial volumes (cf. Fig. 3). The TIB-1 generation apparently also includes the calc-alkaline Tving granitoids (c. 1.77 Ga) of Blekinge in the south (Kornfält 1993), which appear to represent more deep-seated TIB-rocks, uplifted relative to the Småland rocks along the Småland-Blekinge deformation zone (Lindh et al. 2001a).

The WNW-ESE-trending OJB in central Småland, composed of calc-alkaline rocks, was identified by Mansfeld (1996) as c. 1.84–1.82 Ga separate volcanic-arc related terrane (cf. Åhäll et al. 2002) within the SVB (cf. Chapter 2.2; Mansfeld & Beunk 2004), containing also very juvenile, MORB-type components (Sundblad et al. 1997). Åhäll and Larson (2000) and Åhäll et al. (2002) interpreted this terrane as accreted to the Svecofennian margin by c. 1.81 Ga, after which it was intruded/reworked by continental-margin TIB-1 magmatism.

Protoliths for the voluminous SVB granitoid magmatism are normally considered to be equivalent to the juvenile arc-derived early Svecofennian (1.91–1.86 Ga) crust as seen in the Bergslagen area NE of SVB, supplemented by minor mantle-

derived components based mainly on Nd isotope evidence (e.g. Patchett et al. 1987, Andersson 1991, 1997a, other sections of Chapter 2). Such source material may be present at least as far as to the OJB in the south and westwards into the Eastern Segment of the Southwest Scandinavian Domain, although yet unproven. The accretion to or formation of the arc-related OJB along the SW Baltica continental margin at 1.84–1.81 Ga is not in conflict with a development of postcollisional (or ‘postaccretionary’) type magmatism continuously younging southwestwards to the OJB. Gorbatshev (2001) presented evidence for a scenario of WNW-trending SVB belts successively younging from c. 1.82 in the north to 1.79 Ga just north of OJB, representing southwards accretionary and collisional growth (see also Lund et al. 2001). However, these alkali-calcic SVB rocks need calc-alkaline source rocks. A shift, whether gradual or sharp in time, between 1.91–1.86 and 1.84–1.82 Ga calc-alkaline crustal segments is obscured by this voluminous SVB magmatism covering the entire area between Bergslagen and OJB (Fig. 3). Crustal protoliths of the 1.80–1.77 Ga SVB granitoid magmatism south of OJB are, however, most likely of the same age as OJB. The SVB magmatism south of OJB is also less alkaline than in the north, occasionally calc-alkaline (Gorbatshev 2001), and clearly so in Blekinge (Lindh et al. 2001a), possibly again representing a yet younger arc event (at c. 1.77 Ga) in the south.

Geochemical signatures in the mafic SVB rocks of 1.85, 1.80, and 1.70 Ga age generations (Claeson 2001, Claeson & Andersson 2000, Rimsa 2002, Chapter 2.5) indicate the presence of subduction-related mantle sources throughout the formation period of the SVB. This rather suggests continental arc settings (cf. Nyström 1982, 1999, Åhäll & Larson 2000, Claeson 2001).

Westwards, the 1.81–1.76 Ga SVB granitoids are replaced by a younger group of SVB intrusives with ages covering both the TIB-2 and TIB-3 generations (1.71–1.65 Ga) of Larson and Berglund (1992) (cf. compilation in Åhäll & Larson 2000), essentially stretching in a N-S direction. The c. 1.70 Ga rocks are occasionally observed to intrude into TIB-1 rocks (e.g. Wahlgren 1993, Claeson 1999, R. Gorbatshev

pers. comm. 2003), but otherwise the field relations are usually obscured by deformation. The SVB rocks continue into SW Sweden and become progressively overprinted by younger deformation and high-grade metamorphism, dominantly Sveconorwegian in age (e.g. Page et al. 1996, Söderlund et al. 1999, cf. Chapter 2.6). The Protogine Zone marks the onset of westwards penetratively deformed rocks in the Eastern Segment of the Southwest Scandinavian Domain (Gorbatshev 1980), while spaced Sveconorwegian ductile deformation is important also further east up to the Sveconorwegian Frontal Deformation Zone (SFDZ; Wahlgren et al. 1994). During the Sveconorwegian orogeny the rocks of the Eastern Segment were first subjected to considerable tectonic burial (up to eclogite facies conditions in the south; Möller 1998, 1999) and

were later uplifted in the order of tens of kilometres relative to the SVB in the east along the tectonic zones of the Protogine zone (e.g., Johansson 1992, Hegardt 2000).

The penetratively deformed granitoids of the Eastern Segment north of Lake Vänern have been shown on geochemical and geochronological grounds to belong to the SVB rocks (Lindh & Gorbatshev 1984, Lindh & Persson 1990, Söderlund et al. 1999). South of Lake Vänern this is more uncertain, as the gneisses in the Eastern Segment contain high amounts of calc-alkaline rocks (cf. e.g. Gorbatshev 1980, Berglund & Larson 1997). Nevertheless, 'TIB-3' rocks do occur on both sides of the Protogine Zone (Connelly et al. 1996, Berglund & Larson 1997, Wikman 1997, 1998), and some authors prefer to include the 'Gothian basement' gneisses of the

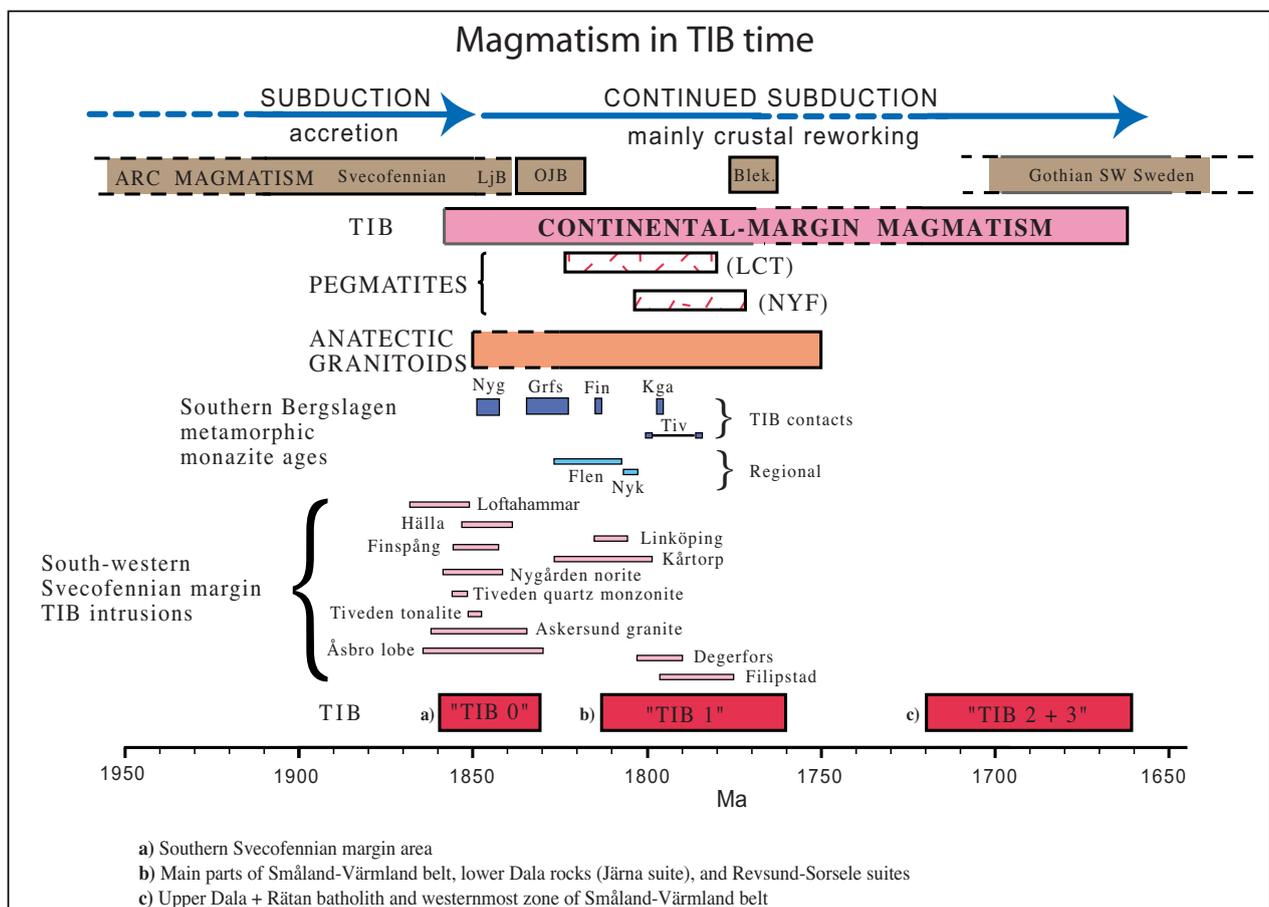


Fig. 4. Magmatic and metamorphic timing in northern Småland-Värmland Belt (SVB) and southern Bergslagen. Contact metamorphic (due to TIB intrusions) monazite ages are from Nygårdens, Graversfors, Finspång, Karlskoga and Tiveden, while the regional metamorphic ages are from Flen and Nyköping (Andersson 1997b). Ages of SVB rocks along the southeastern Svecofennian margin are from Jarl & Johansson (1988), Persson & Wikström (1993), Stephens et al. (1993), Wikström (1996), Andersson (1997a), Andersson et al. (2000), Claesson & Andersson (2000), Wikström & Persson (2002), Bergström et al. (2002). The major TIB episodes are outlined, as well as timing of pegmatites and anatectic granites in the Svecofennian Domain (LCT = lithium-caesium-tantalum-, and NYF = niobium-yttrium-fluorine-type pegmatites; based on Romer & Smeds 1997). Inferred plate-tectonic settings and type of magmatism have been added (see also Chapter 8). LjB = Ljusdal Batholith, OJB = Oskarshamn-Jönköping Belt, and Blek = Blekinge Province.

Eastern Segment among the 'TIB-3' rocks of the western SVB (Söderlund 1999, Andersson 2001). Usually, it is difficult to reliably separate the TIB-3 rocks in the field from the older generation (1.81–1.76 Ga) slightly eastwards (e.g. Wikman 1998, 2000a), although in some areas they appear to occur as distinct textural varieties (Wahlgren 1995, 1996). A geochronologic compilation and subdivision of the TIB can be found in Åhäll and Larson (2000), and summarised in Fig. 4.

In general, the SVB rocks vary compositionally from granite to monzodiorite (Fig. 5a; cf. also Lindh & Persson 1990), and include numerous mafic bodies (Chapter 2.5). Granites and quartz monzonites are dominant, and the geochemical trends are monzonitic and alkali-calcic (cf. Ahl et al. 2001). With respect to alumina saturation (Fig. 5b) they show a wide spread from distinctly metaluminous to strongly peraluminous, but the average is close to molecular $Al_2O_3/(CaO+Na_2O+K_2O)=1$ (1.015; Andersson 1997a). The rocks are generally of I-type, plotting in the intermediate postcollisional field of Pearce (1996a) and transitional between orogenic and anorogenic fields in the plots of Whalen et al. (1987) (Fig. 5c, d). Rocks of more calc-alkaline compositions, granodiorites and even tonalites, do occur among the various SVB age generations (e.g. Wikström & Karis 1998, Wikman 1998), and are even typical of the c. 1.77 Ga orthogneisses

(Tving granitoids) of Blekinge (Kornfält & Bergström 1991, Lindh et al. 2001a). The significance of this, and the high proportion of calc-alkaline gneisses in the Eastern segment south of lake Vänern, is still unclear, although it has been speculated that the progression from alkali-calcic to calc-alkaline magmatism westwards at the TIB-3 stage was related to oceanward migrating, east-dipping subduction beneath the continental margin (e.g. Lindh & Gorbatshev 1984, Åhäll & Gower 1997).

Initial ϵ_{Nd} -ratios of the felsic to intermediate SVB and Dala rocks range from -1.5 to +2.5 (Wilson et al. 1986, Patchett et al. 1987, Andersson 1997a, Nyström 1999, Claeson & Andersson 2000, U.B. Andersson, unpubl. data), and plot within the time-integrated evolution of the early Svecofennian metaigneous crust (Fig. 6). The Nd isotope data thus support an intracrustal derivation from such sources (cf. Lindh & Persson 1990, Lindh & Johansson 1995). The early Svecofennian crust is to a large degree of granodioritic-tonalitic composition (e.g. Nurmi & Haapala 1986). Major and trace element geochemical modelling (Andersson 1997a) indicates that SVB granites with c. 70 % SiO_2 could have been derived by 25–40 % partial melting of such sources, while granitoids of lower SiO_2 contents should contain mixing components other than crustal melts (cf. Chapter 2.5).

Fig. 5a–d. Geochemical plots of TIB and related rocks from the southern, Småland-Värmland areas. GDG = Granitoid-dioritoid-gabbroid suite from the Bergslagen area, i.e. suite of early Svecofennian plutonics, GSDG = Granitoid-syenitoid-dioritoid-gabbroid suite from the Bergslagen area, i.e. other TIB-data from that area. Sources of data: Andersson (1997a), Wikström & Karis (1991, 1998), Wikström (1975), Wikström et al. (1980), Wikström & Aaro (1986), U.B. Andersson (unpubl. data), Andersson & Wikström (unpubl. data), data from "the Bergslagen project, SGU" (Stephens et al. in prep). In parentheses are given the approximate age of each suite. In a) also basic-ultrabasic rocks are included. **a)** total alkali vs. SiO_2 plot with classification fields after Middlemost (1994). The SVB rocks display a pronounced alkali-calcic, monzo-trend, with the exception of the Finspång massif which together with a special suite from Tiveden show calc-alkaline characteristics. The early Svecofennian plutonism is also distinctly calc-alkaline. **b)** The Småland-Värmland Belt granitoids rocks from most areas spread rather evenly around the met-peraluminous border, with the exception of the strongly peraluminous Finspång rocks. **c)** In the FeO^*/MgO vs. $10000^*Ga/Al$ diagram after Whalen et al. (1987) rocks from all areas are transitional between the I+S- and A-type granite fields, but at rather low FeO^*/MgO values compared with classical A-type rocks as e.g. rapakivi granites (cf. Fig. 55c; Rämö & Haapala 1995, Andersson 1997a,d). **d)** In the Rb vs. Y+Nb plot after Pearce (1996a) all the rocks plot in the circular intermediate area encompassing post-collisional granites. However, all analyses of the Gåsborn and Loftahammar granites fall at more elevated Nb+Y contents and thus show more within-plate affinity, compared with the Askersund and Kårtorp rocks which are transitional.

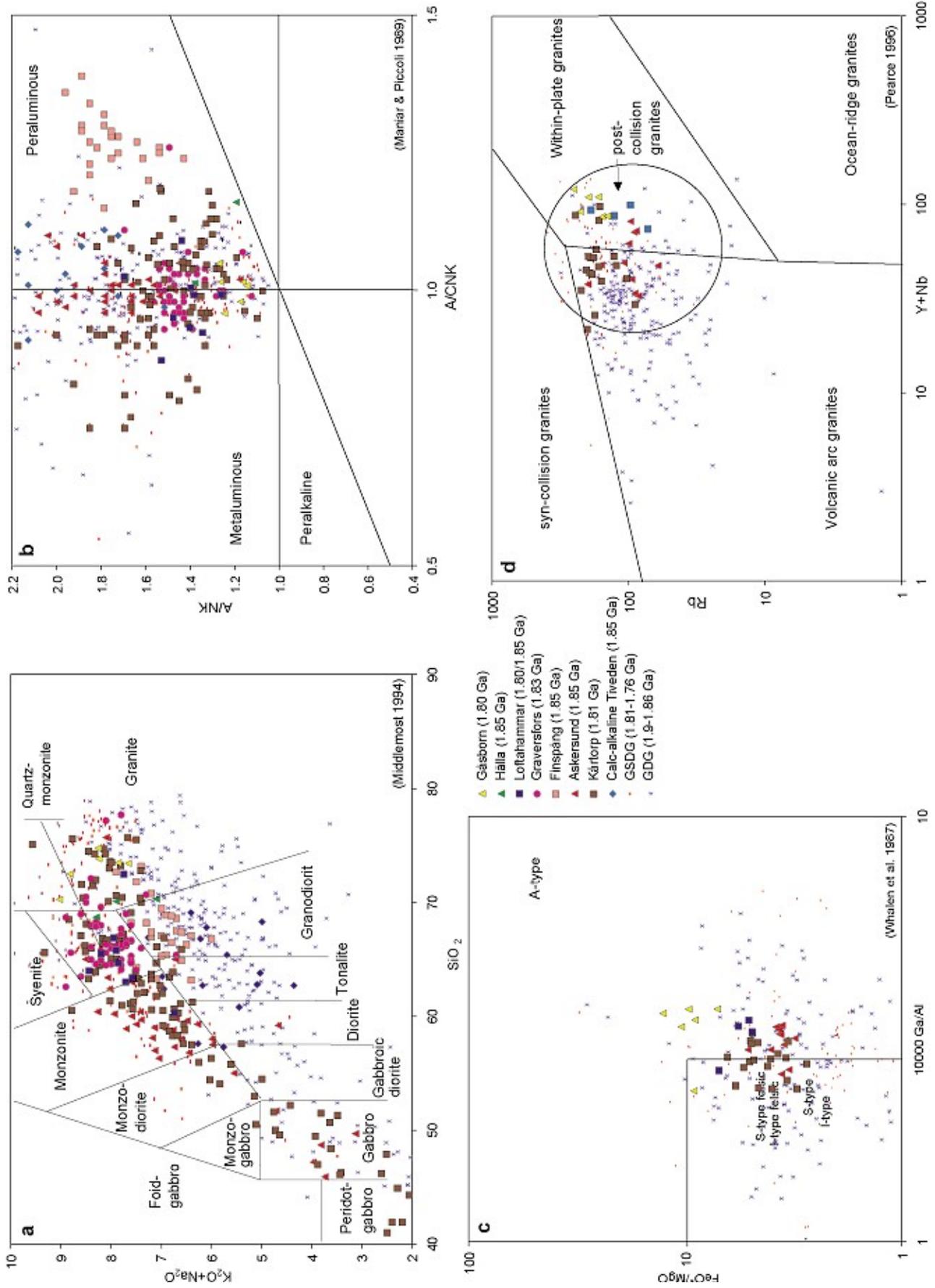


Fig. 5a-d.

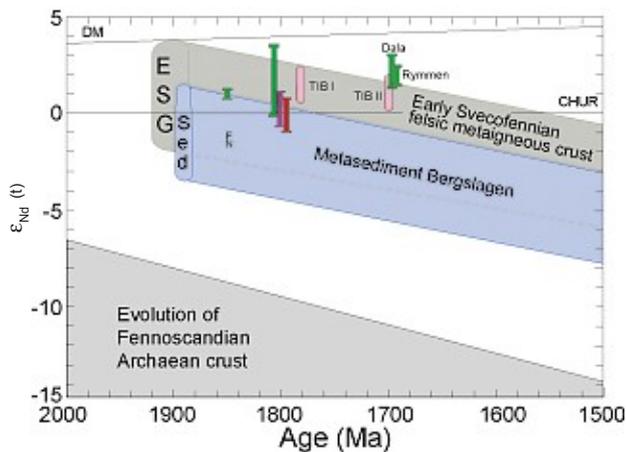


Fig. 6. Schematic representation of initial ϵ_{Nd} values for TIB rocks in relation to the time-integrated ϵ -evolution of some Fennoscandian crustal sources (as compiled in Andersson 1997a). DM is the depleted mantle of DePaolo (1981). Sed = sedimentary rocks from the Bergslagen area, ESG = early Svecofennian granitoids and felsic volcanics. Pink ovals include silicic-intermediate TIB-1 and TIB-2 rocks reported by Wilson et al. (1986), Patchett et al. (1987), and Nyström (1999), and Chapters 2.2, 2.3, 2.4, 3.2, 4.1 (U.B. Andersson, unpubl. data, J. Mansfeld unpubl. data, Ahl et al. in prep.). F is the Finspång augen gneiss (Chapter 2.3.7) and N is a gneissic TIB granite at the contact of the Nygård norite (chapter 2.4.1). Green, violet, and red bars at c. 1800 Ma represent basic, intermediate, and granitic Småland-Värmland Belt rocks, respectively, reported by Andersson (1997a), including data from mafic rocks in the Loftahammar area (Chapter 2.3.2) and the Hoting gabbro of RGS (Larson & Hellström 2003), while the green bars at c. 1700 Ma are mafic rocks from Nyström (1999) and Claeson (2001). Green bar at 1.85 Ga are mafic rocks of the Nygård pluton (Claeson & Andersson 2000).

2.2. The Småland-Värmland Belt in southeastern Sweden

Joakim Mansfeld

In southeastern Sweden the SVB is divided into two areas by the WNW-trending OJB, which is clearly an older unit relative to TIB-1, and part of a calc-alkaline, younger “Svecofennian” phase (Mansfeld 1996). The SVB unit north of the OJB forms a homogenous and continuous batholith, the Vimmerby Batholith (Söderhielm & Sundblad 1996). In regional magnetic and gravimetric anomaly maps the Vimmerby Batholith comprises a homogenous pronounced very high magnetic and low gravimetric ellipsoid body (e.g. Henkel et al. 1990, Eriksson & Henkel 1994). The Vimmerby Batholith is bordered in the north by the c. 1.85 Ga Askersund and Finspång intrusions (cf. Chapter 2.3), to the east by the Svecofennian rocks of the Västervik area, and to the west by lake Vättern. The Vimmerby Batholith comprises mainly red to grayish red coarse-grained granitoids. In its central parts it is associated with rhyolitic volcanic rocks (Fig. 3). These, usually well preserved units, include ignimbrites, tuffs, volcanic breccias, and possibly lavas (Persson 1974, 1985). All U-Pb zircon ages of intrusions in the Vimmerby Batholith range between 1808 and 1794 Ma (Patchett et al. 1987, Jarl & Johansson 1988, Mansfeld 1991, Kornfält et al. 1997).

There are still very few age determinations of the volcanic rocks, but the ages, in combination with field evidence, suggest a co-magmatic rela-

tionship between the intrusive and extrusive rocks, and that the former intruded into the latter. The best age estimate of rhyolites within the Vimmerby Batholith comes from an age of 1813 ± 3 Ma (Wikström 1993), which indicates a c. 10 m.y. age difference between the extrusive and intrusive rocks.

The SVB rocks south of the OJB are not identified as one homogenous unit. In the east the SVB rocks are covered by Cambrian and Ordovician sedimentary sequences. Also the concealed Precambrian basement of Öland probably comprises SVB granitoids. However, there is no clear evidence of any SVB rocks farther to the east, e.g. in the Precambrian basement of Gotland (see e.g. Gyllencreutz & Sundblad 1999). To the south the SVB is separated from the Blekinge area by a major shear zone (Lindh et al. 2001a).

The western border of SVB in southern Sweden is traditionally considered to be the Protogine Zone, but more or less deformed intrusions belonging to the SVB are identified far west of this zone (cf. Chapters 1.2; 2.1). The age pattern of the c. 1.8 Ga rocks south of the OJB is more irregular, although almost consistently younger than the Vimmerby Batholith. Ages for the intrusive rocks varies between 1793 and 1766 (Patchett et al. 1987, Jarl & Johansson 1988, Mansfeld 1991, Wikman 1993). Large areas of felsic volcanic rocks are also associated with the SVB intru-

sions. Two U-Pb ages of rhyolites of 1800 ± 8 (Mansfeld 1996) and $1791 + 50 / - 41$ Ma (Wikman 1993) suggest an age difference of c. 10 m.y. between extrusive and intrusive rocks also in the southern part of the SVB.

The transition from c. 1.8 Ga (TIB-1) to c. 1.7–1.65 Ga (TIB-2&3) SVB granitoids is not possible to be identified petrologically, i.e. there is no difference in appearance or composition between the older and the younger suite. Based on available U-Pb zircon ages the boundary could approximately be placed between Huskvarna at the southern tip of lake Vättern to east of Alvesta and then in a more south-easterly direction towards the anorogenic Spinkamåla intrusion in the Blekinge region. That is, the border between TIB-1 and TIB-2+3 is consistently located east of the Protogine Zone.

Mafic plutons, mainly gabbros, but also quartz diorites, anorthositic gabbros, and ultramafic rocks (dunites, peridotites), are associated with the SVB granitoids (Fig. 3). Especially close to the OJB (both north and south) these mafic plutons are common. Magma mingling in the form of mafic enclaves, dyke trains, and small scale hybridisation is a common phenomenon in conjunction with the mafic bodies. The ubiquitous evidence of mingling suggest a co-genetic relationship between the felsic and the mafic rocks, but so far the only dated mafic pluton is the Rymmen gabbro c. 25 km northwest of Alvesta, which has an age of 1692 ± 7 Ma (Claeson 1999).

Mafic and felsic dykes (the latter also called “Småland dyke porphyries”), including composite dykes, are widespread in the SVB of southeastern Sweden (Nilsson 1992). These dykes confirm a co-genetic relationship between felsic and mafic magmas, and U-Pb zircon ages between 1805 and 1770 Ma firmly puts them as parts of the SVB system (Nilsson & Wikman 1997, Johansson 1999).

One unusual character of the SVB rocks in the eastern part of the Vimmerby Batholith is the occurrence of small base-metal deposits hosted by SVB rocks. These occur in the Ramnebo area, c. 30 km SSW of Västervik (Ahl 1989, Sundblad & Ahl 1999), and around Vimmerby. Further-

more, there is a small galena mineralisation in a rhyolite at Ålatorp c. 35 km ENE of Växjö. The Ramnebo deposit was probably formed by late magmatic fluids, possibly in conjunction with formation of the earliest ductile WNW-trending shear zones. The Ålatorp deposit was probably also formed by late magmatic fluids, and it has been compared to a porphyry copper system (Sundblad 1997, Sundblad & Ahl 1999).

Chemically the SVB rocks in southeastern Sweden are alkali-calcic and they have continuous compositional trends from gabbro to granite (Fig. 5). Rocks with tonalitic, i.e. calc-alkaline, compositions are very rare. Discrimination diagrams based on trace elements according to Pearce et al. (1984) usually yield “within plate granite” characteristics but straddling “volcanic arc granite” compositions (Fig. 5). A subduction component is also evident in mantle-normalised spider diagrams with pronounced negative Nb, Ta, and Ti anomalies. The REE pattern is usually steep for the LREE, with La and Ce enrichment factors up to several hundred. HREE patterns are usually less steep or flat, and Eu anomalies are slightly negative (cf. Persson 1985, Persson 1989, Ahl 1989, Kornfält et al. 1997, Mansfeld unpubl. data). Major and trace element compositions suggest a calc-alkaline crustal precursor as source to the felsic members of the SVB. The most probable source is a crust comparable to the calc-alkaline OJB. This is also supported by ϵ_{Nd} -values of c. +1 to +2 in SVB rocks in southeastern Sweden (Wilson et al. 1985, Patchett et al. 1987, Mansfeld unpubl. results; cf. Fig. 6).

The age relationship between Svecofennian calc-alkaline rocks and the more alkaline SVB rocks in south-central and southeastern Sweden suggests that in a genetic sense the SVB is a true post-orogenic magmatic suite. The c. 1.85 Askersund-Loftahammar intrusions border the c. 1.89 Ga Svecofennian sequences (cf. Chapter 2.3), the c. 1.81–1.80 Ga Vimmerby Batholith borders the late 1.85–1.84 Ga Svecofennian units in the Åtvidaberg area (Dobbe et al. 1995), and the 1.79–1.77 Ga SVB rocks are found south of the c. 1.83–1.82 Ga Oskarshamn-Jönköping Belt.

2.3. Geological features of the Småland-Värmland belt along the Svecofennian margin, part I: from the Loftahammar to the Tiveden-Askersund areas

Anders Wikström & Ulf B. Andersson

2.3.1. Introduction

The relationship between the SVB and the Svecofennian Domain is a highly controversial issue mainly because there are difficulties to strictly define SVB (or TIB) contra Svecofennian rocks and processes.

The recent debate between Andersson and Wikström (2001) and Åhäll and Larson (2001) highlights some of the key issues in the interpretation of the geological development during the final stages of the Svecokarelian orogeny in south-central Sweden. One of the major questions in this debate was how to treat the Askersund suite (or TIB-0; see Chapter 2.1) with an age of c. 1.85 Ga in relation to SVB granitoids with ages of c. 1.800 Ma. Andersson and Wikström (2001) wanted to incorporate the Askersund suite in the TIB while Åhäll and Larson (2001) did not (maintained in Åhäll et al. 2002), mainly for tectonic reasons.

Thus, the distribution of crystallisation ages of the SVB rocks and their relation to the deformation are not clear-cut along the Svecofennian margin (cf. Fig. 7). The earliest recognised group of SVB rocks, TIB-0, has ages in the range 1860–1830 Ma (Figs. 4 and 7), and includes the Tiveden and Askersund areas, the Åsbro lobe, the Nygårdens pluton, the Finspång massif, the Graversfors intrusion, and the Hälla and Loftahammar augen gneisses (Åberg 1978, Persson & Wikström 1993, Wikström 1996, Andersson 1997b, Andersson et al. 2000, 2004, Claeson & Andersson 2000, Wikström & Persson 2002, Bergström et al. 2002), whereas rocks in other marginal areas are younger (1.81–1.78 Ga), e.g. the Kårtoorp-Roxen-Linköping and Karlskoga-Filipstad areas (Jarl & Johansson 1988, Stephens et al. 1993, Andersson 1997a, b), as well as parts of the Loftahammar area where the granitoids are comingled with 1.80 Ga mafic plutonic rocks (Chapter 2.3.2 below).

As can be seen in Fig. 5 indisputable SVB and 1.85–1.83 Ga granitoids have overlapping chemi-

cal signatures (except Finspång) and also have many textural and petrographical features in common. This makes it difficult to distinguish them in the field. The older generation has partly been involved in the Svecokarelian structural development which in the past has led to various interpretations. The old age of this generation is a fairly recent discovery (Persson & Wikström 1993). A summary of the different views on this topic was given by Wikström et al. (1997).

Structurally the rocks of the TIB-0 generation range from seemingly massive to strongly deformed amphibolite-facies augen gneisses. This transition from magmatic to metamorphic structures is in most places gradual. Deformed rock types are conformable with and occupy positions close to ambient Svecofennian gneisses, partly as separate sheets within them (Wikström 1991). Gneissic types are typical for the Finspång, northern Askersund, Åsbro, Hälla, and parts of the Tiveden and Loftahammar areas (Fig. 7). In other places, massive SVB granitoids of this generation (e.g., the Graversfors intrusion and eastern part of the Askersund intrusion) cut the Svecokarelian structures.

The SVB rocks along the southern and western Svecofennian margins are characterised by high-potassium alkali-calcic chemical compositions and dominated by coarse-porphyritic granites to quartz monzodiorites ('Filipstad type granitoids') (Fig. 8), typically displaying irregularly rounded, in part plagioclase-mantled K-feldspar megacrysts. More even-grained, generally felsic granites ('Växjö type granites') occupy minor areas (Fig. 9). Mafic-intermediate rocks are essential parts, e.g. in the Kårtoorp, Tjällmo-Vättern, Tiveden, Linköping, Stavsjö-Jönåker, and Loftahammar areas. Mafic magmatic (partly hybrid) enclaves are unevenly distributed but generally common throughout the whole area.

The age of the Tjällmo-Vättern Zone, situated between the c. 1.85 Ga Tiveden/Askersund and 1.81 Ga Kårtoorp areas, is particularly problematic (Fig. 10). Geological observations as well as

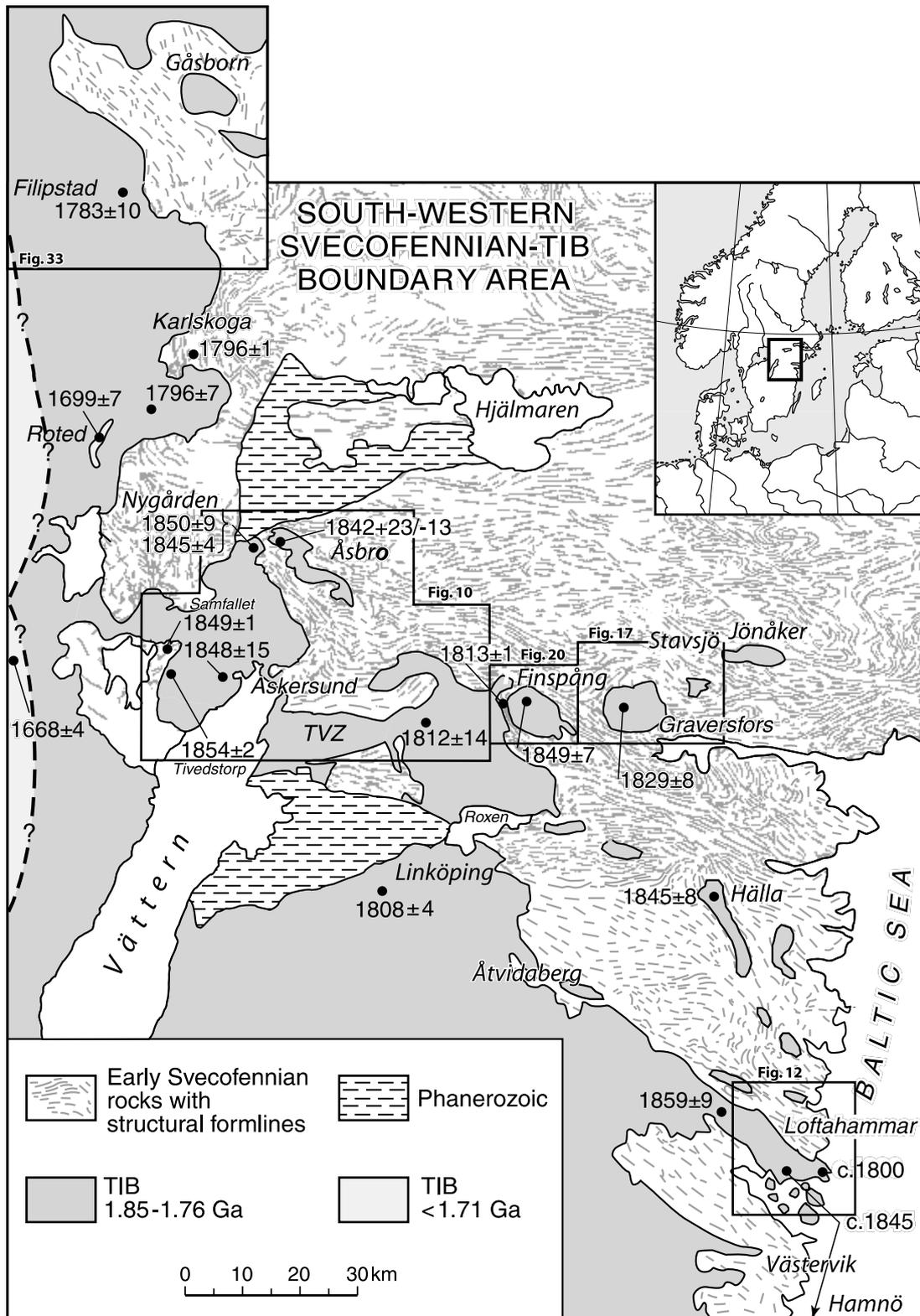


Fig. 7. Overview sketch map of the boundary area between the Småland-Värmland Belt and the southern Svecofennian Domain (modified after Andersson & Wikström 2001). Frames outline extent of subsequent figures in Chapter 2. Age data are from Åberg (1978), Jarl & Johansson (1988), Stephens et al. (1993), Persson & Wikström (1993), Wikström (1996), Andersson (1997a,b), Söderlund et al. (1999), Andersson et al. (2000), Claeson & Andersson (2000), Bergström et al. (2002), Wikström & Persson (2002), and F.J. Hellman (unpubl. data). The distribution of ages shows that both TIB-0 (1.86–1.83 Ga) and TIB-1 (1.81–1.76 Ga) rocks extend to the Svecofennian margin.

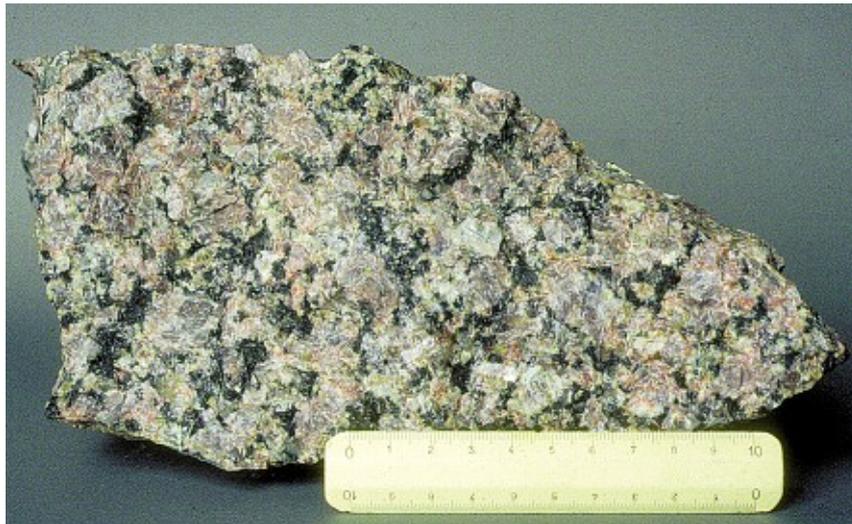


Fig. 8. Typical coarse-porphyritic Småland-Värmland Belt granitoid ('Filipstad type') from the Tjällmo-Vättern zone (sample 8823 in Andersson 1997a).

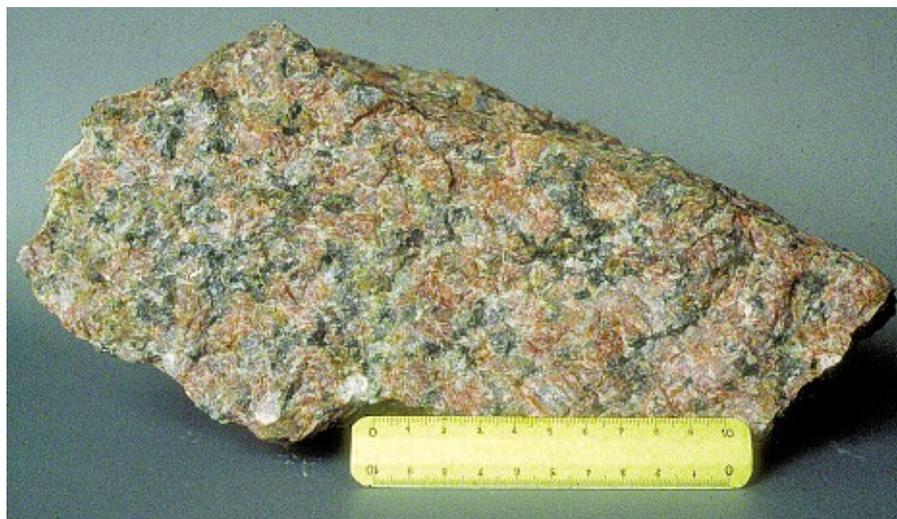


Fig. 9. Example of coarse, even-grained, and felsic Småland-Värmland Belt granite ('Växjö type') from the Tjällmo-Vättern zone (sample 8825 in Andersson 1997a).

geophysical studies indicate continuous transitions at both ends of the zone.

The Svecofennian rocks along the border of the SVB exhibit a granulite facies peak in an overall regional amphibolite facies metamorphism. The peak PT-values for this SVB-related contact metamorphism are 700–830°C and 4–6 kbar (Andersson et al. 1992, Wikström & Larsson 1993, Andersson 1997b, Fig. 11), implying intrusion depths of 15–25 km, while conditions of regional metamorphism have been estimated at <650°C and <4 kbar (Stålhös 1991, Sjöström & Bergman 1998). The indicated increase in pressure in the vicinity of the TIB intrusions may partly be related to country rock depression in

conjunction with the emplacement of the midcrustal TIB magmas, that was later compensated by uplift relative to the regionally metamorphosed areas (Andersson 1997b).

Ages of contact and regional metamorphism are overlapping in the range 1.85–1.78 Ga (Fig. 4; Romer & Öhlander 1994, 1995, Andersson 1997b), and overlap also with those of the SVB magmatism, as well as with the 'late Svecofennian' magmatism in Bergslagen (1.85–1.75 Ga; Öhlander & Romer 1996, and references therein). Beunk and Page (2001) reported a U-Pb titanite age of 1782±11/-9 Ma from the Loftahammar-Linköping deformation zone that transects the Loftahammar granite.

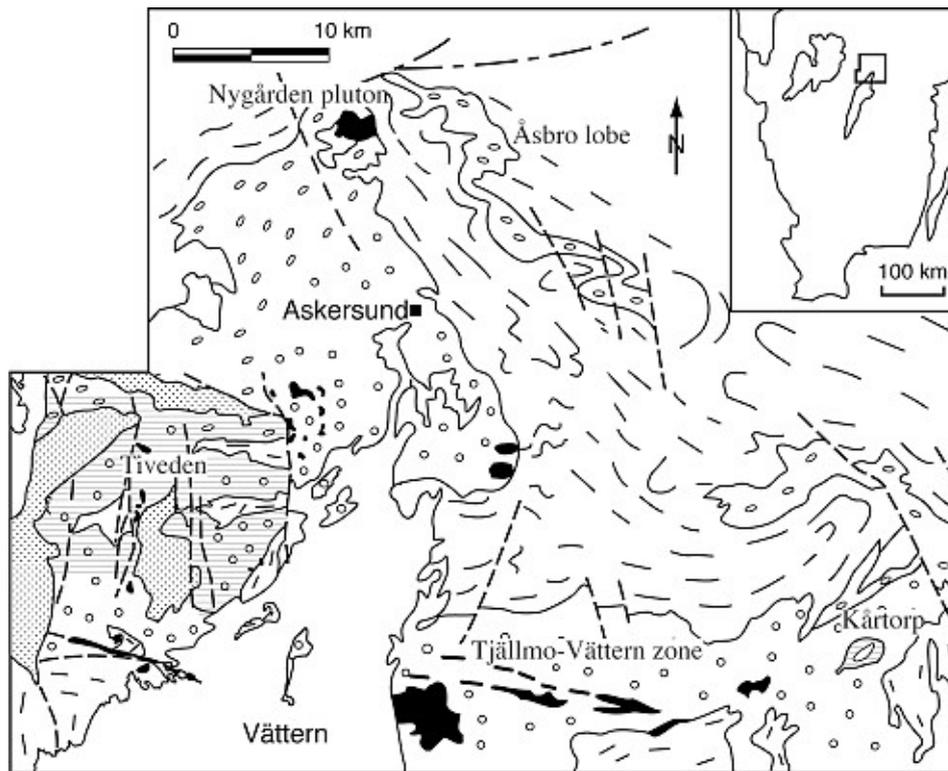


Fig. 10. Sketch map showing the location of the Kårtoorp, Askersund, and Tiveden areas, the Tjällmo-Vättern zone and the Nygårdén pluton (modified after Wikström 1987, Wikström & Karis 1991, Wikström 1995, and Andersson 1997a). Unfilled circles, ruled, and black areas represent granitoid, intermediate and basic Småland-Värmland Belt rocks, respectively. Oval circles show areas of penetratively deformed Småland-Värmland Belt granitoids. Areas with form lines are early Svecofennian rocks. Stippled areas outline calc-alkaline Småland-Värmland granitoid units in Tiveden.

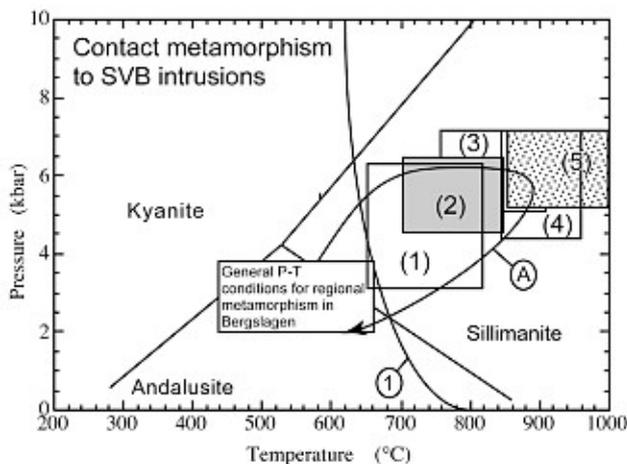


Fig. 11. Estimated peak contact metamorphic conditions in early Svecofennian rocks at different localities close to SVB intrusions (Andersson et al. 1992, Wikström & Larsson 1993, Andersson 1997b, U.B. Andersson unpubl. data). (1) Karlskoga area, (2) Tiveden area, hornfels xenolith in Graversfors intrusion and Gt-Cd gneisses at some tens of m away from the Nygårdén norite, (3) Finspång contact hornfels, (4) contact to the Roted intrusion, Karlskoga area, and (5) just at the contact to the Nygårdén norite. Curve labelled A is a suggested P-T path for the high-grade rocks, in the vicinity of TIB intrusions. Curve labelled 1 shows the approximate conditions for beginning of melting in pelitic systems (after LeBreton & Thompson 1988). Approximate P-T area for regional metamorphism in Bergslagen after Stålhös (1991), Sjöström & Bergman (1998) and Andersson (1997b).

The voluminous SVB magmatism thus occurred simultaneously with high heat flow and anatectic magma generation ('late Svecofennian' granites and pegmatites) within the adjoining Svecofennian (Bergslagen) area. Possibly this was due to a major episode of mafic underplating which initiated heat and magma transport to higher crustal levels (Andersson 1991, 1997a, b, Sjöström & Bergman 1998). The mafic underplating may now be seen as a thick mafic lower crust (high-velocity layer; Korja et al. 1993), particularly under the northern part of SVB and southern Bergslagen area (cf. Lund et al. 2001, and references therein). Areas which have been subjected to comprehensive investigations are described in more detail below.

2.3.2. The Loftahammar area

A geological overview of the Loftahammar area is given in Fig. 12. The stratigraphic position of the Loftahammar coarse-porphyritic gneissic

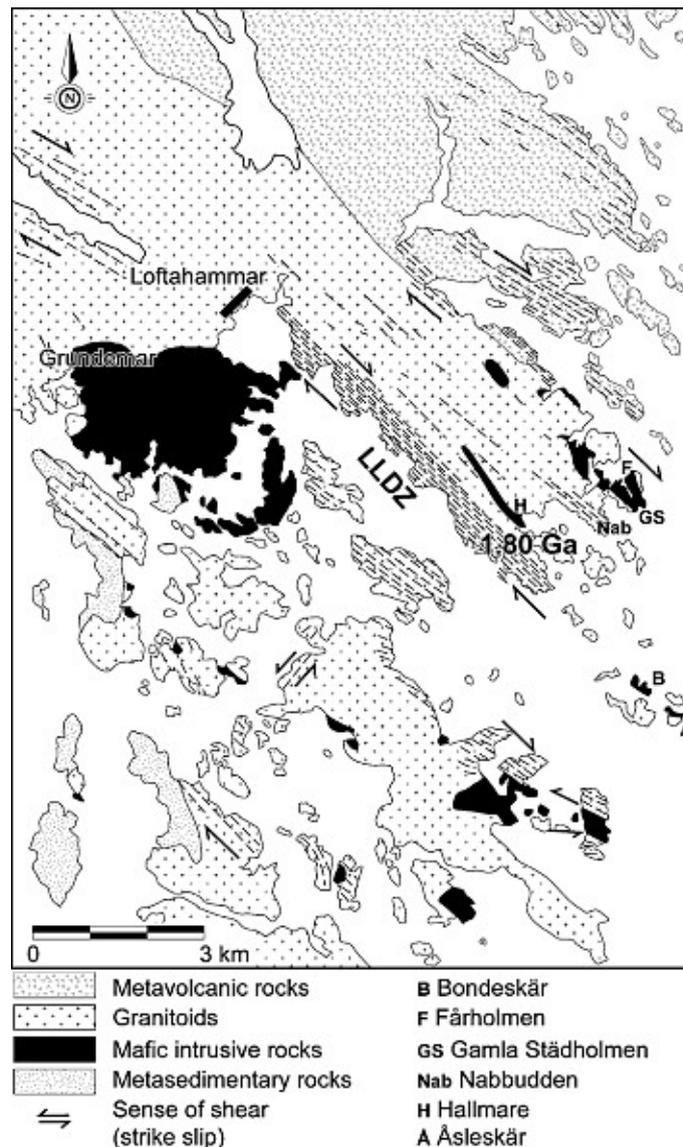


Fig. 12. Outline of the geology in the Loftahammar area (modified after Beunk & Page 2001). Å and F are Åsleskär and Fårholmen, respectively, from which the mafic Nd isotope samples were collected. Both these occur as NW–SE elongated stretches of synplutonic mafic megadykes within the coarse porphyritic Loftahammar granite, where abundant mafic-felsic magma mingling/mixing structures can be observed (cf. Wikström 1988a,b). The Hallmare gabbro (H), dated at c. 1.80 Ga (F.J. Hellman unpubl. data), is part of such a synplutonic system. Nab marks the locality of one of the felsic Nd isotope samples at Nabbudden. LLDZ = the Loftahammar-Linköping Deformation Zone, which extends further to the NW (cf. Fig. 3).

granite or augen gneiss has been extensively debated. The main controversy has been circulating about the issue if this rock belongs to the older Svecofennian plutonic rocks (e.g. Gavelin 1904, 1905, 1910, Gavelin 1984, Kresten 1986, 1988) or if it is part of the SVB (e.g. Holmquist 1905a, b, Westra et al. 1969, Elbers 1971, Priem & Bakker 1973, Wikström 1988a, b). It has also been claimed that the northern part of the massif

is a metasomatically granitised mafic volcanic rock (Kresten 1986, 1988), that contains K-feldspar porphyroblasts (cf. Fig. 13). This was contested by Wikström (1988a, b) who found synplutonic mafic dykes showing abundant mingling and mixing relations with the granite host (Fig. 14). He reinterpreted this unit as mylonitised granite mingled and mixed with coeval mafic magma. Mingling and mixing between mafic and



Fig. 13. Mylonitised, hybrid Loftahammar granitoid, previously formed by magma-mixing/mingling. Diameter of coin is 25 mm.

granitic magmas were regarded already by Gavelin (1910) as the likely cause for these structures. The nature and origin of the K-feldspar megacrysts in the massif have been described and discussed by Mehnert & Busch (1985) and Vernon (1990), who concluded that the augens are porphyroclasts originally crystallised from the granite magma.

The massif is geographically closely related to a major dextral shear zone, the Loftahammar-Linköping Deformation Zone (Beunk & Page 2001; Figs. 3 and 12). Beunk & Page (2001) have mainly described the post-emplacement deformation structures in this zone (and surrounding areas) but some mafic, co-mingled synplutonic dykes within the massif with a regional, seemingly original orientation parallel to this zone, suggest that this deformation zone was active already during emplacement.

Age determinations from the Loftahammar area are somewhat contradictory (Figs. 7 and 12). Åberg (1978) obtained an upper intercept age close to 1845 Ma for zircon fractions pooled from several samples, including the Loftahammar granite and rocks from the Öro-Hamnö intrusion south of the Loftahammar area, which have been compared with the Loftahammar rocks. He also



Fig. 14. Untectonised magma-mingling structures in one of the mafic synplutonic megadykes within the Loftahammar granite at Gamla Städsolmen (GS in Fig. 12). Length of hammer is c. 55 cm.

observed frequent cores in the crystals. Although he avoided such grains, the fractions scatter considerably around the discordia. Kleinhanns et al. (1999) reported U-Pb zircon ages of c. 1.72 Ga and c. 1.85 Ga for two intrusive phases of the Örö-Hamnö intrusion. Pooled together, they yield 1825 ± 9 Ma which was interpreted as the intrusion age (Kleinhanns et al. 1999, Beunk & Page 2001). Recently, Bergström et al. (2002) cited a U-Pb zircon age of 1859 ± 9 Ma for the Loftahammar granite further to the NE along the Svecofennian margin (Fig. 7). The dating was made on four fractions, consisting of 2–5 zircon crystals each, clear and without visible cores, giving a well-defined discordia (P.-O. Persson and H. Wikman, pers. comm. 2002). However, the Hallmare gabbro in the SE, which shows comingling relations with the Loftahammar granite, has yielded a rather precise age close to 1800 Ma (F. Hellman, pers. comm. 2000). These contradictory results suggest a considerable variation in space and time of the intrusion of the Loftahammar granitoid, but components of inherited material in the zircons of the older Loftahammar granitoids cannot be entirely dismissed (cf. Åberg 1978, P.-O. Persson, pers. comm. 2002). However, a recent Nd isotopic study (U.B. Andersson, unpubl. data) on two Loftahammar granites resulted in relatively juvenile $\epsilon_{Nd}(1.80)$ values (between 0 and +1.0), suggesting that crustal source components should be sought among early Svecofennian metaigneous lithologies, in similarity with TIB granitoids from most other areas (Fig. 6). Two samples of the mafic rocks that are comingled with the granites on islets outside the Hallmare peninsula yielded rather depleted $\epsilon_{Nd}(1.80)$ values between +1.0 and +3.5.

Chemical analyses of rocks from the Loftahammar granitoid massif show in general compositions similar to rocks from elsewhere in the SVB (Fig. 2.3). Various mixed hybrid rocks range in composition towards the associated coeval mafic rocks (Andersson & Wikström, unpubl. data).

2.3.3. Augen gneisses in the area between Loftahammar and Norrköping

Within the Svecofennian marginal areas along this transect several bodies of augen gneiss are

found (Wikström & Persson 2002) (Fig. 7). Their lithotectonic position have also been debated, similarly to the Loftahammar granitoids. During early mapping they were considered as ‘younger granites’ and grouped with the SVB batholiths further west (Asklund 1923, 1928, Sundius 1928). Sundius (1927) questioned this classification based in part on the argument that they are regionally metamorphosed and deformed in contrast to the SVB granitoids in the west and also have local gradual transition to the older rocks. However, they are only affected by late phases of regional folding, rendering them an uncertain stratigraphic position. The recent U-Pb zircon age of the Hällaugen gneiss of 1845 ± 8 Ma (Wikström & Persson 2002) sets this group into the same age frame (1.85(6)–1.83 Ga) as other marginal and satellite intrusions along the Svecofennian border zone (TIB-0). Petrographic and geochemical data (geochemistry very limited; Fig. 5) are also indistinguishable from the latter rocks.

2.3.4. The Linköping area

In the area around Linköping (Fig. 7) the SVB rocks and their contact relations to the Svecofennian margin have been studied in detail in several map descriptions (Blomberg 1909, Magnusson 1922, 1924, Gorbatshev 1975, Kornfält 1975, Gorbatshev et al. 1976, Wikman et al. 1980, Persson et al. 1981) and other publications (Gorbatshev 1971, Wilson et al. 1986, Jarl & Johansson 1988). Two types of granitoids are clearly discerned: 1) coarse-porphyritic granites to monzodiorites (‘Filipstad-type’), where the K-feldspar megacrysts diminish in size in the latter, 2) and even-grained and medium- to coarse-grained dominantly granites (*s.s.*) (‘Växjö-type’). The latter are generally considered to be younger than the former. Both types display in this area a ‘postorogenic’ cross-cutting character in relation to Svecofennian structures, and are undeformed except for local flow orientation of crystals associated with emplacement.

However, of special importance in the regional framework is the description of the ‘Linghem schistosity belt’ (Gorbatshev 1971, 1975) which consists of a mainly porphyritic, sheared and cataclastically deformed granite in a planar dislo-

cation structure. This belt is oriented around N 60 W and can be seen in aeromagnetic maps to have a direct connection in the southeast to the Linköping-Loftahammar shear zone within the Loftahammar granite (LLDZ; e.g. Beunk & Page (2001) and ref. therein; Fig. 3). It is clearly stated by Gorbatshev (1971) that this belt is oblique to the regional Svecofennian structures in the area, and consists of deformed SVB granitoids that are intrusive into the early Svecofennian rocks on the sides.

The spatial distribution of different mafic to felsic units west of Linköping have in general an east-westerly orientation (Persson et al. 1981), that we interpret to have formed during the intrusion stage, in similarity with the Tjällmo-Vättern zone further north (cf. Chapter 2.3.9). Intimate relationships between mafic and felsic units within both the porphyritic and even-grained SVB granitoids have been described in terms of megabrecciation of older, early Svecofennian or earlier SVB basites, by the granitoids (Gorbatshev et al. 1976, Wikman et al. 1980, Persson et al. 1981). However, the descriptions indicate that these structures more likely result from the comingling of granitoid and mafic magmas, and Andersson (1991) suggested that extensive magmatic hybridisation, rather than magma fractionation, was responsible for much of the geochemical variation of the intermediate rocks in the area.

A conventional U-Pb zircon age determination of a felsic even-grained granite ('Växjö granite') from the area southwest of Linköping yielded a TIB-1 age of 1808 ± 4 Ma (Jarl & Johansson 1988) (Fig. 7) similar to that obtained from a monzodiorite in the Kårtorp area further north (Chapter 2.3.8), indicating that not only 1.85–1.83 Ga TIB-0 intrusives are present along the Svecofennian margin. Nevertheless, the SVB-rocks just north of the Linköping area (Roxen massif) are essentially indistinguishable from the c. 1.83 Ga Graversfors rocks in terms of their texture and geochemistry (Gorbatshev 1971).

2.3.5. The Graversfors intrusion

The Graversfors intrusion is more or less circular in outline with a diameter of c. 10 km. It is mainly composed of a porphyritic granitoid (Fig.

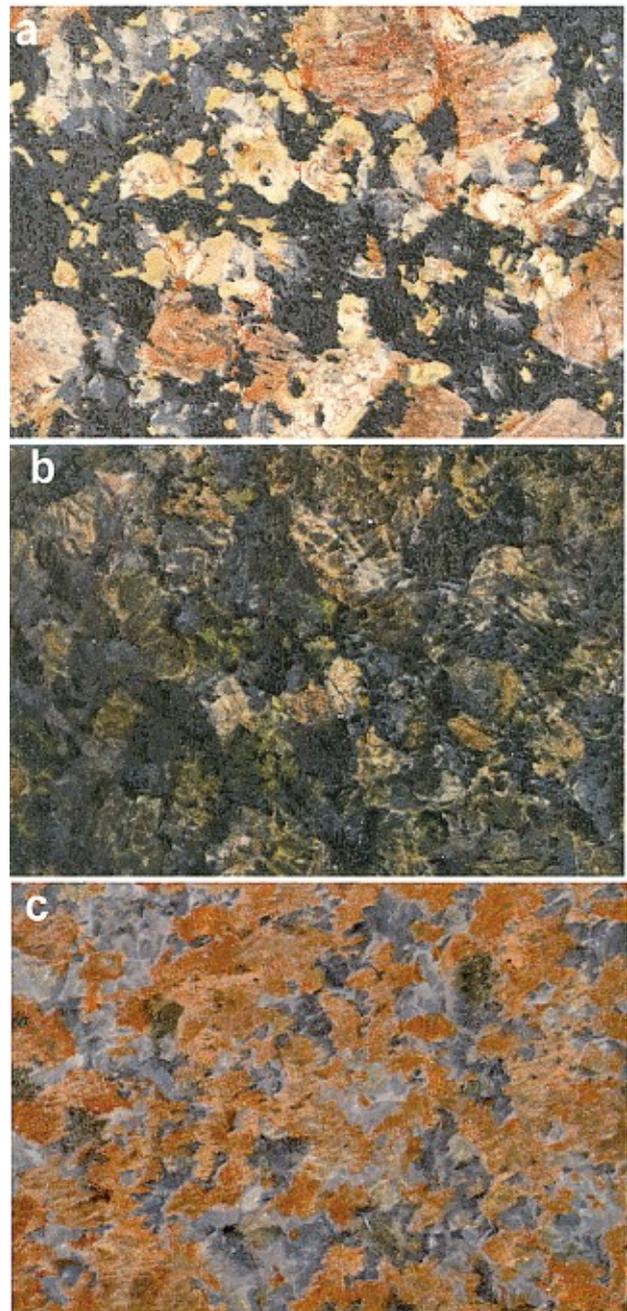


Fig. 15. Varieties of granitoids from the Graversfors intrusion. a) Spatially most important typical coarse porphyritic granite with more or less well-developed plagioclase mantles. b) Dark, quartz monzonitic, sometimes fayalite-bearing variety. c) Red, felsic, more even-grained variety. From Hedström (1908). Widths of photographs is c. 10 cm.

15a) dominated by perthitic microcline phenocrysts, that are locally mantled by plagioclase. Myrmekitic texture is common in the granitoids. Biotite dominates among the dark minerals, while the content of hornblende varies. Locally, there is a rock variety (Fig. 15b) with dark-pigmented feldspars (orthoclase and plagioclase), a few percent of orthopyroxene, and accessory fayalite.

Another local variety (Fig. 15c) consists of red, anhedral orthoclase and brightly blue quartz.

According to a gravimetric interpretation (Wikström et al. 1980), the intrusion has a mushroom shape (Fig. 16) with the trunk in the eastern part. Satellite bodies of the granite penetrate the country rock in a brittle, dyke-like manner along the eastern margin. In contrast, a major anticlinal fold (the Holpen antiform; Wikström 1976) plunging some 20° towards the north-east and clearly related to the shape of the intrusion can be seen along the western contact (Fig. 17). It truncates obliquely the regional structures, that generally strike west-northwest. The half wavelength of this antiform is around 4 km and its amplitude around 2 km. By comparison with structures formed

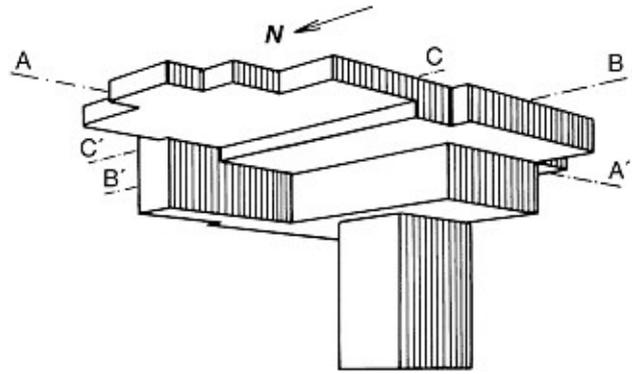
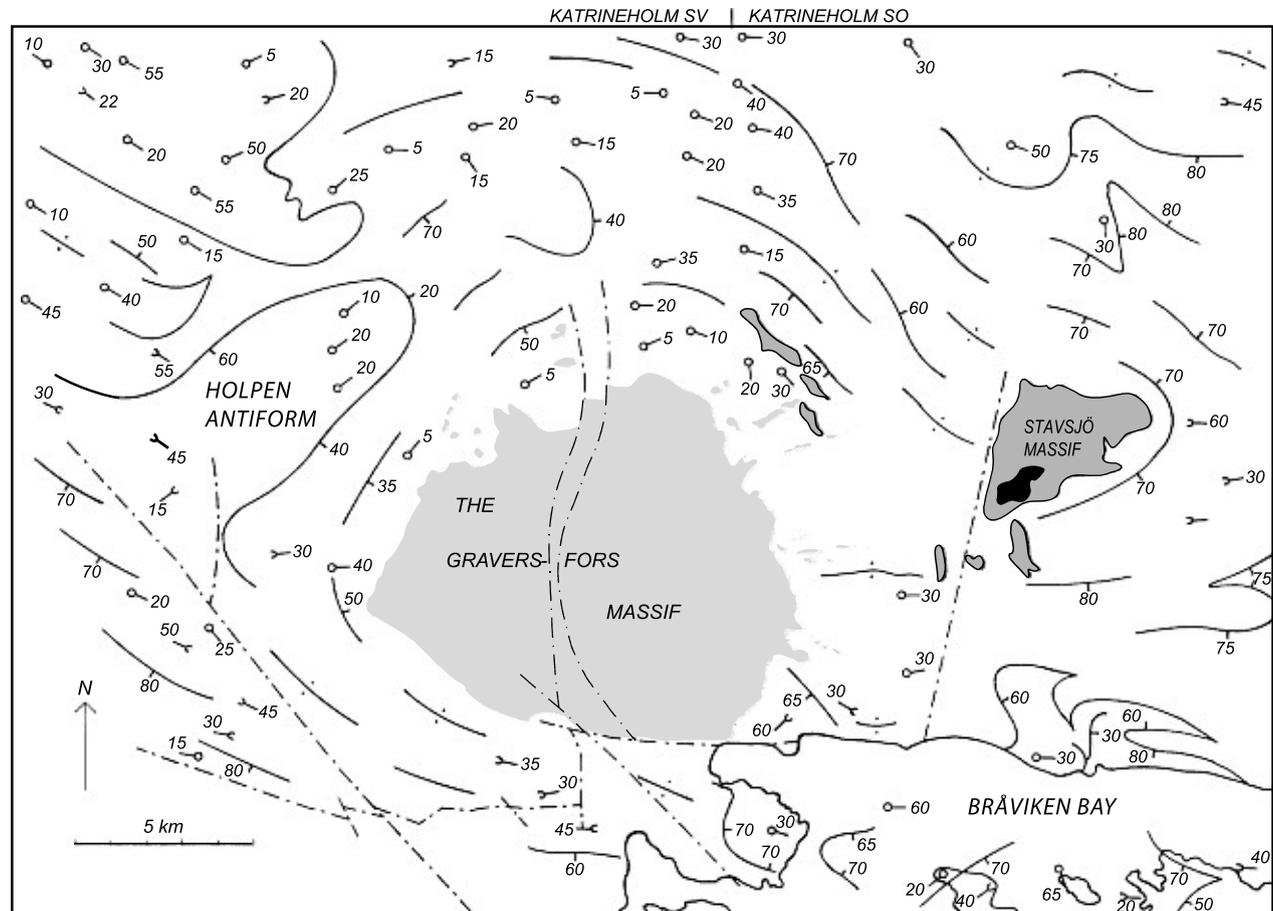


Fig. 16. Perspective drawing of the Graversfors intrusion based on gravity interpretation (from Wikström et al. 1980).

during experiments with diapir models, it was suggested that this fold was formed during the granite intrusion (Wikström et al. 1980). Other



DOMINATING STRUCTURAL ELEMENTS

- GENERALIZED FOLIATION TRENDS
- FOLD AXIS
- LINEATION
- MAJOR FAULT
- ASSOCIATED MAFIC ROCKS

Fig. 17. Main structural features in the area of the Graversfors and Stavsjö intrusions (modified after Wikström et al. 1980).

conclusions were that the somewhat higher density of the Graversfors granite with respect to the country rocks necessitated emplacement in the lower-density magmatic stage and that the intrusion of the Graversfors magma must have occurred close to the Svecokarelian orogeny in time, and simultaneous with some migmatitisation in the ambient rocks which reduced the viscosity contrast.

Geochemically, the Graversfors intrusion falls in the middle of the SVB compositional range (Fig. 5). The within-pluton variation is characterised by low-silica varieties particularly in its eastern part (Fig. 18).

Previous attempts to determine the crystallisation age of the Graversfors intrusion have yielded inconclusive results (Åberg & Wikström 1982). A Rb-Sr whole rock isochron gave 1692 ± 7 Ma, but Rb-Sr whole-rock ages in the Swedish Precambrian are typically 50 to 150 Ma younger than the U-Pb zircon ages of the same rocks. This is most likely the result of heterogeneous initial Sr isotopic compositions in suites of whole-rock-samples (Romer 1994), such that the more mafic samples have lower initial ratios than the felsic ones (Andersson 1997a). Åberg and Wikström (1982) also calculated a very poorly defined U-Pb discordia from three zircon fractions, with an approximate upper intercept at 1.97 Ga. These zircons, however, contained abundant older cores and were therefore interpreted to contain a major inherited, possibly pre-Svecofennian component.

Thermobarometry for the assemblage Gt-Opx-Cd-Sp-Bt-Kfs-Pl-Qz in a hornfels xenolith of the intrusion indicates peak conditions of at least 805°C and 5.8 ± 1 kbar (equivalent to a depth of 21 km) (Fig. 11). A discordia regressed through two highly discordant monazite fractions and the origin yielded 1829 ± 8 Ma and is interpreted to closely reflect monazite growth caused by the intrusion (Fig. 4; Andersson 1997b).

By comparison with the similar Askersund intrusion (age around 1845 Ma) with its discordant eastern and deformed western and northern margins, an alternative explanation of the Holpen antiformal fold to the west of the Graversfors intrusion can be made. The antiform may be a post-emplacement deformation structure, in which case the eastern discordant contact could represent a “lee-side” effect in relation to late tectonic



Fig. 18. Geographical overview of chemical variation of SiO_2 content within the Graversfors intrusion (from Wikström et al. 1980).

compression acting from the present WNW. Such an interpretation and the partly massive, “post-orogenic” appearance imply that a considerable tectonic evolution has taken place in the area prior to c. 1845 Ma.

2.3.6. The Stavsjö-Jönåker intrusions

The Stavsjö and Jönåker massifs (Fig. 7) consist mainly of porphyritic granite with rectangular, probably flow-oriented K-feldspar crystals. Asklund (1925) presented a detailed account of the rocks in the Stavsjö area. Dykes of this granite clearly cross-cut the regional Svecofennian deformation structures. A dyke of the Graversfors granite has been observed to cut a porphyritic granite of Stavsjö type outside the main intrusion (Wikström 1979, Wikström et al. 1980), suggesting that the Stavsjö-Jönåker massifs are early post-kinematic, i.e. >1.83 Ga, although no isotopic data is available on these intrusions.

A variety of mafic to intermediate rocks occur within these intrusions (Asklund 1925, Wikström 1979) and in the Stavsjö massif a norite body is exposed in an area, approximately 500×1000 m. Structures indicating magma mixing and mingling with the granitic magma (e.g. pillowed contacts) are well-developed around the norite. Asklund (1925) argued that these rocks were not formed by fractional crystallisation but instead by a process which he called “liquation”, which has a faint resemblance with the magma mingling and mixing concept. The intermediate rocks are thus most likely interpreted as the result of vari-

able degrees of mixing of granitic and noritic/gabbroic magmas, although restitic elements cannot be ruled out in the hornblende-bearing granitoid varieties.

Small-porphyrific granitoid varieties are associated with both intrusions and have been grouped together with the massifs, although they have a slightly older field appearance (Wikström 1979, Wikström et al. 1980). When mapping was resumed in this area during the 1970s (Wikström 1979) the “postorogenic” character of the intrusions was emphasised. However, directly west of the Stavsjö massif regionally deformed porphyritic granitoids were mapped together with the older Svecofennian plutonic rocks. In retrospect, this was probably not correct since the earliest TIB rocks also elsewhere along the Svecofennian margin have been shown to be affected by late Svecofennian folding and deformation (cf. elsewhere in Chapter 2).

2.3.7. The Finspång massif

As can be seen in Fig. 19 (Wikström & Aaro 1986), the Finspång massif has been interpreted as a folded sheet in which the major granite volumes are found in synforms. As the massif is clearly folded within the regional structures (Fig. 20), its eastern parts were once regarded as belonging to the older Svecofennian plutonic rocks (Wikström 1976). Later mapping to the northwest of the massif, however, revealed a gradual

transition into TIB granitoids, implying a re-evaluation of its classification (Wikström 1984). By comparison with a diapir model made by Ramberg (Fig. 21) the folded parts were interpreted as marginal, deformed lobes in a diapiric mushroom structure (the old age was not known at that time). In the aeromagnetic map, the Finspång massif is distinguished as a low-magnetic structure in contrast to the more magnetic SVB granitoids just to the west and north. No mafic enclaves are present in the massif which is unusual for TIB rocks in general. It has normally been deformed under amphibolite facies conditions and is locally migmatitic near the contacts to the surrounding sedimentary gneisses which contain garnet and sillimanite.

Along the southern margin, seemingly isotropic parts can be seen in two areas (Fig. 20), where the country rocks consist of rather low-grade muscovite-andalusite schists. This feature is interpreted as a “megamullion” structure where the rheological conditions during deformation at this low metamorphic grade were such that the isotropic parts of the Finspång massif acted considerably more competently than the surrounding schists, in contrast to the deformation conditions in the more high-grade parts where the difference in competency was less pronounced.

The geochemistry of the Finspång massif is anomalously peraluminous for SVB rocks (Fig. 5). Since the Finspång magmas were largely intruded into metasediments, the most natural

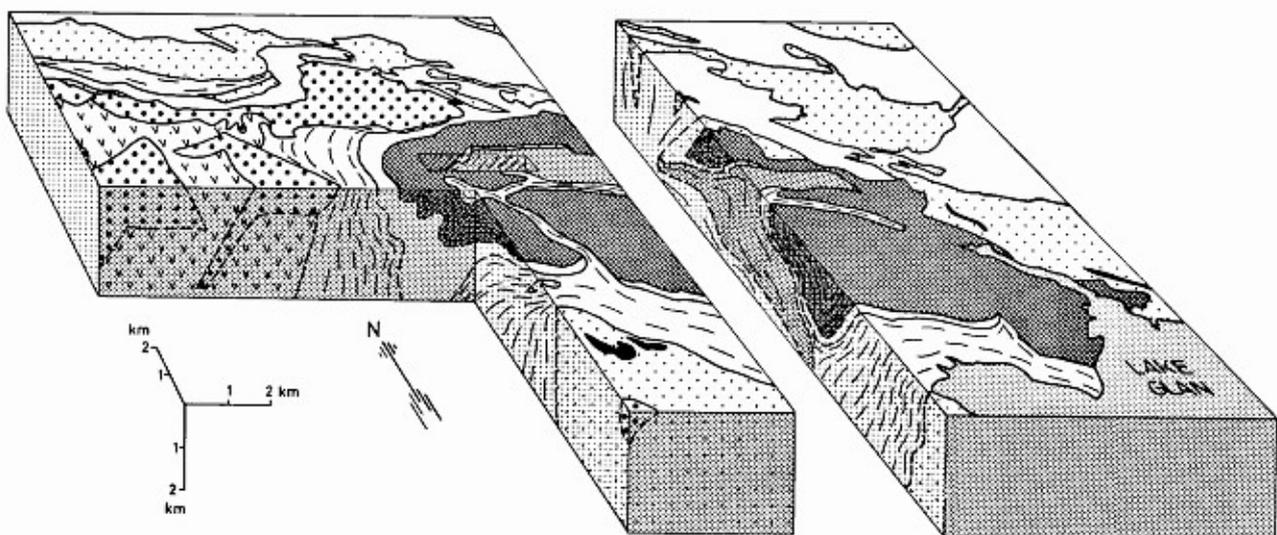


Fig. 19. Three-dimensional structural diagram of the Finspång area, based on geological and geophysical information. Dark: Finspång massif, dotted and V:s: Småland-Värmland Belt granitoids. Others: Svecofennian ortho- and paragneisses (from Wikström & Aaro 1986).

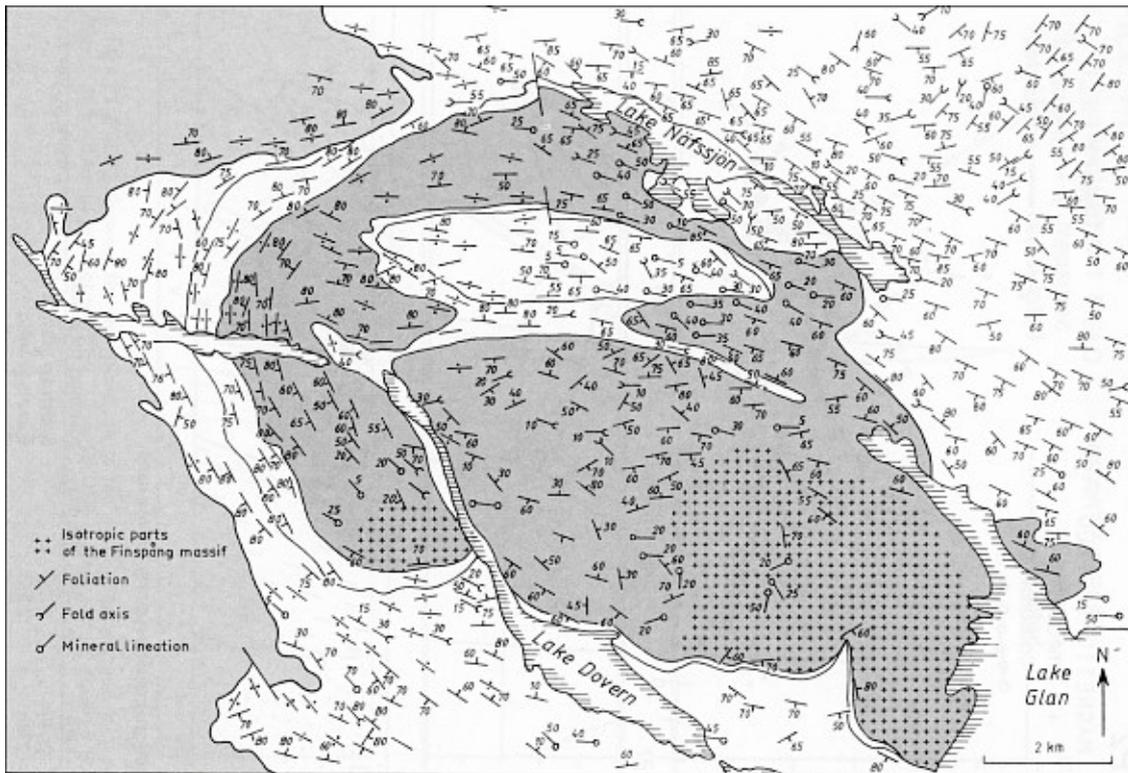


Fig. 20. Measured structural elements in the Finspång area (from Wikström & Aaro 1986).

explanation would be assimilation of considerable quantities of such rocks (cf. also Wikström 1988a, Lindh & Persson 1990, Lindh & Johansson 1995), but could also be due, in part, to more Al-rich protoliths than usual.

SIMS measurement on concordant, magmatic

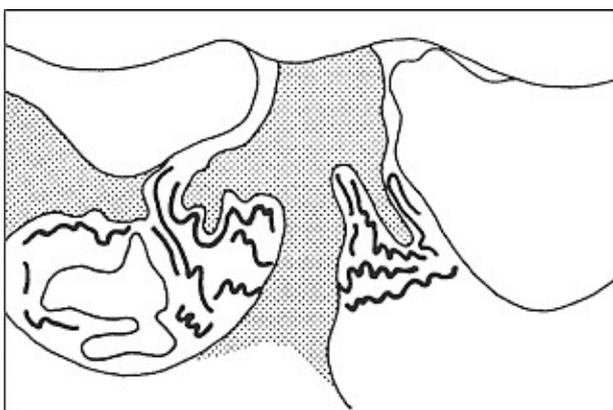


Fig. 21. Diapir structure (redrawn from Ramberg 1967, fig. 41), which shows the marginal parts of the cap folded conformably with the surrounding material, while the trunk has discordant contacts. The model was proposed with the assumption that intrusions of this type had an age of around 1.79–1.80 Ga, i.e. essentially postorogenic Svecofennian. With the discovery of the 1.85 Ga generation together with new field observations, it became clear that regional orogenic deformation forces were important for the development of the marginal structures. However, it is still believed that parts of these structures are also related to intrusion forces (from Wikström 1984).

oscillatorily zoned, and elongated zircons from an augen gneiss in the Finspång massif yielded an age (constrained through the origin) of 1854 ± 5 Ma, interpreted to be the intrusion age, while conventional U-Pb monazite data from the same rock spread in the range 1831–1823 Ma (Andersson et al. 2004; Fig. 4). The latter reflects (partial) recrystallisation during deformation and shows that deformation continued until at least 1.82 Ga. Inherited zircon grains with ages ranging from 1.97 to 2.75 Ga support the presence of sedimentary material in the magma (Andersson et al. 2000, 2004). Åberg & Wikström (1985) determined a Rb-Sr whole rock isochron age of 1834 ± 21 Ma for the Finspång augen gneiss. A recent Nd-isotopic determination of the Finspång augen gneiss (U.B. Andersson, unpubl. data) yielded an rather low $\epsilon_{Nd}(1.85)$ of c. -1.3 , in line with addition of relatively old crustal components to the magma.

2.3.8. The Kårtorp complex

The Kårtorp (Fig. 10) area displays a pronounced positive aeromagnetic anomaly



Fig. 22. Kåratorp quartz monzonite. Lens cap has a diameter of c. 5 cm.

(Andersson 1991). This can be related to monzodioritic-quartz monzonitic intermediate rocks (Fig. 22), with high measured outcrop susceptibilities (Fig. 23) (Andersson 1989). The most mafic monzodioritic rocks occur in the south and grade northwards into quartz monzonites. The transition from granitoid to more mafic rock varieties is characterised by a gradual dispersal of K-feldspar megacrysts and a decrease of their size (due to dissolution in the hotter, more mafic environment), as well as a decrease in quartz and increase in mafic mineral contents. The contacts with the surrounding, typically coarsely porphyritic SVB granitoids are sharp in outcrop scale. The central part of the area is occupied by a red, silicic SVB granite with sharp outward contacts. To the south, outside the Kåratorp complex, minor areas of high-magnetic intermediate rocks occur, as well as numerous mafic (-hybrid) magmatic enclaves (MMEs; Fig. 24). Apatite needles are a typical feature of the hybrids and MMEs, indicating rapid chilling by the cooler granitic magma (cf. Wyllie et al. 1962). A conventional U-Pb zircon determination of the Kåratorp monzodiorite yields a preferred age estimate of 1812 ± 14 Ma (Fig. 4; Andersson 1997a). In addition, contact metamorphic monazite in Gt-

Cd-Sp hornfelses c. 15 km east of Kåratorp has yielded an age of 1813 ± 1 Ma (Figs. 4 & 7) and calculated P-T conditions of $750\text{--}830^\circ\text{C}$ and 5.5 ± 1 kbar (Andersson 1997b) (Fig. 11). For geochemistry, see section 2.5.

2.3.9. The Tjällmo-Vättern Zone

The Tjällmo-Vättern Zone (TVZ) is a zone of granitoid and mafic SVB rocks stretching E-W from Kåratorp in the east to Lake Vättern in the west (Fig. 10). As seen in aeromagnetic maps (with anomaly pattern largely depending on the mafic rocks) it continues westwards undisturbed across the lake to southern Tiveden, but finally turns northwards into the Sveconorwegian deformational pattern (Wikström 1995). The mafic rocks are magmatically oriented in an E-W direction, partly with mingling and mixing relationships to the surrounding granitoids. They are also parallel to the outer intrusive borders to the Svecofennian rocks, suggesting that the flow pattern was governed by orientation along the wall rocks (Wikström 1987).

The mafic rocks occur as i) generally E-W striking dykes, ii) plutonic complexes, often with irregular contact relations to the granitoids, and

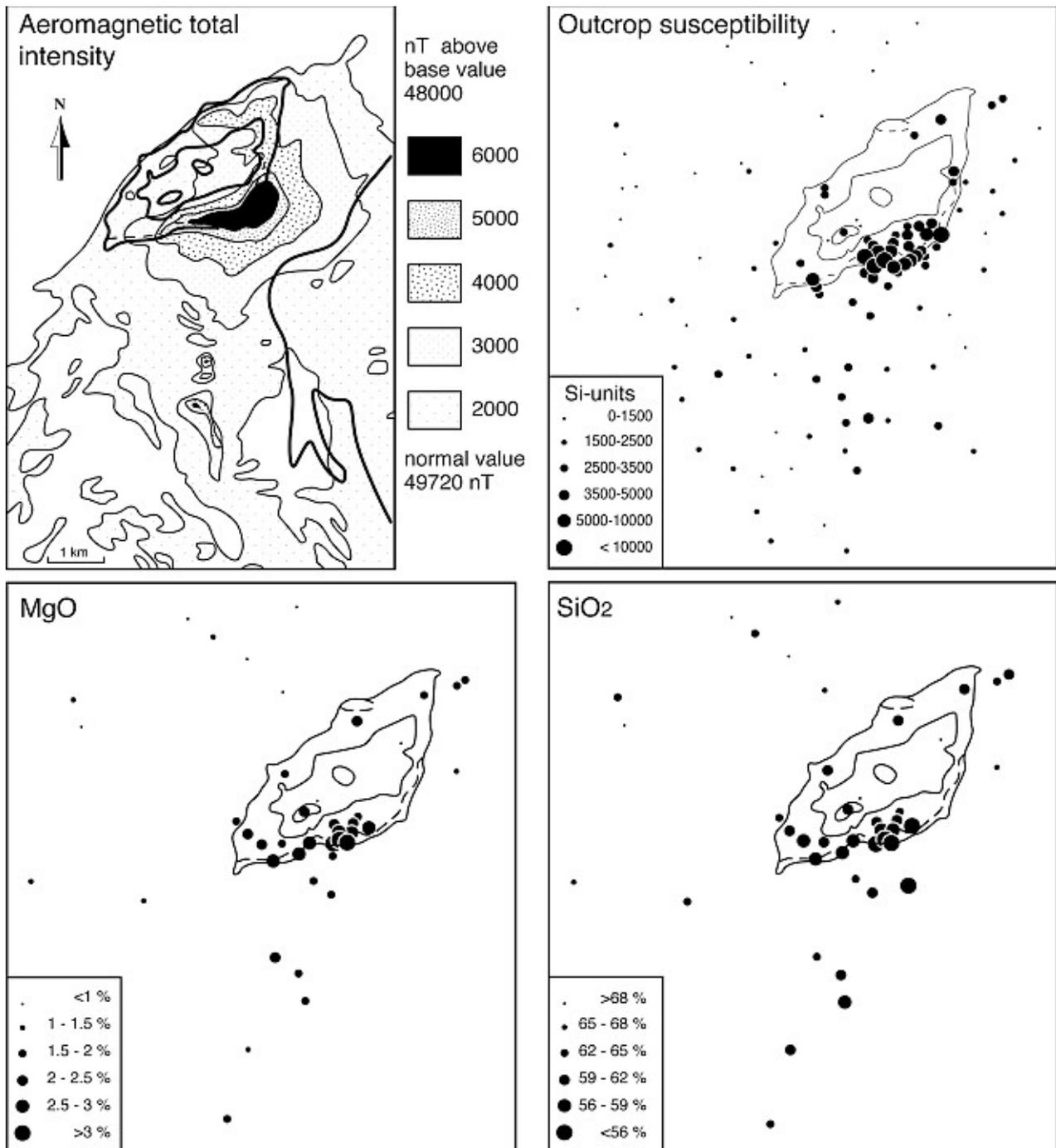


Fig. 23. Comparison of magnetic and geochemical characteristics of the Kårörp area. Increasing basic rock character correlates with increasing susceptibility (from Andersson 1997a).

iii) MMEs, with sizes from less than 10 cm grading into plutonic masses (Fig. 25). The rocks are gabbroic in composition, usually devoid of Opx, and with Cpx by the bulbous contact relations to the granites, indicating co-mingling of magmas. Local mixing is also common. The amphibolitic character may derive from late-magmatic indigenous fluids or, more probably,

from postmagmatic fluids circulating from the surrounding granites.

In a few localities ultramafic rocks occur, containing major oikocrysts of orthopyroxene, amphibole, and phlogopite, with chadacrysts of olivine, as well as minor clinopyroxene, plagioclase and spinel, i.e. they are hydrated spinel-plagioclase lherzolites/harzburgites, or more correctly,



Fig. 24. Hybrid magmatic enclave from the area south of the Kårtorp complex. During mingling between the Småland-Värmland Belt granite crystal mush and mafic magma, numerous xenocrysts from the granite magma were engulfed in the mafic magma droplet before it solidified. Diameter of lens cover is c. 5 cm.



Fig. 25. Mingling/mixing structures between mafic and felsic magmas of the Småland-Värmland Belt, in the Tjällmo-Vättern zone (locality 8840 in Andersson 1997a). Hammer shaft is c. 55 cm.

pyroxene-hornblende-peridotites. Olivine is partly serpentinised and plagioclase sericitised. These rocks were interpreted by Andersson (1997a) as pieces of upper mantle, carried to their present crustal level first by mantle-derived melts and subsequently by the SVB batholith. For geochemistry, see Chapter 2.5.

2.3.10. The Askersund area

A gradual transition from magmatic to metamorphic structures can be clearly demonstrated in the Askersund area (Fig. 26). The Askersund granite is coarsely porphyritic with most characteristics in common with the Graversfors granite.



Fig. 26. Penetratively deformed coarse porphyritic Småland-Värmland Belt granitoid from the Askersund area. Diameter of coin is 25 mm.

The isotropic parts along the eastern discordant contact have within error limits the same age, i.e. c. 1845 Ma, as a marginal sheet of granite (the Åsbro lobe; cf. Fig. 10) which has been metamorphosed and folded conformably with the surrounding gneisses (Persson & Wikström 1993).

A study of anisotropy of magnetic susceptibility (Wikström et al. 1997) was carried out to further study this transition which can be followed in a fairly well exposed area to the northwest of Askersund town. Although that investigation was of precursory nature, gradually increasing degrees of anisotropy towards the gneiss region could be demonstrated along two profiles. In the investigated samples, the magnetic remanence was reoriented with poles corresponding to young Sveconorwegian – Vendian positions (Sjöberg et al. 1999). A possible interpretation of these features is that the emplacement occurred in an active transpressional tectonic regime where the main forces acted approximately from the present northwest.

Numerous composite dykes consisting of net-veined complexes of mafic pillows in a granitic matrix have intruded the Askersund granite (Fig. 27) (Wikström 1992). This apparently occurred during the last stages of the host granite crystallisation as they range from irregular bodies to late fracture-filling types. Some of these composite



Fig. 27. Net-veined dyke rock from the Askersund area. Numerous pillowed mafic fragments in granitic matrix. This granitic matrix is mostly medium- and even-grained, occasionally with larger megacrysts, and could represent late stage granitic liquids possibly partly mixed with components of remelted crystal mush due to superheating during injection of mafic magma. Keys for scale are c. 6 cm.

dykes are incompetently deformed, while their competent, ambient granite does not show such structures. A major positive gravity anomaly to the south of Askersund has been interpreted as being due to a major volume of mafic rocks beneath the granitoids (Wikström & Karis 1998); the composite dykes are additional evidence for this. The more silica-rich granites of the Askersund area are separated from the dominantly intermediate SVB rocks of the central Tiveden area by the N-S trending Aspa fault zone (Wikström 1995), (the Sveconorwegian Frontal Deformation Zone of Wahlgren et al. 1994). Along that zone there was likely a relative uplift of the western (intermediate rocks) area (Andersson 1997a).

2.3.11. The Tiveden area

The central part of the Tiveden area (Fig. 10) is also associated with a large positive aeromagnetic anomaly correlating with outcropping coarse-porphyrific monzodioritic-quartz monzonitic SVB rocks (cf. Andersson 1991). The monzonitic rocks gradually turn into the normal coarse-porphyrific granites towards north and south (Andersson 1997a, Wikström & Karis 1998).

Both clino- and orthopyroxene are frequently observed in the monzonitic rocks, but not olivine. The pyroxenes are normally in various stages of alteration to amphibole + quartz. Biotites are associated with abundant oxides, apatites and zircons. The colour of these rocks is generally reddish violet to brown, but some varieties can be almost black due to the dark colour of the feldspars (Fig. 28). This dark colour of the feldspars (both plagioclase and K-feldspar) may derive from non-oxidised Fe-bearing mineral inclusions, such as hercynite and ilmenite (cf. Estifanos et al. 1998), but this has not been studied. The SiO₂ contents of the monzonitic rocks are generally in the range 57–60 wt%.

A conventional U-Pb zircon age determination on a monzonitic type, sampled c. 1.8 km NNW of Tivedstorp, yielded an age of 1854±2 Ma (Wikström 1996) (Figs. 4 & 7). Another conventional U-Pb zircon dating of a sample of weakly deformed tonalite from Samfallet yielded an age of 1849.5±1 Ma (Wikström 1996), suggesting that it represents a calc-alkaline SVB granitoid rock variety (Fig. 10). Also field evidence (Wikström & Karis 1998, Figs. 31 and 36) demonstrate a close age relationship where calc-alkaline, mainly even-grained and alkali-calcic



Fig. 28. Example of coarse greenish-black monzodiorite from Tiveden (locality 8859C in Andersson 1997a). Both K-feldspar and plagioclase are abundant but dark. Ortho- and clinopyroxene occur in variable amounts.

coarse-porphyrific SVB granitoids seem to have existed “side by side” without noticeable interaction with each other. Locally, however, the plagioclase dominated granitoids are contact-metamorphosed by the coarse-porphyrific type. In the central parts of the area, a greyish relatively plagioclase-rich SVB variety with only scattered K-feldspar megacrysts is diffusely separated from the normal densely coarse-porphyrific type.

Metamorphic assemblages of Gt-Cd(-Opx)-Sill-Bt-Kfs-Pl-Qz in contact-metamorphic slices of supracrustal rocks gave estimated peak conditions of 770°C and 5.5±1 kbar (16–24 km) (Fig. 11; Andersson 1997b). Conventional U-Pb mona-

zite ages from the contact metamorphic rocks in Tiveden range from 1818 to 1784 Ma, where two fractions from one sample yield concordant ages 16 Ma apart (1800 and 1784 Ma; Andersson 1997b), suggesting several episodes of monazite growth in the sample. These low metamorphic ages are at strong variance with the c. 1850 Ma intrusive ages. Therefore, either there is an inherited component concealed in the multi-zircon grain fractions of the SVB quartz monzonite, or the low ages are due to effects of diffusional readjustment upon cooling of the monazites to their closure temperature. The geochemistry is dealt with in section 2.5.

2.4. Geological features of the Småland-Värmland belt along the Svecofennian margin, part II: the Nygård, Karlskoga and Filipstad areas

Ulf B. Andersson, Dick T. Claeson, Karin Högdahl & Håkan Sjöström

2.4.1. The Nygård norite pluton and its surroundings

The Nygård norite pluton (Figs. 10 and 29) intruded both early Svecofennian supracrustal rocks and coarse-porphyrific SVB granitoids at 1850±9 Ma (Pb-Pb zircon evaporation, Claeson & Andersson 2000; Fig. 4). Detailed mapping of magmatic flow structures and compositional banding indicate that magmas intruded in three successive pulses (Larsson 1935) (Fig. 30). Clinopyroxene norite and norite are the dominant rock types, the latter especially in the last and largest intrusive pulse, but pyroxenitic and anorthositic varieties also occur as bands or segregations (Larsson 1935). Solid solution ranges in plagioclase are An₅₈₋₇₆, in orthopyroxene Mg# 61–71, and in clinopyroxene Mg# 72–82 (Claeson & Andersson 2000, unpubl. data). Olivine is lacking. A number of mafic dykes cut the pluton; some apparently during a stage before full crystallisation of the norite (late-plutonic), showing bulbous mingled contacts. Others have sharp, chilled margins and may be substantially younger.

Initial ϵ_{Nd} (1.85 Ga) ratios of the norites (Claeson & Andersson 2000) show slightly depleted values, +0.6 to +1.1 (Figs. 6 and 41). Two doleritic dykes within and outside the Nygård pluton have

strikingly different ϵ_{Nd} values at 1.85 Ga, but converge at 0.9 Ga to compositions similar to the Blekinge-Dalarna dolerites and thus are most probably of comparable age. Initial Sr-ratios for the noritic rocks are in the range 0.7023–0.7047.

The surrounding SVB granitoids are deformed and contact metamorphosed (contains garnet) on

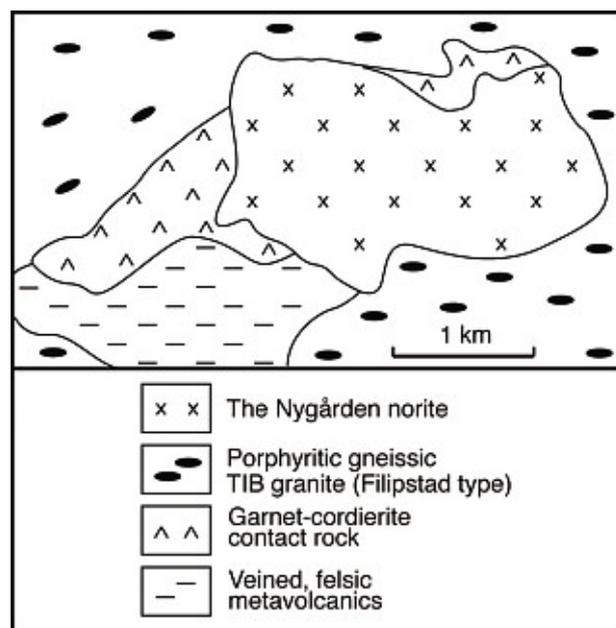


Fig. 29. Simplified map of the geology around the Nygård norite pluton (redrawn after Wikström & Larsson 1993).

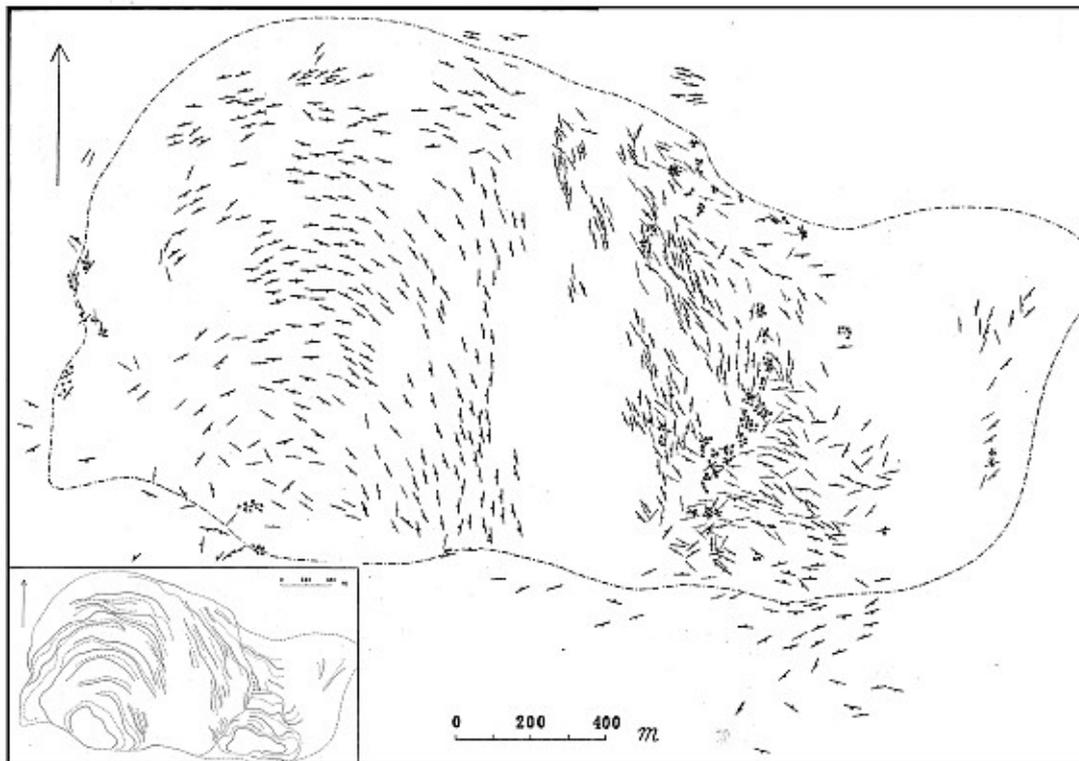


Fig. 30. Magmatic flow structures measured in the Nygård pluton (modified from Larsson 1935). Inset shows the general pattern of the fluidal structures.

the northwestern side of the intrusion, while they are undeformed and magmatically hybridised with the norite in the southeast (Wikström & Karis 1998). The reason for this difference is not known, but indicates that the granite and norite are penecontemporaneous, which is supported by the 1855–1842 Ma ages reported for SVB granitoids in the Askersund-Tiveden areas (cf. Chapter 2.3).

The Svecofennian supracrustal rocks in contact with the norite are strongly metamorphosed. They are transformed to extensively melted and homogenised crystal mushes (garnet-cordierite gneisses), containing unmelted restite enclaves. This rock has partly back-veined the norite (Larsson 1935, Wikström & Karis 1998) (Fig. 31). Adjacent to the norite, these gneisses are melt-depleted and poor in K-feldspar and quartz. Assemblages of Gt(-Opx)-Cd-Sp-Bt(-Sill)-Pl-Kfs-Qz indicate c. 925°C and 6.3 kbar conditions at the contact, and c. 800°C and 5.5±1 kbar some metres away, corresponding to a depth of 16–24 km (Fig. 11; Andersson 1997b). Wikström & Larsson (1993) determined slightly lower P-T conditions, presumably from non-peak assemblages. Two

concordant monazite fractions from the garnet-cordierite gneisses yielded an age of 1845±4 Ma for metamorphism (Fig. 4), confirming that the migmatisation was coeval with the emplacement of the norite.

2.4.2. The Karlskoga area

Highly metamorphosed and migmatised early Svecofennian rocks are present adjacent to the SVB intrusions also in the Karlskoga (Fig. 7) area. These Svecofennian rocks comprise homogenised garnet-cordierite gneisses and migmatitic orthopyroxene granulites (Wikström & Karis 1997, Stephens 1998). The peak P-T conditions in these rocks have been estimated from thermobarometry (Fig. 11) at 670–770°C and 4–5 kbar (15–18 km; Andersson et al. 1992, Andersson & Harlov unpubl. data). Conventional U-Pb monazite geochronology on a garnet-cordierite gneiss gives 1796±1 Ma for the age of metamorphism (Andersson 1997b). This was confirmed by ion probe data from metamorphic zircons (Andersson et al. 2000, 2004). Consequently, this contact metamorphic age gives an

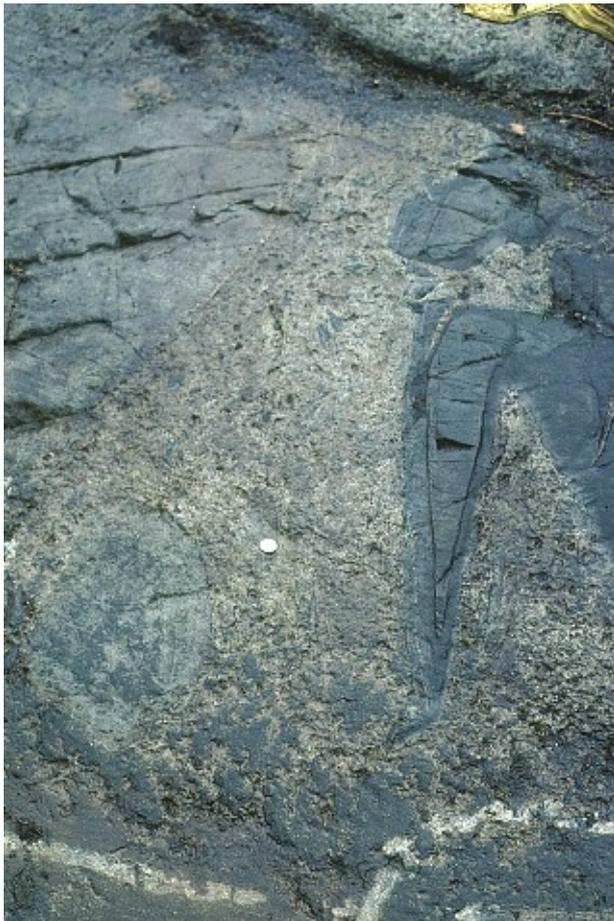


Fig. 31. Back-veining of mobilised country rocks into the Nygårdens norite. The norite induced high-grade metamorphism and melting in the surrounding supracrustal rocks. Homogenised, semi-magmatic garnet-cordierite gneisses formed and remained mobile after the solidification of the norite, which was then locally broken up. Diameter of coin is 25 mm.

estimate for the crystallisation age of the surrounding coarse to small porphyritic SVB

granitoids, and includes them into the TIB-1 (cf. above; 1.81–1.76 Ga). Westwards, these granitoids have been increasingly affected by ductile (from non-penetrative to penetrative) Sveconorwegian deformation (Chapter 2.6). Compositionally, this suite varies from monzodiorite to granite, with abundant associated mafic rocks, that commonly exhibit mingling relations with the granitoids (Wahlgren 1992, 1993). A younger suite of SVB intrusions belonging to TIB-2,3 (1.70–1.65 Ga) becomes predominant in the western, more strongly deformed part of the area (Söderlund et al. 1999).

The mafic Roted intrusion, that yielded a conventional U-Pb zircon age of 1699 ± 7 Ma, has developed an orthopyroxene and garnet-bearing hornfels aureole in the surrounding porphyritic SVB granitoids (Annertz 1984, Stephens et al. 1993). Thermobarometry from this aureole gives apparent PT-conditions of 850–950°C and 5–7 kbar (18–25 km; U.B. Andersson unpubl. data), similar to other rocks in contact with SVB intrusions (Fig. 11).

A distinct unit of equigranular to slightly porphyritic granite in the Karlskoga area shows numerous green patches and larger areas (0.1 to hundreds of metres in diameter) of charnockite (Andersson et al. 1992). This rock usually appears to be older than the surrounding coarse-porphyritic SVB granitoids, but field relations are often diffuse and gradational (Stephens et al. 1993, Wikström & Karis 1997). Due to its gener-

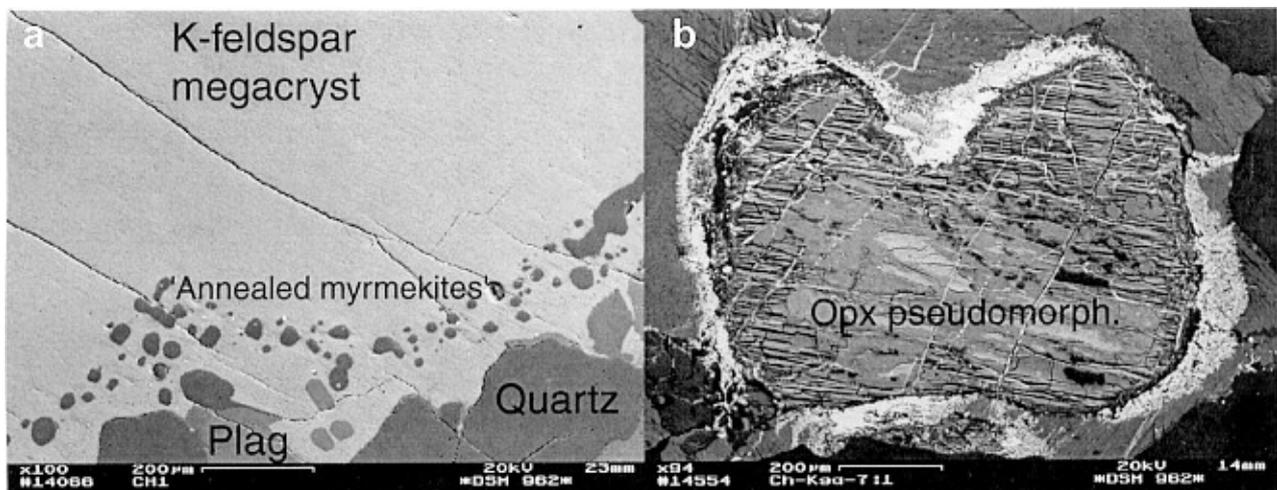


Fig. 32. a) “Annealed myrmekites” in Karlskoga charnockite with granoblastic texture. Trails of quartz and plagioclase blebs in the fringes of larger K-feldspar grains suggest recrystallisation of myrmekites during charnockitisation. b) Orthopyroxene pseudomorph in transition zone between charnockite and granite. These usually consist of biotite (low in Cl and Ti) + quartz + magnetite ± amphibole (hastingsite) ± chlorite ± carbonate, and indicate that the granites formed by retrogression of charnockite.

ally weakly deformed nature and a U-Pb zircon dating yielding 1796 ± 7 Ma, it is at present included in the SVB-suite rocks (Stephens et al. 1993). The transition between granite and charnockite is represented by an abrupt change in colour over distances of one to two centimetres. There are no indications of associated melting or migmatization, but merely a change in the colour of feldspar. Transition is thus sharp in outcrop scale, but in thin section the charnockite is characterised by the presence of orthopyroxene (En_{21-27}). A strongly granoblastic texture, with inclusion trails of small, rounded quartz and plagioclase grains, is typical and is suggested to represent high-temperature recrystallised myrmekites (Fig. 32a). This texture prevails in the granite as well. Together with the presence of abundant orthopyroxene pseudomorphs in the transition zones (Fig. 32b), consisting of biotite, quartz, amphibole, and Fe-oxides, this supports the interpretation that the granite was formed mainly by re-granitisation of previous charnockite (Andersson & Harlov 2001, in prep.).

The preferred interpretation is that an original granite magma, which probably crystallised at c. 1.80 Ga, was more or less immediately subjected to penetrative high-temperature fluid flow (presumably containing saline brines), that converted the granite into charnockite. The source of these fluids may have been mafic SVB rocks below the complex, as indicated by magnetic anomalies (Wahlgren 1993, Wikström & Karis 1997). Re-granitisation was accomplished by H_2O -rich fluid flow emanating from the surrounding SVB granites during their crystallisation somewhat later.

2.4.3. The Filipstad area

2.4.3.1. General features

An overview of the geology of the Filipstad area is given in Fig. 33. The coarse-grained, porphyritic granitic rocks of the SVB are traditionally referred to as Filipstad granite. The name was originally introduced by Törnebohm (1881) for this characteristic rock type in the Filipstad area, and later applied to all coarse-porphyritic granitoids of the SVB (Magnusson et al. 1963).

The composition ranges from granite to granodiorite, quartz monzonite, and even to some tonalitic varieties (Lundegårdh 1987). The associated even-grained, so called Kristinehamn- and Hagfors granites are mostly felsic granites with some granodioritic, quartz syenitic and quartz monzontitic portions (Törnebohm 1881, Björk 1986, Lundegårdh 1987).

The porphyritic texture in the granitoids is made up of 2–4 cm, often irregularly rounded microcline megacrysts, which are frequently mantled by plagioclase rims, a few millimetres wide (An_{15-21} ; Magnusson 1929). The matrix is medium- to coarse-grained and composed of K-feldspar+quartz+plagioclase+biotite±hornblende. Titanite, apatite, zircon, epidote and opaque minerals (magnetite and pyrite) are common accessory phases (Magnusson 1929, Björk 1986, Lundegårdh 1987). Also fluorite has been observed in deformed varieties (Magnusson 1929).

The Filipstad-type granite dominates in the northern part of the SVB, and a sample taken east of Filipstad yielded a U-Pb zircon age of 1783 ± 10 Ma (Jarl & Johansson 1988). Cross-cutting aplitic and granitic dykes are fairly common, whereas pegmatites are relatively rare and occur immediately west of the boundary to the Svecofennian Domain, as well as within and adjacent to small Filipstad-type exposures just east of the domain boundary (K.Högdahl, unpubl. data.).

Mafic and intermediate rocks within the SVB suite are abundant in the Filipstad area (cf. Björk 1986, Lundegårdh 1987) and are found as small, centimetre-sized enclaves to kilometre-sized elongate bodies. Vinnefors (1985) studied in detail some mafic complexes within the SVB granitoids in eastern Värmland, while Claeson (2001) focussed on the Eriksberg intrusion immediately south of Filipstad (cf. Chapter 2.4.3.2.). Most mafic rocks appear to be co-magmatic (and coeval) with the granitoids (Vinnefors 1985, Lundegårdh 1987) although many of them have previously been interpreted to be large xenoliths of Svecofennian metabasic rocks (e.g. Björk 1986). They exhibit abundant mingling and mixing relationships with the Filipstad granitoids (Fig. 34; Högdahl & Jonsson 2004.), e.g. magmatically enclosed K-feldspars and quartz ocelli (i.e. xenocrysts mixed in from the associ-

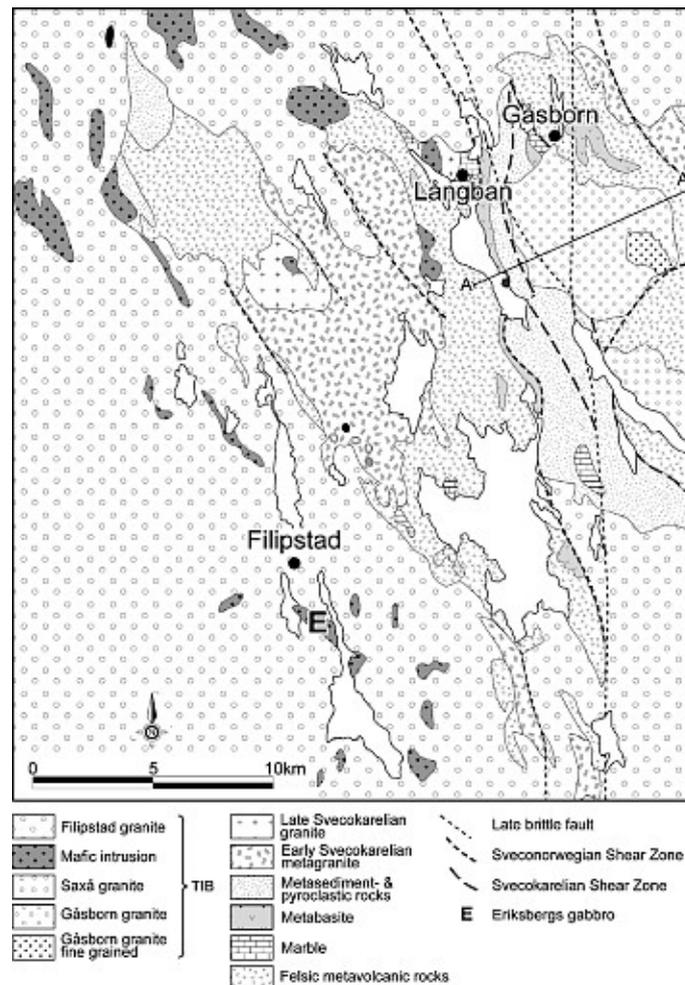


Fig. 33. The Filipstad granite, defined as part of the Transscandinavian Igneous Belt (TIB), dominates the regional geology of the Gåsborn-Filipstad area. The granite contains numerous coeval mafic bodies, often showing mingling relations to the granite. The Gåsborn pluton in the northeastern part of the map is considered to be a satellite intrusive body of TIB, located in a tongue of Svecofennian rocks surrounded by Filipstad granite. The pluton intruded the westernmost parts of the volcano-sedimentary rocks of the Bergslagen area. The northwest-southeast trend of the supracrustal sequences and early Svecofennian metagranite is due to the combined effect of Svecofennian and Sveconorwegian deformation locally resulting in shear zones. (After Lundegårdh 1987, 1995, Björk 1986, Lundström 1995, Cruden et al. 1999).

ated granite magmas). A likely example of mixing is a quartz monzonitic variety of the Kristinehamn granite (Törnebohm 1881), which is now interpreted to have formed by mafic-felsic magmatic hybridisation in the Filipstad suite (K.Högdahl, in prep.). Modern geochemical and isotope studies of the main SVB rocks in the Filipstad area are still lacking.

The eastern contact of the Filipstad granite embay a wedge of Svecofennian rocks (Fig. 33). The contact is irregular, partly tectonic and several small elongated exposures (up to a few hun-

dred metres) of SVB rocks (granitoids and associated mafic rocks) are found within the Svecofennian Domain along the SVB margin. Larger isolated plutons like the Gåsborn granite (Chapter 2.4.3.3 below) and the medium- and even-grained Saxå granite (Fig. 35a) have been classified as SVB granites on petrographic and structural grounds (Björk 1986, Cruden et al. 1999, and references therein), but geochronological data are still lacking. Coeval, local, possibly late Svecofennian granites within the Svecofennian wedge yield ages of 1.79-1.77 Ga, over-



Fig. 34. A mafic magmatic enclave with cauliflower structures along the margin towards the comingled Filipstad granite magma. Boulder, 15 km north of Filipstad. Length of compass is 10 cm.

lapping with the Filipstad granite (Högdahl & Jonsson 2004).

In the eastern part of the area the Filipstad suite rocks are essentially undeformed, but are locally transected by steep, some centimetres wide, predominantly NNW-striking plastic shear zones which are most likely of Sveconorwegian age (1.1–0.9 Ga). Further west Sveconorwegian deformation is penetrative and the Filipstad-type granitoids have a gneissic fabric (Lundegårdh 1995).

2.4.3.2. The Eriksberg gabbro

The Eriksberg gabbro (e.g. Magnusson, 1925, Vinnefors, 1985), located just south of Filipstad (Fig. 33), has experienced only minor deformation and preserves 1.79 Ga old continental-arc cumulates (Claeson 2001). The composition of the gabbro ranges from troctolite to leucotonalite with postcumulus (oikocrystic) amphibole present in nearly all of the earliest formed cumulates, and cumulus (granular) amphibole in some of the more evolved varieties. High-resolution chemi-

cal mapping of a large, single, oikocrystic amphibole grain from the Eriksberg gabbro, by laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS), documents the progressive evolution of interstitial liquid in a hydrous basaltic system (Meurer & Claeson 2002).

The first reported igneous occurrence of the orthoamphibole gedrite was documented in a troctolitic cumulate in the Eriksberg gabbro, where it crystallised from evolved interstitial liquid that was either reacting with, or buffered by, cumulus olivine (Claeson & Meurer 2002). The gedrite is a sodic type that coexists with plagioclase, orthopyroxene, ferritschermakite-magnesiostastingsite, and Na-rich phlogopite. Geothermometry indicates that the assemblage equilibrated at around 900°C and 4–6 kbar.

The leucotonalite dykes that occur within the Eriksberg gabbro are coarse-grained at the contacts with the gabbro and fine-grained in their central part, suggesting that the magma initially was close to or H₂O-saturated and experienced a pressure quench. They have accessory apatite, monazite, allanite, xenotime, zircon, and an unidentified Th-silicate (Claeson 2002). They are interpreted as late-stage, strongly-evolved fractionates from a primary high-alumina olivine tholeiite magma (Claeson 2002). Zr thermometry gives an upper estimate of emplacement temperature for the dykes at 794 °C, and REE thermometry indicates that solidification of the dykes occurred at temperatures between 752 °C (8 wt% H₂O) and 764 °C (6 wt% H₂O) (Claeson 2002).

2.4.3.3. The Gåsborn pluton

The Gåsborn pluton is a c. 6x6 km satellite body of Filipstad-type granite, located c. 20 km NE of Filipstad (Fig. 33). It is a moderately exposed, semi-circular pluton emplaced into Svecofennian supracrustal rocks. East of the pluton these rocks comprise felsic metavolcanic units of the lower parts of the Svecofennian stratigraphy, whereas rocks of the upper parts of the stratigraphy consists of metasedimentary rocks, felsic metatuffs and pyroclastic rocks are exposed west of the granite (Fig. 35a). The intrusion consists of biotite granite (*s.s.*) with a restricted silicic composition (70–77 % SiO₂; U.B. Andersson unpubl.

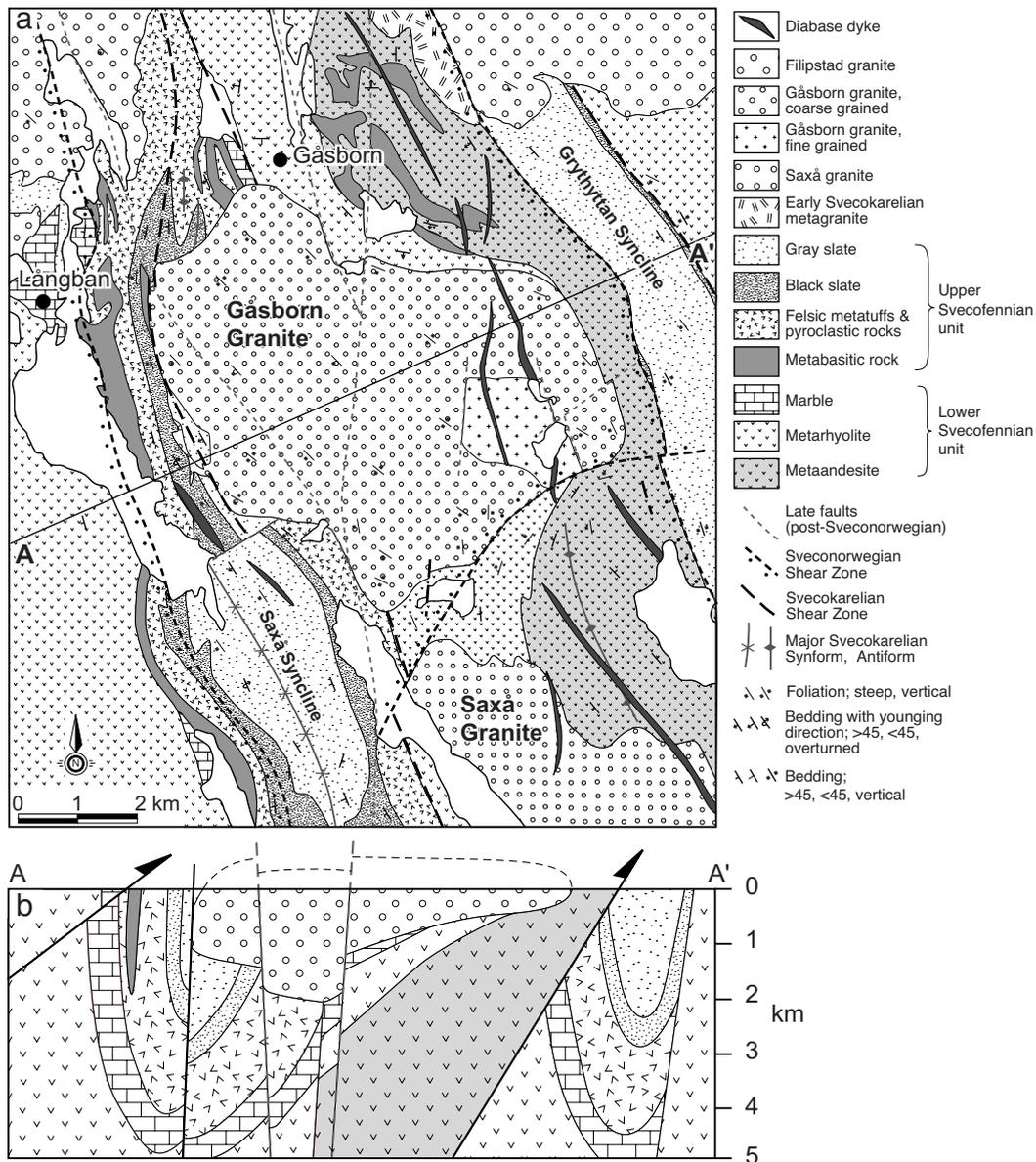


Fig. 35. **a)** Geological map of the Gåsborn granite. The pluton is discordant to the wall-rocks along its northern, western and southeastern margins. Due to emplacement-related as well as post-solidification late Svecofennian deformation, there is considerable distortion of Svecofennian wall-rock structures, such as the Saxå syncline and the antiform to the southeast of the granite. Svecofennian shear zones exist along the western margin of the pluton, to the north and south, and to the east (eastern limb of the Grythyttan Syncline). The shear zone separating metarhyolite from felsic metatuffs and pyroclastic rocks to the north and south of the pluton is the inferred conduit for the Gåsborn granite magma (Cruden et al. 1999). Sveconorwegian shear zones envelope the pluton to the west (e.g. close to Långban) and east (along the west limb of the Grythyttan Syncline). A–A' shows location of profile in b). (After Cruden et al. 1999 based on Björk 1986, Baker 1985, Baker et al. 1988, Lundegårdh 1987, Lundström 1995). **b)** Cross-section A–A' through the Gåsborn granite. The interpretation is based on surface mapping of the pluton constrained at depth by local aeromagnetic and gravity data. Sveconorwegian reverse shear zones and steep post-Sveconorwegian normal faults modified the originally asymmetric pluton. A major Svecofennian shear zone that off-sets marble and metavolcanic rocks below the pluton is the inferred conduit for the Gåsborn granite. (After Cruden et al. 1999).

data) and essentially no amphibole or muscovite. Common accessory phases include zircon, apatite, titanite, and rather abundant fluorite. The composition is subaluminous (A/CNK close to 1) and similar to other SVB granites, but relatively evolved with particularly high HREE abundances

(Figs. 5, 36). The intrusion age of the pluton is not known, but it is inferred to be of approximately the same age as the surrounding SVB granitoids (c. 1.78 Ga; Cruden et al. 1999).

In the southeastern part of the pluton there is a 1.5x2 km area of a medium-grained sparsely

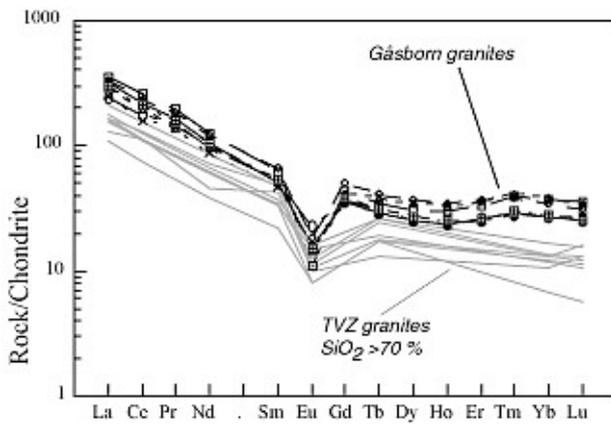


Fig. 36. Chondrite-normalised REE patterns for Gåsborn granites (U.B. Andersson, unpubl. data) in comparison with silicic Småland-Värmland Belt granites from the Tjällmo-Vättern zone (Andersson 1997a).

porphyritic granodiorite. Such granodiorite occurs as small enclaves within the entire pluton. The composition of this phase is very close to that of the main granite (U.B. Andersson unpubl. data). It is interpreted to be an early pulse of magma that crystallised close to the roof of the pluton and subsequently sank into the main magma (Magnusson 1925, Cruden et al. 1999). This also suggests that the original intrusion was horizontally stratified with an upper lid of porphyritic granodiorite (Cruden et al. 1999).

Apart from some metre to kilometre scale apophyses at the western boundary, the Gåsborn granite is discordant to the surrounding supracrustal rocks. It locally exhibits chilled margins and contact metamorphic effects are limited except for a spotted hornfels developed in grey slates west of the pluton. In this locality the mineral assemblages change towards the contact from pyrophyllite+biotite±andalusite to andalusite+almandine+biotite to andalusite+cordierite to sillimanite+K-feldspar. In addition to these parageneses preliminary thermometry indicate a temperature increase from 430° to 680° C at the contact. Pressure is bracketed by mineral reactions between 2 and 3 kbar (J.-O. Arnbom unpubl. data cited in Cruden et al. 1999), corresponding to an intrusion depth of c. 10 km.

A weak to strong, steep, predominantly NW striking preferred orientation of biotite and K-feldspar megacrysts has developed throughout

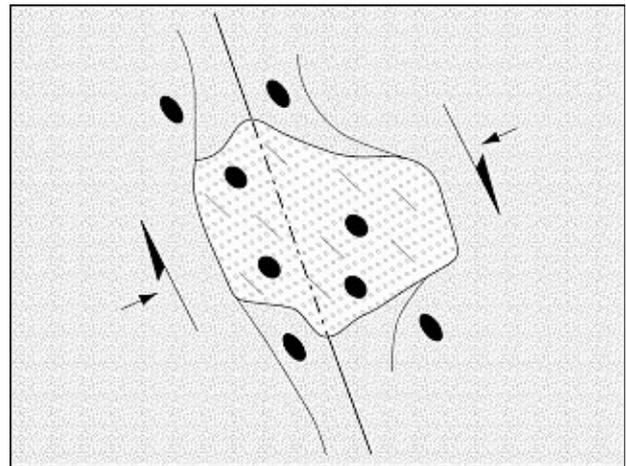


Fig. 37. Sketch of the restored shape and kinematics of regional Svecofennian deformation of the Gåsborn granite after removal of the offsets on post-Sveconorwegian faults. Black ellipses in the pluton are average sectional YZ-ellipses associated with the foliation (thin straight lines) determined by Fry-analysis of K-feldspar phenocrysts. Ellipses in the wall-rocks surrounding the granite represent the inferred regional strain increment due to Svecofennian transpression. The northnorthwest-southsoutheast black line across and below (dashed) the pluton represents the inferred conduit for the Gåsborn granite magma. Thin curved lines represent the traces of the distorted Saxå syncline on the western side and the stratigraphic metaandesite/metarhyolite contact on the eastern side of the pluton, respectively. (After Cruden et al. 1999)

the granite. Microstructures indicate that this fabric, and local structures in the wall rock, developed during the cooling history of the pluton, from high temperature solidus to regional metamorphic conditions (Cruden et al. 1999). Localised, from millimetres to centimetres wide, plastic shear zones were formed simultaneously. This deformation during cooling also deflected less competent wall rocks around the western and eastern contacts of the pluton.

Gravity anomaly data indicate that the pluton is c. 300 m thick in the east and approximately 3 km in the west where a NNW-trending root zone is suggested to exist (Cruden et al. 1999). This root zone roughly coincides with the inferred underlying tectonic contact between the lower and upper Svecofennian supracrustal units (Figs. 35a, b). During emplacement this structure was reactivated in a regional dextral transpressive environment (Fig. 37), and it has been implied that it acted as a conduit for the Gåsborn granite magma, as well as for the Saxå and to some extent for the Filipstad granites, based on the elongated gravity and aeromagnetic lows (Cruden et al. 1999). The

Gåsborn pluton itself is thought to have spread out laterally eastwards, from the feeder in the west, mainly by floor depression during inflation (Cruden et al. 1999; cf. Cruden 1998). As late Svecokarelian deformation continued after emplacement the shape of the Gåsborn granite and its wall rock was modified by a NE-SW shortening, during which steep, oblique dextral shear zones with SW side-up displacements were formed. The final shape was somewhat modified by Sveconorwegian E-W shortening, resulting in a shear zone that deformed the south-eastern

margin of the pluton as well as NNW-SSE reverse shear zones in the surrounding rocks. Also later brittle, normal faults have formed across the pluton.

Nd isotopic data (U.B. Andersson unpubl. data) on two samples from the pluton yielded initial ϵ_{Nd} values of c. +1 to +2 (at the approximated intrusion age of 1.80 Ga), which is fairly juvenile but in the range of values from SVB granites elsewhere. The result does not support material older than 2.1 Ga in the source (cf. Fig. 6, Chapter 2.1).

2.5. Geochemical character of mafic-hybrid magmatism in the Småland-Värmland Belt

Ulf B. Andersson, Olav Eklund & Dick T. Claeson

Mafic rocks are an important integral component in many parts of the TIB (Fig. 3), which is particularly true for the SVB. The Järna granitoids as well as the volcanic rocks of the Dala Province contain abundant mafic lithologies (Hjelmqvist 1966, Nyström 1999), and in the Rätan Batholith mafic bodies occur in several places (Gorbatshev 1997). In contrast, within the Revsund granitoid suite mafic rocks are uncommon (Lundqvist et al. 1990, Gorbatshev 1997), except in some areas in its northernmost part (e.g., Weihed & Antal 1998, Bergström & Sträng 1999, Bergström & Triumf 2002, Larson & Hellström 2003). Mafic-hybrid magmatic enclaves are frequent in many areas of the SVB, in the Järna granitoids (Ahl et al. 1999), and within the Revsund suite (Lundqvist et al. 1990, P. Weihed, pers. comm 1996).

Intermediate rocks of quartz-monzonitic to monzodioritic compositions are typical of the TIB (cf. Fig. 5), in the SVB particularly in central Småland (Persson 1985, 1989, Wikman 1998, 2000b), northern Öster- and Västergötland, and southern Närke (Wilson et al. 1986, Andersson 1989, 1991, 1997a), in the Järna granitoids (Ahl et al. 1999) and in the Revsund suite (Persson 1978, Lundqvist et al. 1990, Gorbatshev 1997, Andersson 1997a).

Within the SVB, mafic to intermediate rocks belong to all TIB age generations. Some examples are the c. 1.85 Ga Nygårdén norite pluton

(Claeson & Andersson 2000) and Tiveden-Askersund rocks (Wikström 1996), the 1.81–1.76 Ga Kårtorp (Andersson 1997a), Mjölby (Wilson et al. 1986), central Småland (Persson 1985, 1989), eastern Värmland (Vinnefors 1985, Claeson 2001), and southern Småland-Blekinge (Rimsa 2002) areas, and the c. 1.70 Ga Rymmen (Claeson 1999) and Roted (Annertz 1984, Stephens et al. 1993) intrusions.

It is just most recently that trace element data has become available for mafic rocks in different TIB regions. There may be problems in comparisons between the different regions, since some areas represent volcanic rocks, while other represent plutonic ones. To avoid “non-basaltic” samples, i.e. cumulates, ultramafic rocks and strongly fractionated varieties, the following criteria have been used to identify rocks as close as possible to primary basaltic compositions: SiO_2 40–52.5, $\text{MgO} < 12$, $\text{Al}_2\text{O}_3 < 20$ wt%, $\text{Sc} < 50$ and $\text{Ni} < 200$ ppm. From the rocks that fulfilled these criteria, samples with a proper set of analysed elements were selected for spider, REE and trace element discrimination diagrams. The geochemical data from the Eriksberg intrusion is used with restriction here because of its cumulate character (except in Fig. 39E). An exception is the data set from the Kårtorp area, which comprises fractionated varieties of mafic rocks from SVB with Mg\# around 20.

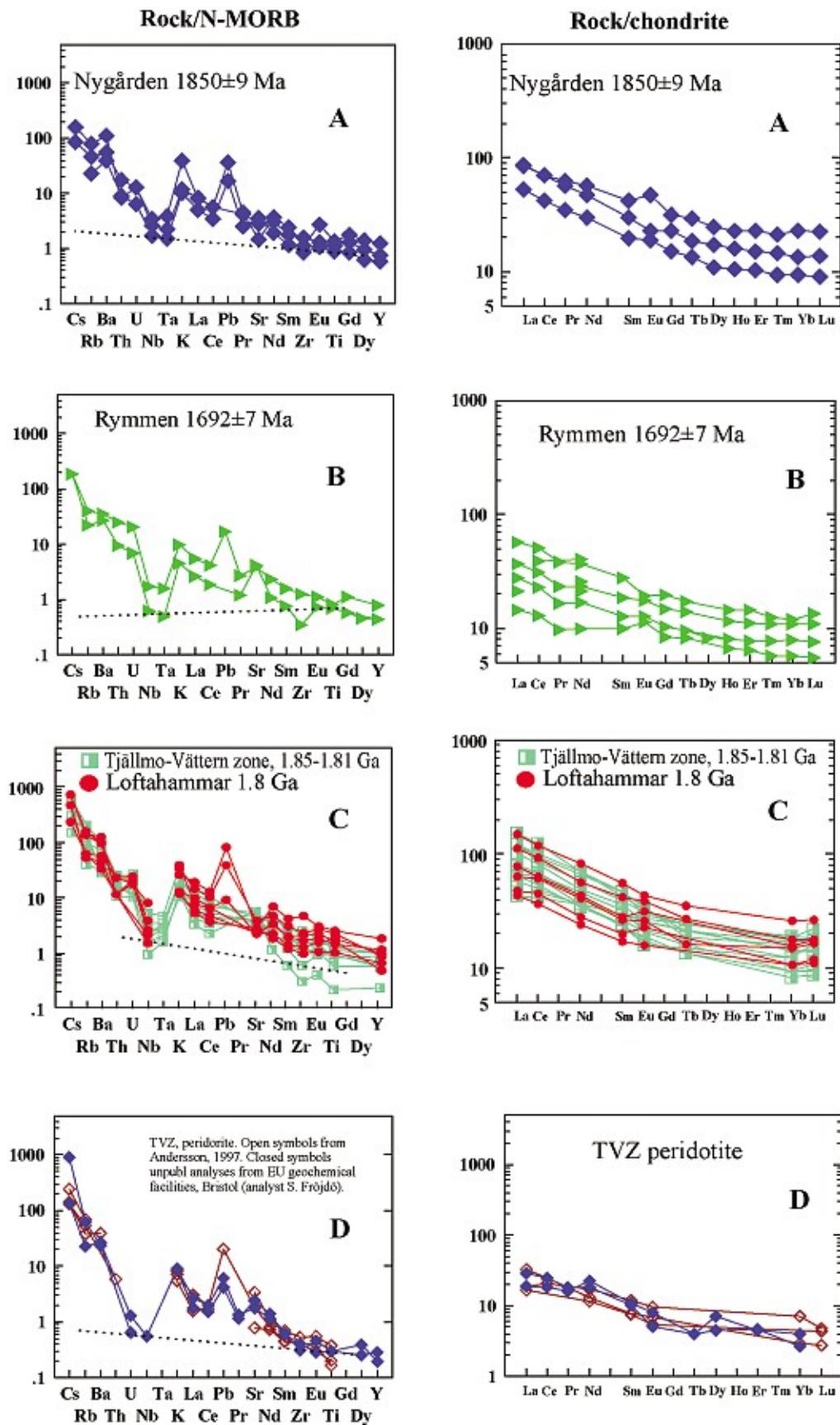
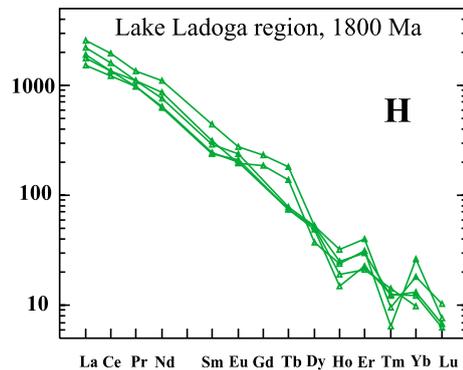
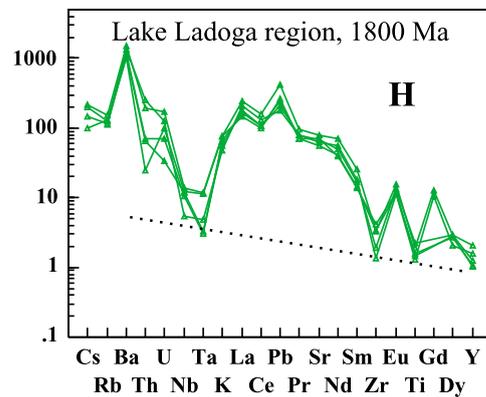
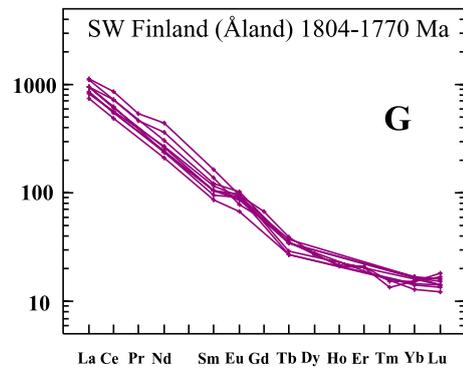
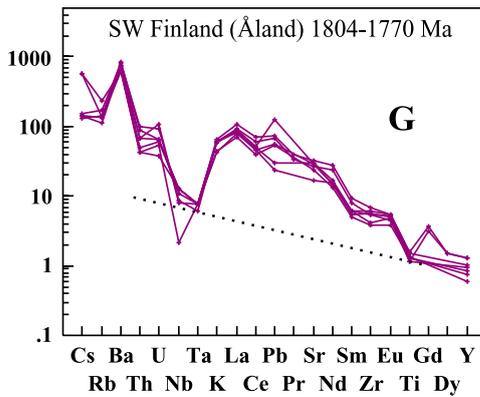
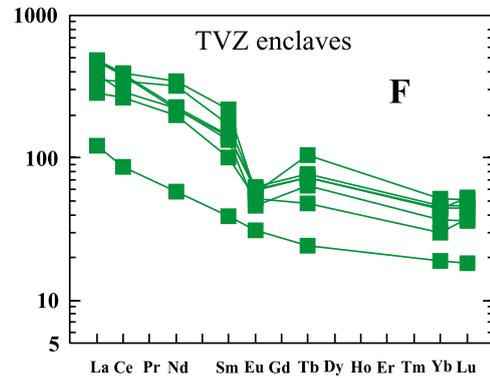
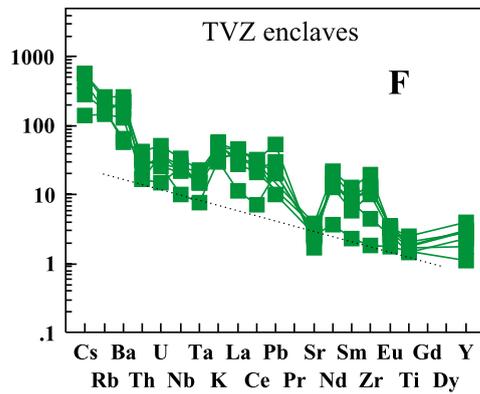
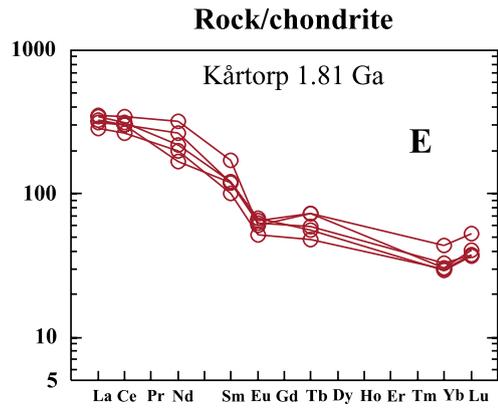
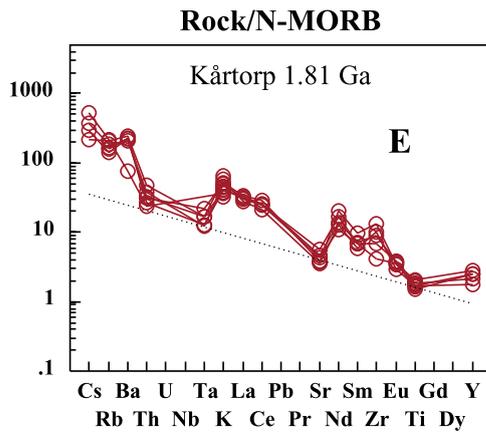


Fig. 38. A–H. N-MORB-normalised (Sun and McDonough 1989) spider diagrams and chondrite-normalised (Sun and McDonough 1989) REE diagrams for mafic rocks from the Småland-Värmland Belt, southwestern Finland and Lake Ladoga region. Rocks from all areas show a relative enrichment in the LIL elements (in the east particularly for Ba). Significant troughs for Nb and Ta are noted for mafic SVB rocks of different age generations, except for the somewhat anomalous rocks in the Kårtorp area and related enclaves. LRE elements are enriched,



but less strongly compared with LILE, and HFS elements are not enriched at all in the SVB rocks (except for the enclaves and Kårtorp rocks). The coeval postcollisional rocks further east are much more strongly enriched in LREE and HFSE, but not in HREE. Data from: Andersson (1997a), Rutanen et al. (1997), Eklund et al. (1998), Claesson (2001), Andersson & Claesson (unpubl.), Andersson & Wikström (unpubl.), Eklund et al. (in prep.).

The SVB mafic to intermediate rocks vary considerably in character. At present, analytical data exists from a limited number of occurrences, amongst which the following will be discussed and compared: the Nygårdén norite pluton (Claeson & Andersson 2000, and unpubl. data), the Kårtorp complex (Andersson 1997a), the Tjällmo-Vättern zone (TVZ) + Tiveden area (Andersson 1997a), mafic rocks in the Loftahammar area (Andersson & Wikström, unpubl. data), the Rymmen gabbro (Claeson 2001), and the Eriksberg gabbro (Claeson 2001). Comparison is also made with the roughly coeval c. 1.8 Ga post-collisional shoshonitic (lamprophyric) magmatism in SW Finland and in the western Lake Ladoga area (Rutanen et al. 1997, Rutanen 2001, Konopelko 1997, Konopelko et al. 1998, Eklund et al. 1998).

Claeson (2001) argues strongly that the cumulate-rich (mostly cumulus olivine plus plagioclase), LILE, Sr, Pb, and LREE enriched rocks of the 1.69 Ga Rymmen and 1.79 Ga Eriksberg gabbros were formed in convergent settings of continental arcs. Sources were depleted lithospheric mantle wedge material, subsequently metasomatically enriched by subduction-derived fluids. Some compositional ranges of minerals are: plagioclase An_{69-96} , orthopyroxene Mg# 55–83 and clinopyroxene Mg# 67–88. The parental magmas are inferred to have been low-K, high-alumina olivine tholeiites, which differentiated under relatively static conditions at 6–8 kbar (Rymmen; Claeson 1998) and 4–6 kbar (Eriksberg; Claeson 2001); crustal contamination was insignificant.

The chemistry of the 1.85 Ga Nygårdén noritic to gabbro-noritic pluton is subalkaline (Claeson & Andersson 2000, and unpubl. data). This intrusion is as old as the oldest SVB granites in the area and is one of the very few noritic intrusions in the SVB. However, also the Stavsjö intrusion east of Graversfors contains gabbro-noritic parts (Asklund 1925, Wikström et al. 1980). The trace element signatures are similar to those of the Rymmen and Eriksberg gabbros, with enrichment in LILE, Sr and LREE, but depletion in HFSE, particularly Nb and Ta, relative to N-MORB (Figs. 38A, B), suggestive of a subduction-related origin. The REE patterns show enrichment in LREE relative

to HREE, with flat HREE, and slightly positive or negative Eu anomalies. The orthopyroxene-dominated character and partly less primitive mineral compositions, particularly plagioclase (An_{58-76}), suggest a magma relatively rich in SiO_2 , possibly related to a component of crustal contamination in the Nygårdén pluton. (see Chapter 2.4.1. for field and petrographic description).

Recently, Rimsa (2002) showed that suites of mafic intrusions in the SVB granitoids of southernmost Småland and in the Tving granitoids of Blekinge have similar calc-alkaline to tholeiitic, destructive margin characteristics, on both sides of the Småland-Blekinge deformation zone.

The mafic rocks of the TVZ have not been dated, but occur in between the c. 1.85 Ga Tiveden and 1.81 Ga Kårtorp areas. The TVZ gabbroic rocks are enriched in LILE and the more incompatible HFSE relative to N-MORB (Andersson 1997a), but otherwise show the typical subduction-related Nb and Ta depletion (Fig. 38C). They classify as continental-arc calc-alkali basalts (Figs. 39A, B, C). Note that Andersson (1997a), based on incorrect Nb analyses, classified them as continental-type calc-alkali to tholeiitic basalts.

The peridotites found within the TVZ are also enriched in LILE and LREE relative to MORB, but depleted in HFSE (Fig. 38D). These may represent megaxenoliths of previously depleted upper mantle source lithologies, later metasomatised to their present state. This is supported by their enriched chemistry and mildly depleted Nd-isotopic composition (initial ϵ_{Nd} : +1 to +2). However, an origin as cumulates from primitive water-rich magmas cannot be ruled out. Major and trace element modelling (Andersson 1997a) suggests that the most primitive mafic rocks among the TVZ basites may have been derived by 25–30 % melting of source rocks similar to these peridotites. From such parental magmas, the evolution up to the most evolved TVZ basites could be accomplished by 30–45 % fractional crystallisation of dominantly clinopyroxene, later joined by plagioclase. The most primitive mafic rocks in the suite are found among the dykes that may represent a late pulse of slightly differentiated magma of the same type as the one that was parental to the earlier, more evolved basic TVZ rocks.

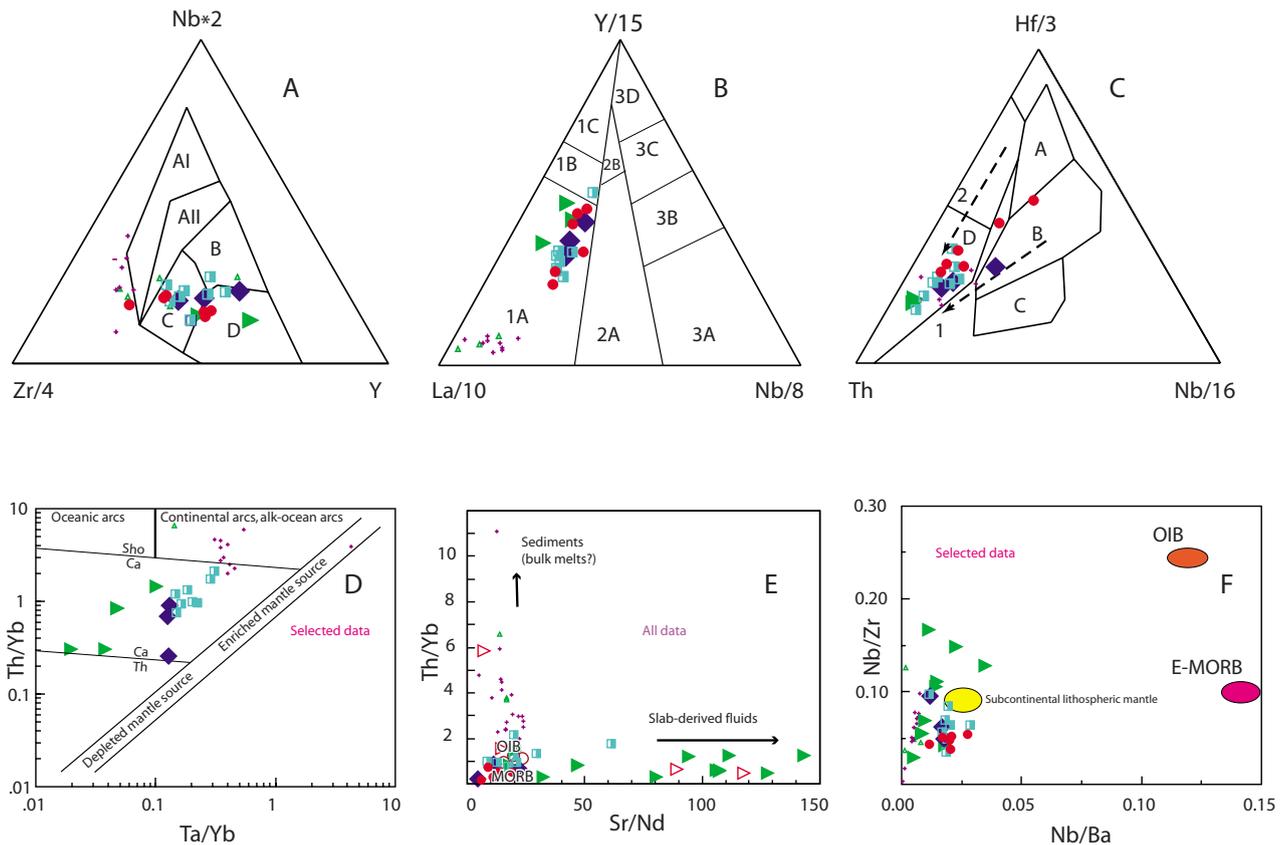


Fig. 39. Various discrimination diagrams for mafic rocks of the Småland-Värmland Belt, SW Finland and Lake Ladoga region. The symbols used in the discrimination diagrams are: blue diamonds = Nygård norite, green triangles = Rymmen gabbro, blue half-filled squares = mafic rocks from the Tjällmo-Vättern Zone, red triangles = Eriksberg gabbro, filled red circles = mafic rocks from the Loftahammar area, small lilac crosses = shoshonitic monzonites and lamprophyres from SW Finland, small green triangles = shoshonites from lake Ladoga region. Data sources the same as for Fig. 38.

A. Discrimination diagram for basalts after Meschede (1986). The field definitions are as follows: AI, within plate alkali basalts; AII, within-plate alkali basalts and within-plate tholeiites; B, E-type MORB; C, Within plate tholeiites and volcanic-arc basalts; D, N-type MORB and volcanic arc basalts.

B. Discrimination diagram for basalts after Cabanis and Lecolle (1989). Field 1 contains volcanic-arc basalts, field 2 continental basalts and field 3 oceanic basalts. The subdivisions of the fields are as follows: 1A, calc-alkali basalts; 1C, volcanic-arc tholeiites; 1B is an area of overlap between 1A and 1C; 2A, continental basalts; 2B, back-arc basin basalts; 3A, alkali basalts from intercontinental rift; 3B, 3C, E-type MORB (3B enriched, 3C weakly enriched), 3D, N-type MORB.

C. Discrimination diagram for basalts after Wood (1980). The fields are: A, N-type MORB; B, E-type MORB and tholeiitic WPB and differentiates; C, Alkaline WPB and WPB and differentiates; D Destructive plate-margin basalts and differentiates. According to Pearce (1996b), arrow 1 represent crust-magma interaction while arrow 2 represent subduction zone enrichment.

D. Tectonic discrimination diagram for mafic rocks after Pearce (1983). Ca = calc-alkaline, Th = tholeiitic. In this diagram with selected data the Rymmen analyses show an oceanic arc affinity while the Nygård and Tjällmo-Vättern Zone analyses tend to be of more continental arc character.

E. Diagram discriminating between basalts enriched by slab-derived fluids, by sediments or crustal materials (after Woodhead et al. 1998). If there was a volcanic arc setting Th/Yb vs. Sr/Nd may give an indication if the mantle was enriched by fluids (here represented by Sr over Nd) or by melts (here represented by Th over Yb) from the subducting slab (Woodhead et al. 1998). The Rymmen gabbros show clear indication for sources enriched by fluids, and so do at least partly also mafic rocks from Eriksberg and Tjällmo-Vättern Zone. Most samples, however, show no relative enrichment in Sr or Th, including all of the Nygård and Loftahammar rocks. For the rocks from SW Finland and Lake Ladoga area enrichment seems to be derived mainly from melting of subducted sediments (Eklund et al. in prep.). It should be noted that this diagram was constructed for volcanic arc rocks, wherefore Th may also indicate crustal melts.

F. Nb/Zr vs. Nb/Ba diagram discriminating basalts derived from a lithospheric mantle source from basalts derived from an asthenospheric source according to Hooper and Hawkesworth (1993). In the selected data all rocks from the Småland-Värmland Belt plot around the field defined for the subcontinental lithospheric mantle with low relative Nb contents indicating a negligible imprint of an asthenospheric source. This applies also to the post-collisional shoshonites from SW Finland and Lake Ladoga region.

The most mafic rocks of the 1.81 Ga Kårtoorp complex are monzodiorites with strongly elevated HFSE contents (Fig. 38E) but LILE contents similar to those of the more evolved basites in the TVZ (cf. Fig. 38C; Andersson 1997a). Mafic-

hybrid magmatic enclaves within the SVB granitoids of the Kårtoorp and TVZ areas have trace element contents identical to, and partly even higher than in the Kårtoorp rocks (Fig. 38F). The HFSE contents of these rocks are by far

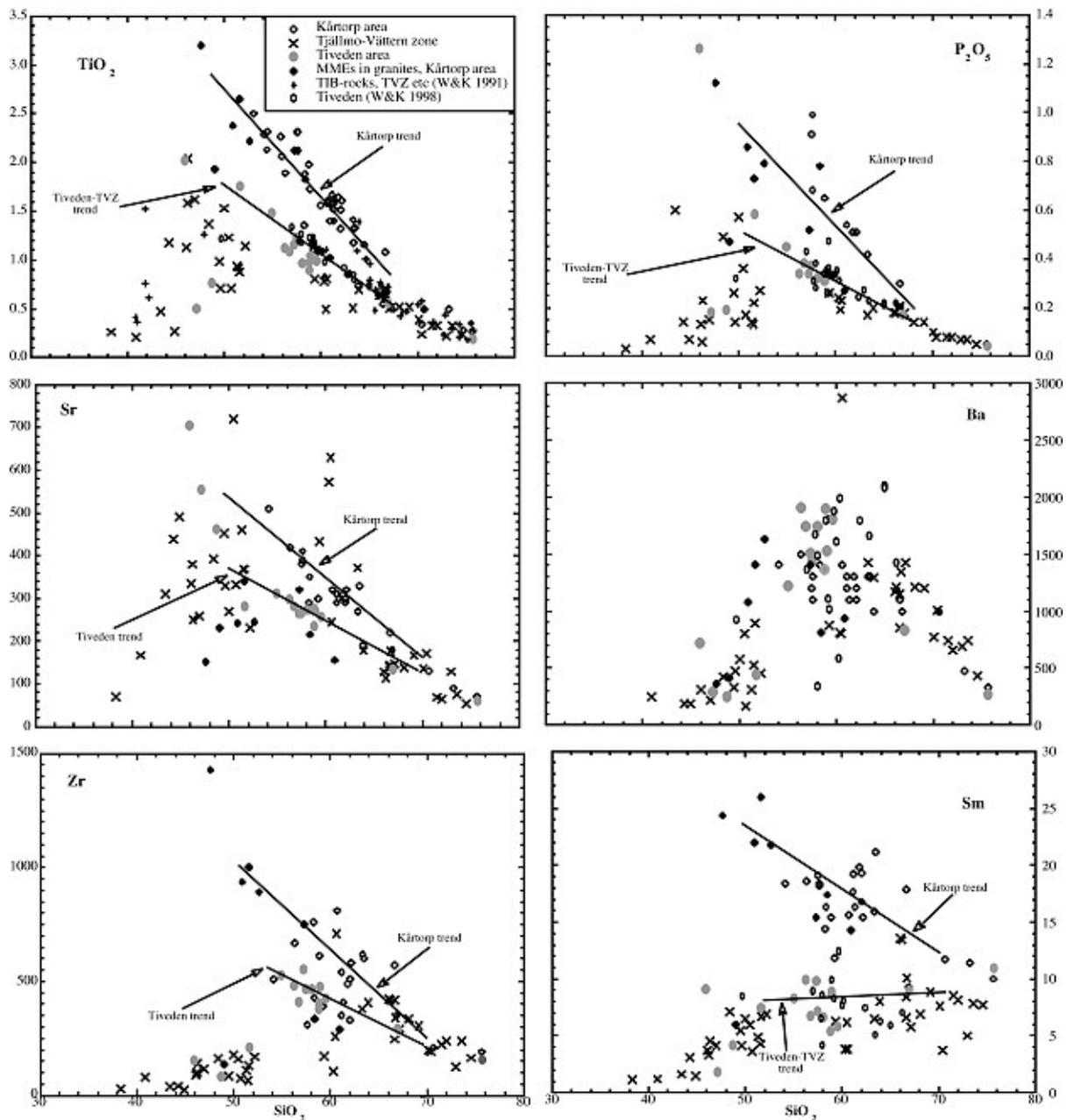


Fig. 40. Whole-rock geochemical trends of selected elements from the Tjällmo-vättern Zone, Kårtoorp, and Tiveden rocks of the Småland-Värmland Belt (Andersson 1997a). MMEs = mafic-hybrid magmatic enclaves. W&K 1991 refers to Wikström & Karis (1991) and W&K 1998 to Wikström & Karis (1998). The Kårtoorp and Tiveden rocks form separate trends, and the Kårtoorp rocks and enclaves are enriched in HFSE.

higher than those in the associated granitoids. The chemical compositions show close resemblance to lamprophyres, but the Kårtoorp and enclave rocks have considerably lower Mg-numbers (mostly below 20) than normal lamprophyres (generally above 40), (e.g. Sabatier 1991). They are also strongly depleted in mafic elements and Sr, and are possibly related to parental magmas similar in composition to the evolved TVZ basites. The enclaves and mafic Kårtoorp rocks may have

been derived by extreme fractionation (>80 %) from the latter, of mainly plagioclase and clinopyroxene, but neither Fe-Ti oxides nor apatite, since the P_2O_5 and TiO_2 contents are high in these highly evolved rocks (Fig. 40) (Andersson 1997a).

At the southeastern edge along the exposed Svecofennian margin, in the Loftahammar area (Figs. 7, 12), abundant mafic rocks are associated with the Loftahammar granitoids (cf. Gavelin

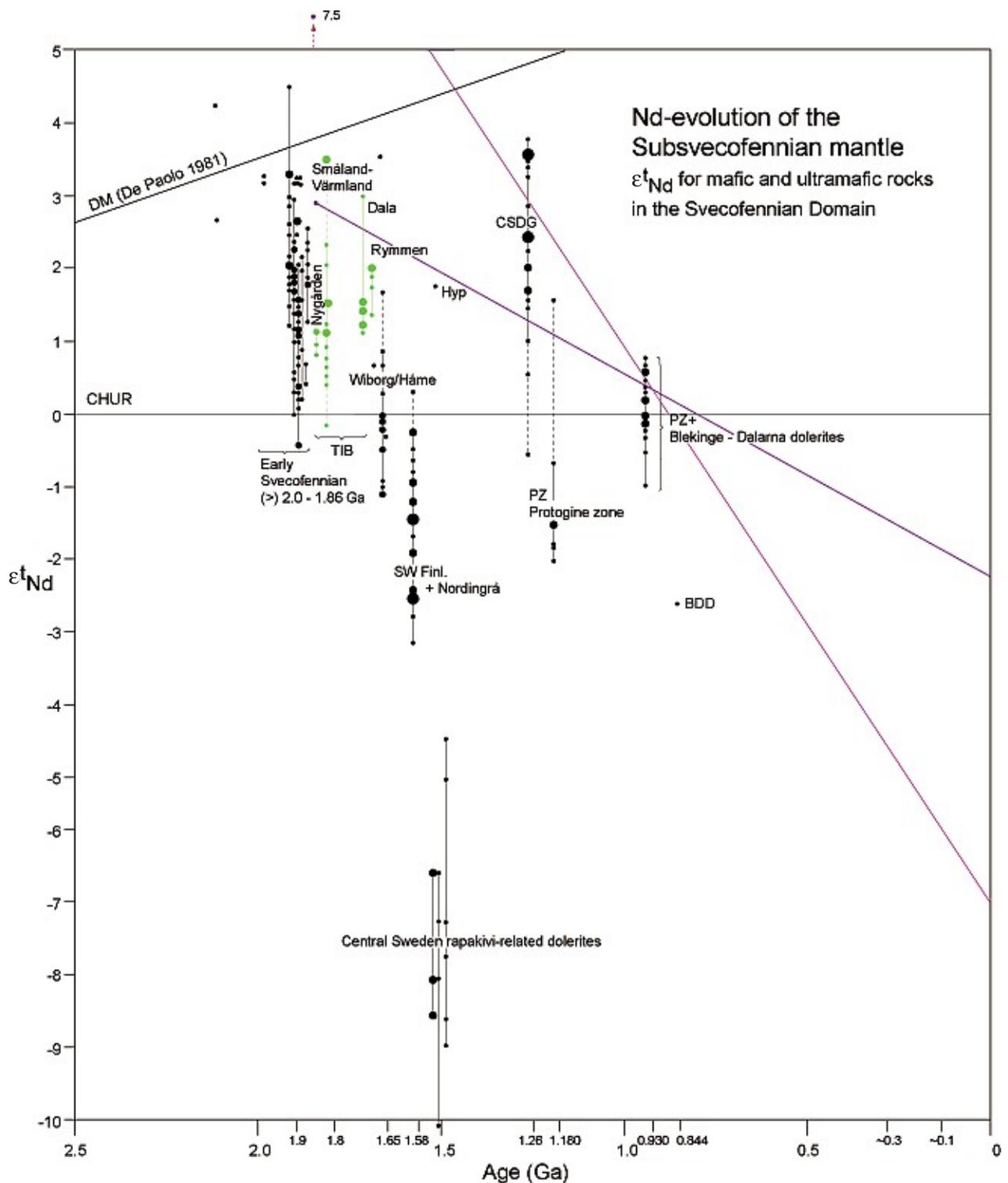


Fig. 41. Compilation of initial ϵ_{Nd} values of mafic rocks from the Svecofennian and TIB domains of the Fennoscandian Shield. Green corresponds to TIB rocks. The TIB rocks are, in general, 'mildly depleted' with ϵ_{Nd} values between +0.5 and +2.5, in similarity with the majority of the early Svecofennian mafic rocks. Younger mafic rocks vary widely in initial ϵ_{Nd} composition. The c. 1.25 Ga rocks in central Sweden and western Finland (central Scandinavian dolerite group, CSDG) tend to be more depleted than the TIB rocks, while the c. 1.6 Ga rapakivi-related rocks range from c. 0 in SE Finland, -1 to -3 in SW Finland and Nordingrå, to between -6 and -10 in central Sweden. The c. 1.2 Ga Protogine zone (PZ) dolerites are slightly enriched (-1 to -2), while the younger PZ and Blekinge-Dalarna dolerites (BDD) cluster close to CHUR. One of the two dykes from the Nygård area has an unrealistically high ϵ_{Nd} (1.85) but their evolutionary lines converge at BDD initial compositions, suggesting that they most probably belong to this suite. References for the data: Huhma (1986), Björklund & Claesson (1992), Patchett & Kouvo (1986), Patchett et al. (1987, 1994), Rämö (1990, 1991), Lindh et al. (2001b), Andersson (1997a, c), Andersson et al. (2002) Fröjdö et al. (1996), Nyström (1999), Claesson (2001), Claesson & Andersson (2000), Persson (1997), Kumpulainen et al. (1996), Billström & Weihed (1996), Valbracht (1991), Claesson (1987), Johansson & Johansson (1990), Larson & Hellström (2003), U.B. Andersson (unpubl data).

1904). They occur as larger intrusions (e.g. the Grundemar gabbro), as numerous smaller occurrences, and as synplutonic dykes showing abundant signs of mingling and mixing relations with the surrounding granitoids (e.g. Gavelin 1910, Wikström 1988a, b). One gabbroic sample from a synplutonic dyke system at Hallmare gave an age close to 1.80 Ga (F. Hellman, pers. comm. 2000), which is at some variance with the older ages obtained for the granitoids (cf. Chapter 2.3.2). However, more than one generation of TIB-basites in the area cannot be dismissed. Geochemically, these rocks appear to be of calc-alkalic continental-arc affinity (Andersson & Wikström unpubl. data), in similarity with SVB basites from the other areas (Figs. 38C, 39).

The *intermediate rocks* of the Kårtorp area follow straight-line trends between a strongly HFSE-enriched mafic end-member represented by some mafic enclaves (Andersson 1997a), and the coarse-porphyrific (Filipstad type) SVB granites of the area with a SiO₂-content close to 70 % (Fig. 40), suggesting an origin by plutonic magma mixing processes. Rocks of all intermediate compositions are present, showing gradual transitions in the field, with more sparsely distributed and smaller feldspar and quartz crystals upon increasing basic composition.

The intermediate monzo-rocks of Tiveden have completely different compositions (Fig. 40) with much lower contents of HFSE, compared with the Kårtorp hybrids (Andersson 1997a). While the felsic end-member is also here represented by the SVB granites of c. 70 % SiO₂, a possible mafic end-member must have been much less enriched in HFSE and similar in composition to the most evolved basites of the TVZ. The intermediate rocks are, however, enriched in certain elements, e.g., Al, Ba, Eu, Zr, and Hf, relative to both end-members (Fig. 40), and display flat to positive Eu-anomalies (Andersson 1997a). This implies a contribution to these rocks from a cumulus component, comprising both feldspars and zircon. Textures of closely packed euhedral plagioclase and in some instances subhedral-euhedral K-feldspar can explain the geochemical data. Whether the geochemical evolution of these rocks was dominated by a process of restite unmixing (Chappell et al. 1987, Chappell 1996), or was the

result of mixing of two magmatic components and a cumulus component, remains unclear.

In a *general comparison*, it thus appears that mafic rocks from all areas were derived from lithospheric mantle sources, at least partly enriched by slab-derived fluids. In a subduction zone, non-conservative elements are contributed from the slab to the subarc mantle wedge and advected into the melting column, whereas conservative elements are retained in the downgoing slab. During slab dehydration Nb, Zr, Hf, Ti and HREE are conservative and, hence, define a baseline for the subarc mantle wedge. The incompatible elements Cs, Rb, Ba, K, Pb, and Sr are highly non-conservative, and U, Th and LREE are moderately conservative. Consequently, these elements are enriched in the mantle wedge by fluids derived from the slab and define positive anomalies above the baseline. If thermal conditions in the subduction zone are such that the slab melts, then Nb, Zr and Hf become non-conservative and plot above the baseline interpolated from Ti (Kerrick & Wyman, 1996).

The geochemical data summarised above suggests that the granitoids of SVB over wide areas, particularly along the Svecofennian margin, are associated with mafic rocks of destructive margin, continental-type affinities, which seem to support an Andino-type setting for the SVB (cf. Nyström 1982, 1999). Whether this is true for the entire SVB area must await further studies of mafic rocks all over the TIB, and particularly in eastern-central Småland.

In relation to TIB, coeval post-collisional mafic magmatism further east, within the Svecofennian Domain up to the Archaean craton, becomes gradually richer in LILE and HFSE from SW Finland to Russian Karelia (Figs. 38G, H) (Konopelko 1997, Eklund et al. 1998, Konopelko et al. 1998). It is suggested that the melts were derived from strongly enriched lithospheric mantle sources with low solidus temperatures. These enriched mantle sources melted at the same time and in the same tectonic framework as the extensive magmatic processes further west in the TIB area (Eklund et al. 2000, in prep.).

The *Nd isotopic compositions* of the mafic to intermediate rocks from the TIB (Wilson et al. 1986, Andersson 1997a, Nyström 1999, Claeson

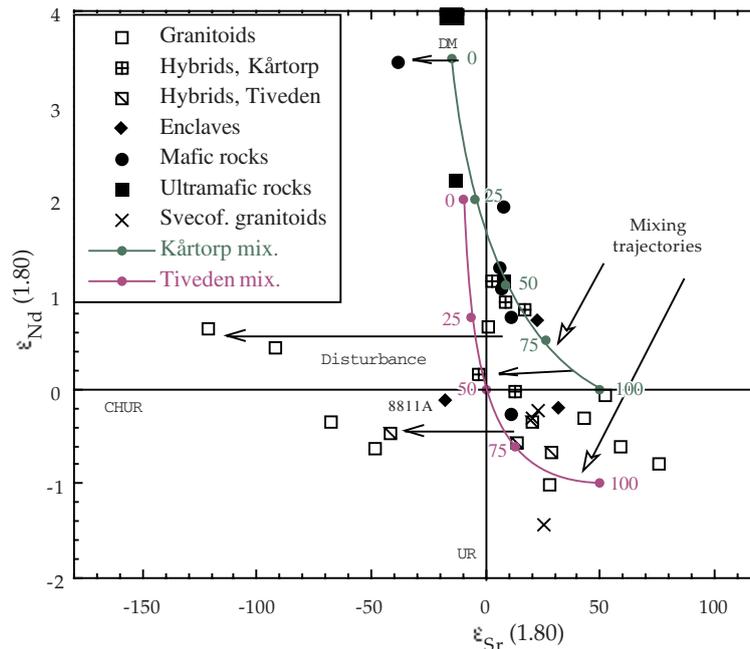


Fig. 42. $\epsilon_{Nd}(1.80) - \epsilon_{Sr}(1.80)$ diagram for Småland-Värmland Belt rocks from the Kårtorp, Tjällmo-Vättern Zone, and Tiveden areas (modified from Andersson 1997a). Values (at 1.80 Ga) for three early Svecofennian granitoids are also included. The Rb-Sr whole-rock system is obviously disturbed for several rocks, particularly granites, due to postmagmatic loss of ^{87}Sr and/or increase of the Rb/Sr ratio. In spite of this, and the narrow ϵ_{Nd} range with considerable overlaps, the intermediate rocks plot in between the granitic and basic endmembers. Two calculated mixing lines are given as possible examples. Values used in the calculations are, for the Kårtorp curve, basic endmember: $\epsilon_{Nd} +3.5$, 17 ppm Nd, $\epsilon_{Sr} -15$, 260 ppm Sr, granitic endmember: $\epsilon_{Nd} \pm 0$, 40 ppm Nd, $\epsilon_{Sr} +50$, 150 ppm Sr; and for the Tiveden curve, basic endmember: $\epsilon_{Nd} +2.0$, 17 ppm Nd, $\epsilon_{Sr} -10$, 720 ppm Sr, granitic endmember: $\epsilon_{Nd} -1.0$, 37 ppm Nd, $\epsilon_{Sr} +50$, 150 ppm Sr. Dots on the curves represent mixing proportions of 25, 50 and 75 %.

2001, Claeson & Andersson 2000, Larson & Hellström 2003, U.B. Andersson unpubl. data) in relation to the evolution of Svecofennian crustal sources, and to other mafic rocks of different ages in the Svecofennian and TIB Provinces are shown in Fig. 6 and Fig. 41, respectively. In general, the initial ϵ_{Nd} compositions show a mild to relatively strong depletion, consistent with the inference from geochemistry that the basic TIB magmas were derived from mantle sources previously melt-depleted but overprinted by variable degrees of metasomatic enrichment (Andersson 1997a, Nyström 1999, Claeson 2001). It is possible that this mantle depletion took place already prior to the early Svecofennian arc-accretion at 1.91–1.86 Ga. During the latter period, subduction may have caused mantle enrichment. This is

indicated by very strong variation in the degrees of depletion of the early Svecofennian mafic rocks (Fig. 41). Depleted mantle sources, partly enriched during early Svecofennian subduction, are thus viable as protolith material, tapped particularly by the early basic TIB-1 magmas, while younger TIB-basites may derive from mantle sections depleted during TIB-1 subduction and enriched during continuous subduction.

The intermediate SVB rocks have intermediate isotopic compositions relative to the associated mafic and felsic rocks (Fig. 6). This is seen in plots of the initial $\epsilon_{Nd} - \epsilon_{Sr}$ values (Fig. 42) even though there is scatter that may to some degree be due to the small variation in ϵ_{Nd} and postmagmatic disturbance of the Sr isotope system in many of the samples (Andersson 1997a).

2.6. Tectonometamorphic reworking of TIB rocks during the Sveconorwegian orogeny, south-central Sweden

Carl-Henric Wahlgren & Michael B. Stephens

An important tectonic model for the Sveconorwegian orogen north and northeast of Lake Vänern, south-central Sweden, was presented by Berthelsen (1980). Both the Mylonite Zone and the frontal area of the Sveconorwegian orogen were interpreted to be related to large-scale compressional tectonics. Earlier thrusting to the present west was inferred to be followed by later thrust movement to the present east.

New structural and geochronological data from the northeastern part of the Sveconorwegian orogen have recently been presented (e. g. Wahlgren et al. 1994, 1996b, 1996c, Page et al. 1996, Stephens et al. 1993, 1996, Söderlund et al. 1999) and the following text presents a brief overview of the results in these studies. These data confirm the broad structural geometry and tectonic regime envisaged by Berthelsen (1980), but the new kinematic data demand some revision of the model presented earlier. An attempt to understand the deeper crustal geometry of a part of this area using reflection seismic profiling has been presented by Juhlin et al. (2000).

North and east of Lake Vänern, the Eastern Segment of the Sveconorwegian orogen, i.e. the area between the Mylonite Zone (MZ) in the west and the Sveconorwegian Frontal Deformation Zone (SFDZ; Wahlgren et al. 1994) in the east, is dominated by intrusive rocks belonging to the c. 1.855–1.66 Ga Transscandinavian Igneous Belt (Fig. 3). The SFDZ corresponds more or less to the Sveconorwegian front of Berthelsen (1980). All age-generations of TIB intrusions have been recorded in the area. Older (c. 1.855–1.84 and 1.81–1.76 Ga) intrusions dominate in the eastern, frontal part of the orogen, while U-Pb zircon and titanite ages demonstrate that distinctly younger (c. 1.70–1.66 Ga) TIB intrusions dominate farther west. In the easternmost part of the orogen (westernmost Bergslagen), Svecofennian supracrustal rocks (c. 1.91–1.89 Ga), calc-alkaline intrusions (c. 1.89–1.875 and 1.855–1.84 Ga) and a suite of granites and pegmatites (c. 1.845–1.75 Ga) occur. The supracrustal and c. 1.89–

1.84 Ga intrusive rocks, including the oldest TIB rocks, display older, pre-Sveconorwegian (Svecokarelian) deformation and metamorphism. In the northeasternmost part of the Sveconorwegian orogen, volcanic rocks belonging to the TIB (c. 1.80 and 1.70 Ga) and Mesoproterozoic sandstone (“Dala sandstone”) are present. A significant lithological component in the TIB-dominated area north of Lake Vänern is the c. 1.57 Ga dolerite dyke swarm. The youngest rocks which are affected by ductile deformation are c. 1.00–0.90 Ga dolerite dykes, which mainly occur in the easternmost, frontal part of the orogen, east and northeast of Lake Vänern.

During the c. 1.1–0.9 Ga Sveconorwegian orogeny, all the above mentioned rocks were more or less strongly deformed and metamorphosed. In the eastern part of the orogen the Sveconorwegian structural overprinting is spaced to semi-penetrative, whereas the deformation is more or less penetrative between Kristinehamn, at the northeastern shore of Lake Vänern, and the MZ. The transition from penetrative to semi-penetrative deformation coincides more or less with the location of the traditional “Protogine Zone”. Besides new fabric development, the Sveconorwegian deformation is also responsible for some reorientation of older Svecokarelian structures in the easternmost part of the orogen into the Sveconorwegian approximately N-S structural trend. The syn-deformational metamorphic grade increases from low-grade in the east to medium- to high-grade in the western, penetratively deformed area, which is in accordance with the east to west increase in bulk strain.

In the area immediately north of Lake Vänern, between the MZ in the west and the SFDZ in the east, the shear foliation constitutes a strongly asymmetric fan-like structure (Fig. 43) in an east-west cross-section. In the penetratively deformed area between the MZ and Kristinehamn, the shear foliation is subhorizontal. In the Kristinehamn area, the shear foliation dips gently to moderately to the east, is vertical farther to the east and dips

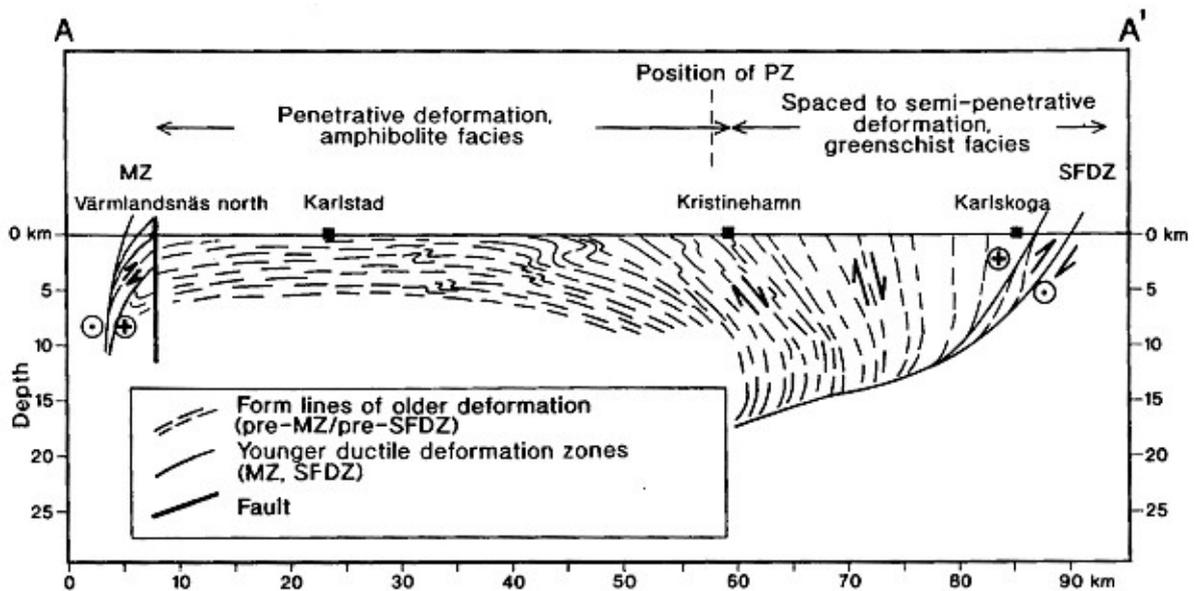


Fig. 43. Structural cross-section across the Eastern Segment of the Sveconorwegian orogen north of Lake Vänern, from the Sveconorwegian Frontal Deformation Zone in the Karlskoga area in the east to the Mylonite Zone in the northern part of the Värmlandsnäs peninsula in the west. The cross-section is based on data in Wahlgren et al. (1994) and Stephens et al. (1996).

steeply to the west in the eastern frontal part of the orogen. The general strike is N-S. Dip-slip movements predominate and a kinematic analysis based on several reliable kinematic indicators has revealed a constant top-to-the-east sense of displacement across the entire fan-like structure. Thus, the broad-scale structural geometry in the frontal part of the orogen is similar to that presented by Berthelsen (1980). However, the established top-to-the-east sense of displacement across the entire frontal part of the orogen does not support thrusting to the west along the east-dipping shear zones in the western part of the area as suggested by Berthelsen (1980).

Two phases of Sveconorwegian deformation have been identified in the area. Apart from the predominant, more or less regionally developed, older shear foliation and ductile deformation zones which strike c. N-S, a set of younger well-defined deformation zones occurs in the easternmost part of the orogen. These zones define the SFDZ (Wahlgren et al. 1994) and the most prominent zones strike NNE-NE, dip westwards or are subvertical, and display both dextral and reverse senses of shear. Although less abundant, zones striking NW-WNW and displaying a sinistral component of shear sense also occur.

The older fabric which is oriented in the fan-

like configuration is interpreted to be the result of an east-verging thrust system which subsequently was rotated into the SFDZ. The thrust system is inferred to be the initial result of oblique collision and crustal shortening in a WNW-ESE direction. Shortening at this stage was absorbed by crustal thickening. Subsequently, the deformation was constrained to discrete zones at shallower crustal levels. The MZ overprints and defines the western flank of the east-verging thrust system, and is the result of sinistral transpression in connection with escape-like tectonics. Top-to-the-east, possibly out-of-sequence thrusting along the SFDZ marks the final expression of the oblique collision.

The fan-like configuration of the shear foliation east of Lake Vänern is confirmed in a 17 km long reflection seismic profile from the eastern shore of Lake Vänern south of Kristinehamn and eastwards (Juhlin et al. 2000). Apart from slight discrepancies, there is good general agreement between the fan-like configuration as interpreted from surface structural information and the seismic image. The interpretation of the seismic data also supports a two-stage structural development, where the west-dipping SFDZ overprints the east-dipping thrust system.

⁴⁰Ar/³⁹Ar age determinations of hornblende in

the penetratively deformed area north of Lake Vänern have yielded ages in the range 1009–965 Ma, which is inferred to be the minimum age for the crustal thickening event during which the regional foliation was developed (Page et al. 1996). U-Pb ages of c. 976 and 956 Ma for metamorphic titanites in metagranites from the same area (Söderlund et al. 1999) confirm the Sveconorwegian age of the regional foliation. The preservation of igneous titanites, which dis-

play U-Pb ages similar to U-Pb zircon ages of c. 1661 and 1674 Ma for the metagranites, indicate that no major tectonothermal event has affected the Eastern Segment north of Lake Vänern from the time of TIB emplacement until the late Sveconorwegian orogenic overprinting. $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages in the time range 930–904 Ma are interpreted to date the final compressional displacements along the SFDZ (Page et al. 1996).

3. THE DALA PROVINCE

3.1. Dala volcanism, sedimentation and structural setting

Jan-Olov Nyström

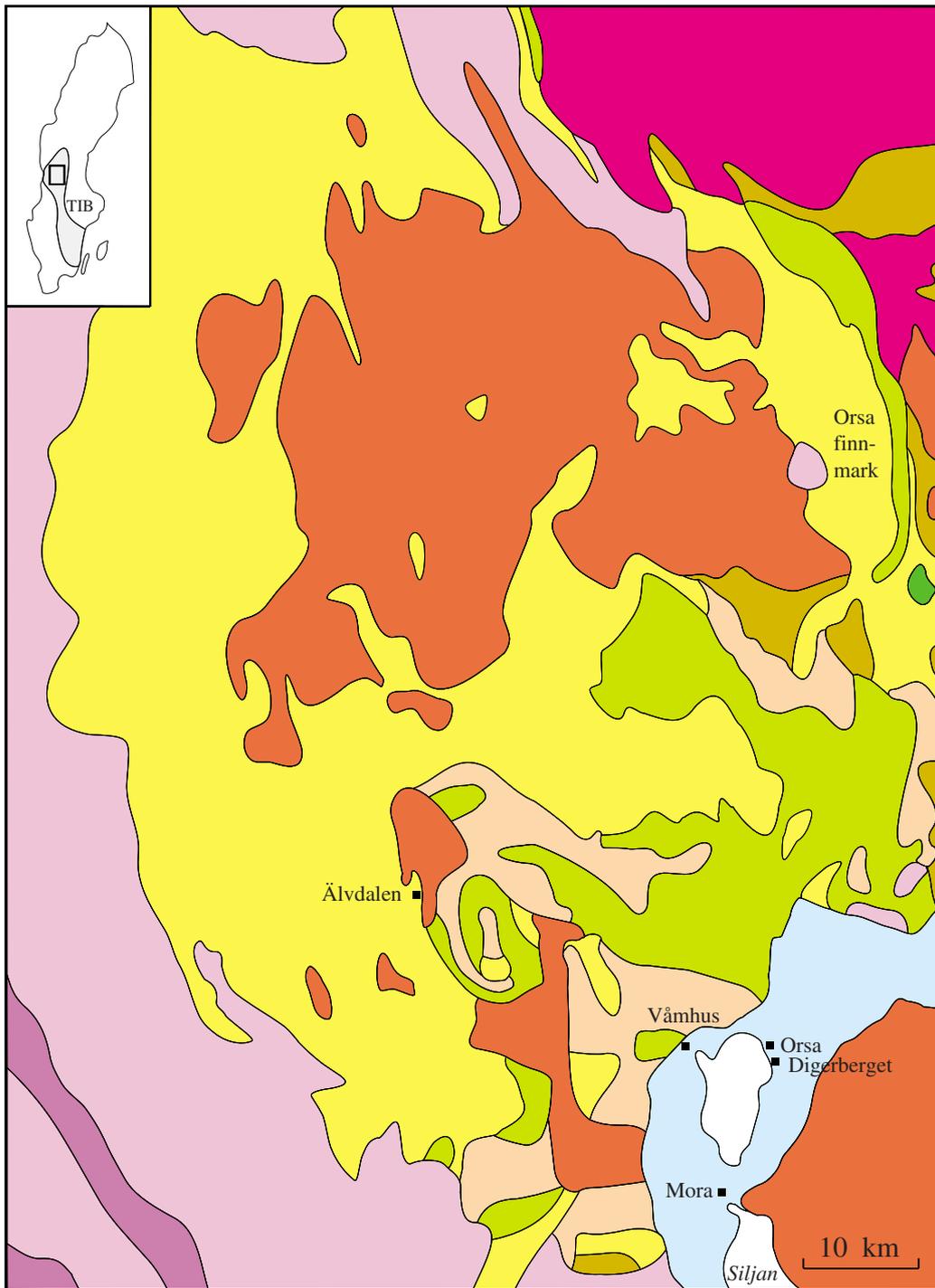
3.1.1. Geology and petrography

The Dala volcanites and associated granites have earlier been called the sub-Jotnian complex. The term refers to their position relative to an unconformably overlying 800 m thick pile of Jotnian sandstone with intercalated flows of basalt that occupies large areas in western Dalarna. Hjelmqvist (1966) divided the sub-Jotnian complex into an Upper Dala group and a Lower Dala group. The former included seemingly unmetamorphosed volcanic rocks of different composition, whereas the latter were mainly acid metavolcanic and metasedimentary rocks of controversial age distributed in several areas. Based on U-Pb dating, Lundqvist and Persson (1996, 1999) found that the volcanic rocks formed during two major magmatic events, TIB-2 at 1.7 Ga and TIB-1 at 1.8 Ga, and concluded that the Upper and Lower Dala groups of Hjelmqvist (1966) should be abolished since they are not in harmony with the radiometric data.

This chapter which is based on Nyström (1999) treats the Dala volcanites and associated rocks belonging to the TIB-2 group, excluding granites (Fig. 44). They form a several thousands of meters thick sequence of ignimbrites, lavas, and intercalated sedimentary rocks dominated by conglomerates and sandstones (Digerberg formation) derived mostly from volcanic rocks similar to those

in the sequence. Basal layers of the Dala volcanites, resting unconformably on a strongly eroded basement of folded and regionally metamorphosed Svecokarelian supracrustal and granitoid rocks, are exposed in Orsa finnmark (Los-Hamra region; Lundqvist 1968). The volcanic sequence is flat-lying; most observations of dip are in the range 10–25°. However, near its base and in local zones moderate to steep dip is recorded.

In contrast to many other volcanic rocks in the TIB, the original structures and textures of the Dala volcanites are generally preserved, without penetrative deformation. Primary volcanic minerals are common as phenocrysts in basic to intermediate lavas. Secondary mineral assemblages in altered parts of rocks show that the Dala volcanites have been affected by burial metamorphism (Nyström 1983). The metamorphic grade decreases from greenschist facies in Orsa finnmark (bottom) to pumpellyite-actinolite facies in the more centrally situated Älvdalen area, and to prehnite-pumpellyite facies near Våmhus (present top) where megablocks of the volcanic sequence were displaced during the meteorite impact that gave rise to the Siljan ring structure (Wickman 1981, Nyström 1983; the latter facies also characterises the Jotnian rocks). The burial metamorphic pattern and the regional unconformity at the top of the sequence indicate considerable



- | | |
|---|--|
| Paleozoic rocks | Gabbro |
| Jotnian Öje basalt | Dala porphyry |
| Jotnian Dala sandstone | Dala porphyrite |
| Rätan granite | Digerberg formation |
| Dala granite | Older rocks |

Fig. 44. Simplified geologic map of the central-northern part of Dalarna Province and adjacent region to the north. The numerous dykes and sills of dolerite in the region are omitted for clarity.

erosion. Since rocks metamorphosed at zeolite facies are lacking, the original thickness of the sequence was, very likely, thousands of meters thicker.

The Dala volcanites comprise two main rock types often referred to as porphyrites and porphyries (Hjelmqvist 1966, Lundqvist & Persson 1999). The Dala porphyrites are with a few exceptions lavas whereas the Dala porphyries consist of ignimbrites and less abundant subvolcanic rocks, ranging from small dykes to stocks of considerable size. On Hjelmqvist's (1966) geological map of Dalarna (Kopparbergs län) the porphyrites are subdivided into andesite, gray porphyrite and red porphyrite. The andesites of Hjelmqvist are basic fine-grained rocks of both volcanic and subvolcanic character: basalt flows and a kilometre-sized microgabbro intrusion southeast of Älvdalen. The grey porphyrites correspond to a varied suite of subaerial lavas ranging from basalt to andesite in composition. They also include dacitic ignimbrite with mafic enclaves, earlier regarded as lava. This ignimbrite is present in three separate areas and can be followed for a distance of 30 km. It is a remnant of a thick sheet of wide distribution, and serves as a stratigraphic marker. The red porphyrites are lava flows of uniform appearance and dacitic composition.

The intercalated Digerberg formation consists of conglomerate, sandstone, and pyroclastic material (agglomerate and tuff). The conglomerates vary from >100 m thick units to a few centimetres thick trains of clasts in sandstone. The clasts are well-rounded and matrix-supported. The appearance of the conglomerates suggests deposition in a fluvial environment. Thick volcanic agglomerates suggesting volcanic centres are mentioned in Hjelmqvist (1966). An alternative interpretation is that localities with red porphyrite passing into thick agglomerates represent autobrecciated lava flows. The red porphyrites are commonly associated with conglomerates.

Porphyries occupy ca. 2000 km² and are much more abundant than porphyrites south, west and north of Älvdalen (Fig. 44). Hjelmqvist (1966) distinguished four types of porphyries on his map (schlieric or ignimbritic porphyry, phenocryst-rich porphyry, Bredvad porphyry and unspecified porphyry). Ignimbrites are present among all

of them as shown by fiamme and/or vitroclastic texture. The Bredvad porphyry, for example, that covers the western half of the porphyry area, has a relatively coarse recrystallised groundmass but fiamme are still discernable. This seemingly uniform porphyry possibly comprises several ash flows which would be consistent with some variation in phenocryst abundance and grain size. Subvolcanic porphyries have granophyric groundmass and their phenocrysts tend to be unbroken.

According to the stratigraphy of Hjelmqvist (1966) for the Upper Dala formation, the red porphyrites formed the lowest unit, followed upwards by Digerberg formation, grey porphyrites, and porphyries at the top. Comparison with regions of active volcanism and an inferred caldera structure in the Älvdalen area led Nyström (1982) to conclude that no stratigraphy of general validity for the entire region can exist, which Lundqvist (1968) already demonstrated in Orsa finmark.

The lavas range from black or dark grey basalts to brownish red dacites; the andesites are generally dark to medium grey. Among the basalts there are both fine-grained types with no or only a few small phenocrysts and highly porphyritic varieties (Figs. 45A–B); the less basic lavas are porphyritic as a rule (Figs. 45C–D). The most common minerals occurring as phenocrysts are pyroxene and plagioclase, followed by olivine (pseudomorphs), dark mica, amphibole and Fe oxide.

Pyroxene phenocrysts are relatively resistant to alteration and in some lava flows pyroxene is even preserved in the groundmass. Only clinopyroxenes have been found; they grade from diopside in basalts to augite in andesites and dacites. Chromian diopside (ca. 0.5 wt% Cr₂O₃) occurs as core in phenocrysts in the most basic lava sample. Olivine, invariably altered to phyllosilicates and other phases, is recognised by the typical habit of its pseudomorphs. It is common in the basic lavas and occurs even in andesites (Figs. 45B and 45D).

Samples with primary volcanic plagioclase can be found in most lava flows in the Älvdalen area except in the five most basic lavas (<51.5 wt% SiO₂) where plagioclase phenocrysts are uncommon or absent. Unaltered plagioclase phenocrysts generally show zoning of normal type. The

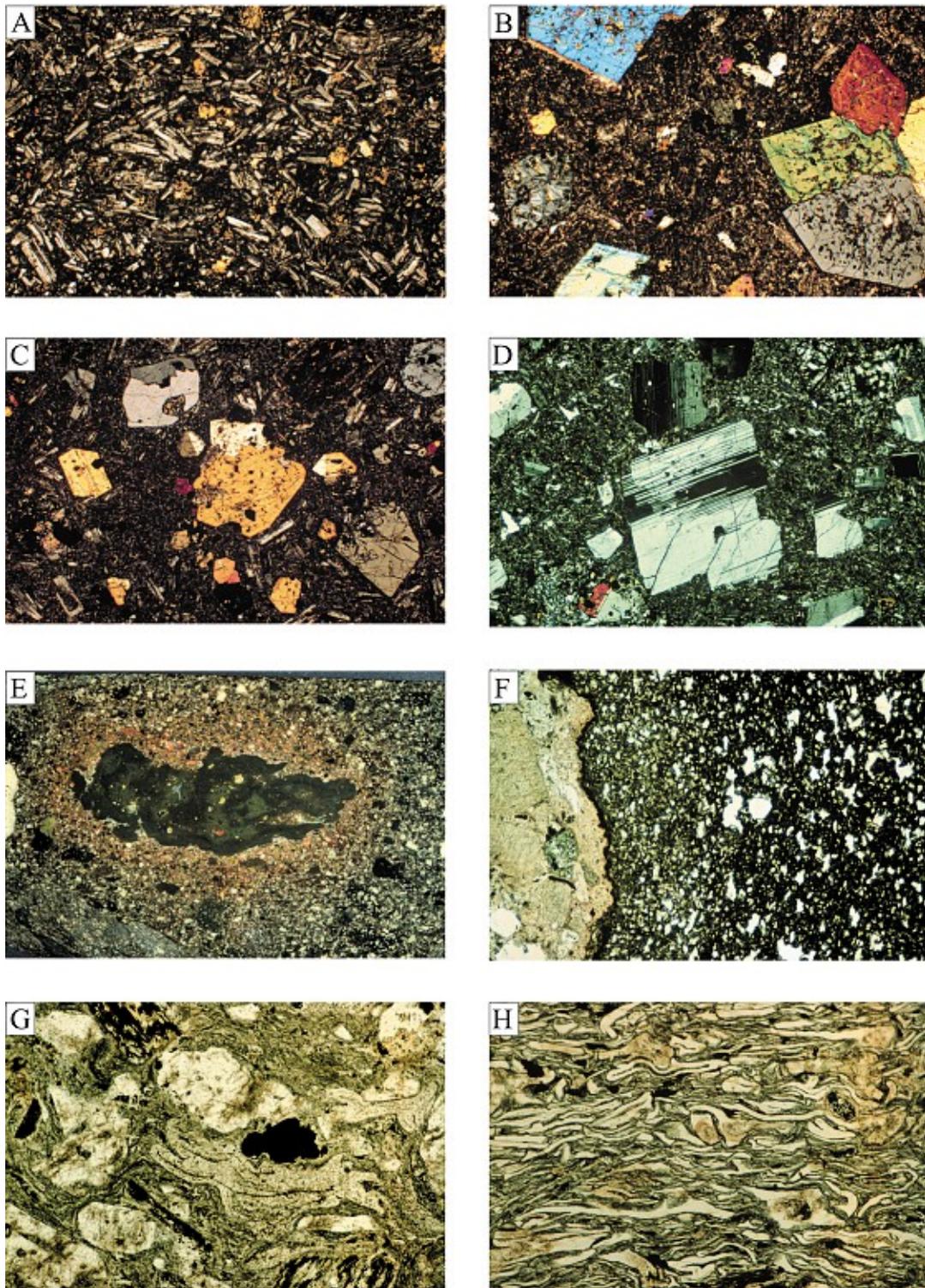


Fig. 45. Volcanic rocks from Älvdalen (the depicted areas in most thin sections are 2.5 x 4 mm; A–D crossed polars, F–H plane polarised light). (A) basalt with plagioclase and pyroxene crystals in devitrified glassy matrix, (B) basalt with phenocrysts of pyroxene, and altered olivine at left side, (C) basaltic andesite with phenocrysts of pyroxene and plagioclase; note embayed quartz grain at upper left side, (D) andesite with phenocrysts of plagioclase, pyroxene, and altered olivine at upper right side, (E) hand specimen of mixed ignimbrite (see text) with an 11 cm long mafic enclave surrounded by many smaller ones, (F) contact between mixed ignimbrite and mafic enclave rich in quartz-filled vesicles which increase in average size away from the quenched contact, (G) mixed ignimbrite with phenocrysts of embayed plagioclase, partly altered dark mica, and pyroxene in a welded vitroclastic matrix; depicted area = 0.6 x 1 mm, (H) well-preserved shards in rhyolitic ignimbrite.

volcanic plagioclase still remaining is labradorite in basalts and basaltic andesites, and andesine in andesites and more acid rocks. Presence of bytownite zones in the phenocrysts of a very well-preserved andesite suggests that the original plagioclase had a wider compositional range. A single or a few crystals of sieve-textured plagioclase, i.e., plagioclase with the inner portion or a thin outer zone displaying a spongy cellular texture, can be observed in almost half the samples of basaltic andesite and andesite. The borders of the crystals are euhedral, clear and without cavities. This texture can result from dissolution and/or melting due to reheating, and it is described in rocks with other textures compatible with magma mixing (Andersson & Eklund 1994, Hibbard 1995). Several of the samples with sieve-textured plagioclase also contain pyroxene phenocrysts with a partly embayed inner part.

The primary amphibole is pargasite in basic to intermediate lavas, and edenite in more SiO₂-rich rocks. It is greenish brown in thin section and displays a broad reaction rim toward the groundmass. Pseudomorphs after radially grown prismatic mineral(s) can be seen in some rims; none of the rim minerals have been determined. Occurrence of small pargasite phenocrysts in a basalt demonstrates that amphibole crystallised early. The secondary amphibole replacing pyroxene in altered parts is a pale green actinolite. Unaltered dark mica can only be found in the best preserved lavas. It is replaced by 'Fe oxide' in the ignimbrites. Chemically, the mica forms two populations according to the emplacement level of the rock containing it. The micas in volcanic rocks are more Mg-rich (phlogopites) than subvolcanic ones (biotites). Following current terminology in which end member names are preferred, all the micas are phlogopites.

A few andesites contain scattered and relatively large crystals of K-feldspar recognised megascopically by its pink colour (plagioclase in the same samples is grey to white). However, K-feldspar is ubiquitous in the groundmass of the lavas, even in rocks as basic as basalts. Backscatter electron images show that it tends to form continuous or discontinuous thin rims around plagioclase crystals, i.e., giving rise to antirapakivi mantling. The K-feldspar can also occur as small

laths. The Ab content of the K-feldspar is high in the most basic lavas, and there is a pronounced linear decrease with increasing SiO₂ content of the rock in the analysed samples. Small grains of embayed or rounded quartz (Fig. 45C) have been observed in thin sections from several flows of basaltic andesite and andesite. This suggests that corroded quartz is relatively common.

The extensive sheet of dacitic ignimbrite with mafic enclaves, here referred to as the mixed ignimbrite, is recognised in the field by the presence of dark grey or black enclaves in a medium to reddish grey porphyritic rock (Fig. 45E). The enclaves are commonly one or a few centimetres large and have a rounded or lobate-irregular outline. Some enclaves contain quartz-filled vesicles which are smaller or absent near the contact with the host rock (Fig. 45F), suggestive of quenching. Typically, the enclaves are fine-grained and carry only a small number of plagioclase and pyroxene phenocrysts. The host rock, in contrast, is rich in phenocrysts of plagioclase. Other phenocryst minerals are pyroxene, biotite and Fe oxide; quartz and amphibole occur in small amounts. The basal part of the mixed ignimbrite sheet outcrops at one locality. Samples collected just above the contact show fiamme with vesicles of the original pumice still visible. Unwelded shards are found near the bottom of the ignimbrite sheet and in one pisolite-bearing level higher up, which indicates that the sheet consists of more than one flow unit. Otherwise, discernable shards are welded as a rule (Fig. 45G). These features strongly suggest that intrusion of a basic magma, now represented by the enclaves, into a less hot dacitic magma triggered a series of eruptions that gave rise to the composite sheet of mixed ignimbrite.

The acid volcanic and subvolcanic rocks (porphyries) have colours ranging from pink, red and brown to grey and black. Lundqvist (in Ahl et al. 1997) divided them into two types with regard to their phenocryst composition: feldspar porphyries and quartz-feldspar porphyries. The former are quartz trachytes to rhyolites which often display vitroclastic texture (Fig. 45H), whereas the latter, uncommon in most of the Dala region, are SiO₂-rich rhyolites. According to Lundqvist (1968) the feldspar phenocrysts are perthitic K-

feldspar, structurally intermediate between orthoclase and microcline, and plagioclase. The plagioclase in phenocryst-rich porphyries may show normal zoning with cores of andesine or oligoclase (and rarely labradorite) surrounded by margins of oligoclase or albite, but the more abundant porphyry varieties poorer in phenocrysts generally contain albite (secondary). Perthitic K-feldspar forms thin mantles on the plagioclase and perthitic K-feldspar phenocrysts, and albite mantles the perthite. Mafic minerals (altered mica and pyroxene) are present in minor amounts. The quartz phenocrysts in quartz-feldspar porphyries are small, generally corroded and occur sparingly except in the western and northern parts of the region.

3.1.2. Geochemistry

Chemical analyses of 52 samples of Dala volcanites show a bimodal distribution, with a gap at 64–68 wt% SiO₂ between porphyrites (lavas and microgabbro) and porphyries. The gap is obscured by an ignimbrite rich in feldspar phenocrysts, a red porphyrite and samples from the mixed ignimbrite (Fig. 46; see Nyström, 1999, for sample locations and analytical data). There is a second gap at 54–58 wt% SiO₂ which means that basalts and basaltic andesites form a well-defined population of basic lavas. The five most basic lavas differ significantly; they contain abun-

dant and often large phenocrysts of ‘olivine’ and pyroxene; plagioclase is absent or scarce as phenocrysts. Thus, with regard to wt% SiO₂ the Dala volcanites can be divided into four groups: (a) basic basalts (<51.5), (b) less basic basalts and basaltic andesites (51.5–54.5), (c) andesites and dacites (59–64), and (d) porphyries (>68), excluding the few samples mentioned above.

A conspicuous chemical feature of the Dala volcanites is their high alkali content, as pointed out by Lundqvist (1968). A plot of K₂O vs. SiO₂ indicates that the Dala volcanites have a chemical affinity transitional between the high-K calc-alkaline and shoshonitic series (Fig. 47). Most of the basic lavas should be classified as absarokites and shoshonites. In view of the transitional chemical affinity of the suite of lavas they are here referred to as basalts, basaltic andesites and andesites for simplicity.

Shoshonitic rocks erupt under specific tectonic regimes, typically in extensional settings: active continental margins above the deeper part of the Benioff zone, and late in the evolution of island arcs with a thickened crust. For this reason it is important to establish the shoshonitic character of the basic Dala volcanites beyond doubt. It could be argued that their high K₂O content is a secondary feature since K is a mobile element during alteration and the rocks have been affected by burial metamorphism. However, the rims of K-feldspar around plagioclase crystals in the

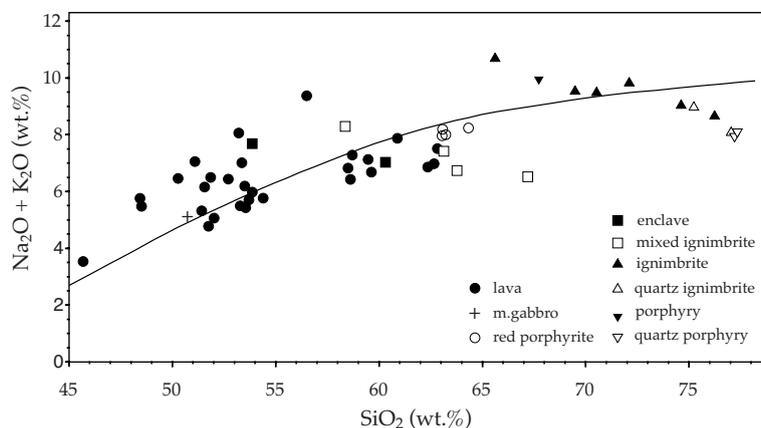


Fig. 46. Total alkali vs. silica variation diagram (TAS) for Dala volcanites and two associated subvolcanic intrusions, a microgabbro and a porphyry. Among the lavas, red porphyrites are indicated with a special symbol; mixed ignimbrite = ignimbrite with magma-mixing features including mafic enclaves. The boundary line separates the subalkaline series (below) and alkaline series (above). All oxides in diagrams and text are recalculated anhydrous. The data for the Dala rocks plotted in Figs. 46–53 are from Nyström (1999).

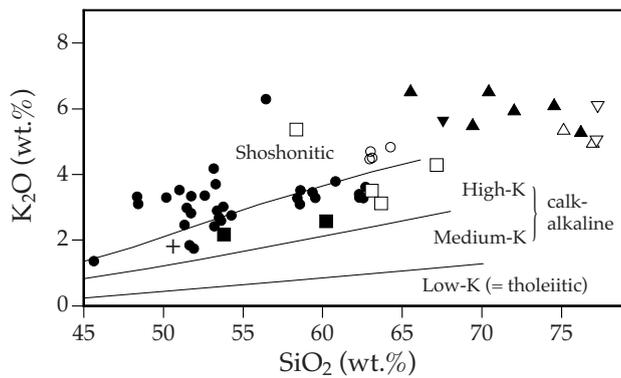


Fig. 47. K_2O vs. SiO_2 diagram for Dala volcanites and associated subvolcanic intrusions. Symbols as in Fig. 46.

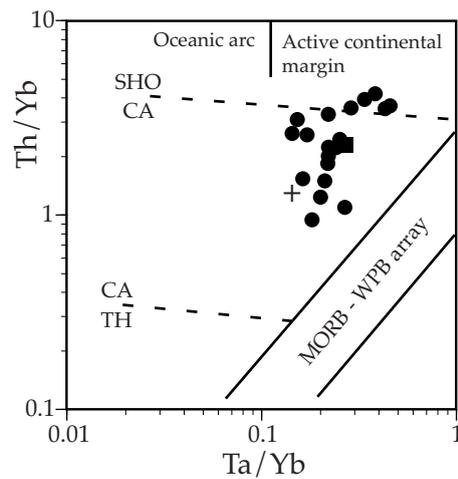


Fig. 48. Th/Yb vs. Ta/Yb diagram after Pearce (1982) for basic lavas belonging to the Dala volcanites, an associated microgabbro (cross) and a mafic enclave from a mixed ignimbrite (filled square). WPB = within-plate basalt, SHO = shoshonitic, CA = calc alkaline, TH = tholeiitic.

lavas and the composition of the K-feldspar indicate that the groundmass-forming melt became enriched in K as crystallisation proceeded. Moreover, other diagrams based on major elements and immobile trace elements (e.g., Fig. 48) support a shoshonitic affinity.

Another conclusion that can be made from Figure 48 is that the basic rocks seem to have formed in an active continental margin, provided that present tectonic processes can be extrapolated back 1.7 Ga. Formation in a continental volcanic arc at a plate margin is also suggested by the Zr-Y-Ti contents of the basalts. The geochemistry of the Dala basalts is inconsistent with eruption in a continental rift: MORB-normalised multi-element variation diagrams for the analysed basalts have patterns that clearly contrast with the patterns of within-plate basalts (Figs. 49A–B). The most conspicuous difference is a trough defined by low Ta-Nb contents in the diagrams for the Dala basalts. In fact, pronounced troughs for Ta-Nb and Zr-Hf are characteristic of subduction-related volcanic arc lavas (Fig. 49C; Pearce 1983). Again, the Dala basalts show the closest similarity with shoshonitic basalts.

All the lavas including the mixed ignimbrite (Dala porphyrites) have similar, strongly fractionated REE patterns with concave-up MREE-HREE. With increasing SiO_2 content the MREE-HREE become successively more concave-up, and a very weak to small negative Eu anomaly appears among andesites and dacites (Figs. 50A–D). Basalts and basaltic andesites have a chon-

drite-normalised La/Yb ratio $(La/Yb)_c$ in the range 10–15 which is quite high compared with the ratio for calc-alkaline basic lavas from Cenozoic volcanic arcs along continental margins but lower than the $(La/Yb)_c$ ratio of shoshonites erupted in the inner arc at greater distance from the trench, for example in the Central Andes (Déruelle 1991, Kontak et al. 1986, Schreiber & Schwab 1991). The high ratio is due to enrichment in LREE in spite of relatively high HREE values. The HREE values of the basalts indicate absence of HREE-retaining garnet in their source. In addition, the lack of a negative Eu anomaly suggests that the source was plagioclase-free or that plagioclase had been consumed by melting. The concave-up MREE-HREE pattern is consistent with pyroxene and/or amphibole remaining in the source since the REE partition coefficients in these two minerals are highest for the MREE, slightly less high for the HREE and low for the LREE.

The ignimbrites and associated subvolcanic intrusions (porphyries) have REE patterns resembling those of the lavas, but with more concave-up MREE-HREE. Most of the rocks are of rhyolitic composition and have a distinct to strong negative Eu anomaly, suggesting that calcic plagioclase was retained in the source. The largest Eu anomaly is shown by the porphyries with quartz phenocrysts (Fig. 50E). However, intru-

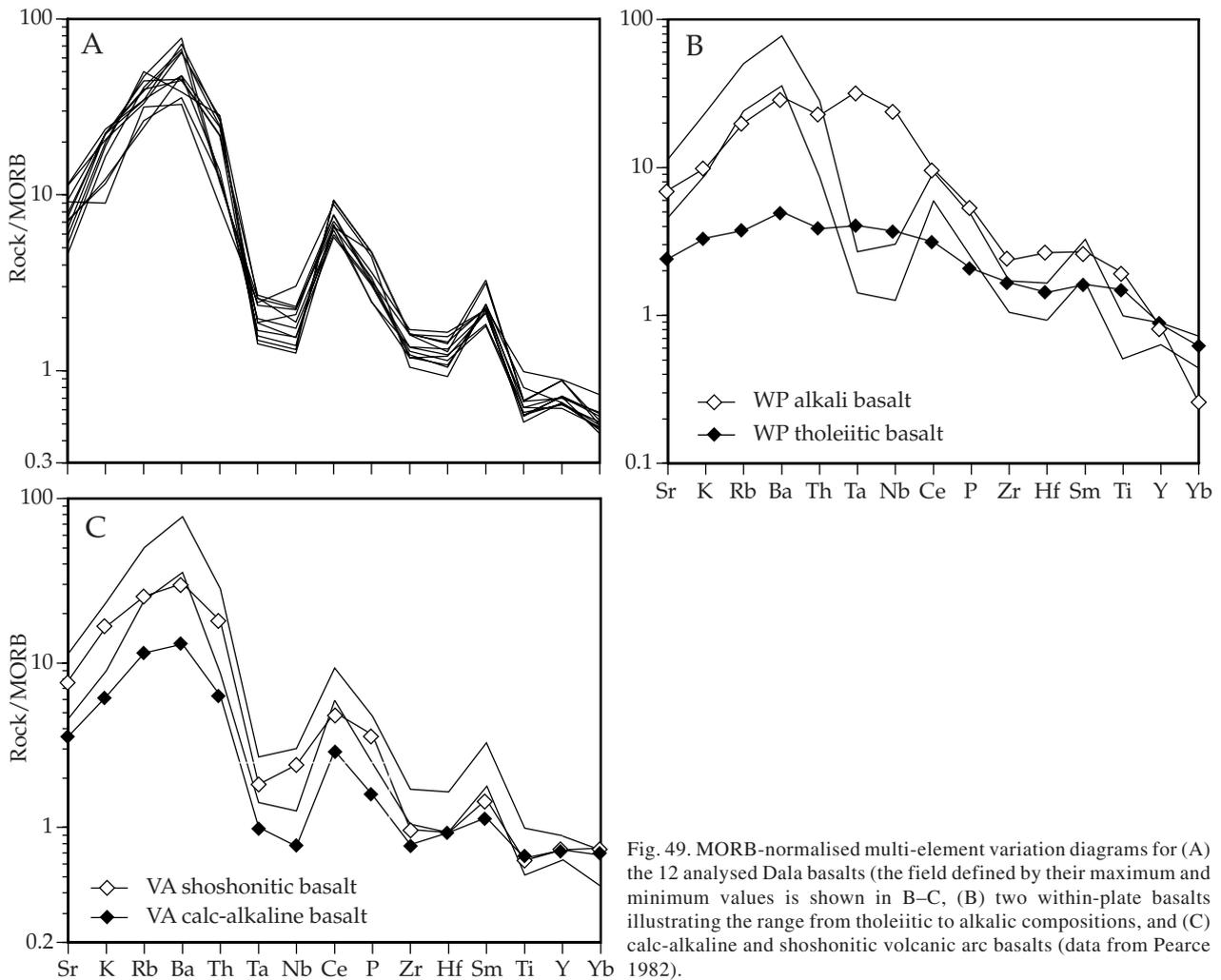


Fig. 49. MORB-normalised multi-element variation diagrams for (A) the 12 analysed Dala basalts (the field defined by their maximum and minimum values is shown in B–C), (B) two within-plate basalts illustrating the range from tholeiitic to alkalic compositions, and (C) calc-alkaline and shoshonitic volcanic arc basalts (data from Pearce 1982).

sive as well as extrusive porphyries of dacitic composition lack Eu anomaly, and have REE patterns almost identical to those of dacitic lavas (red porphyrites) and the mixed ignimbrite (Fig. 50F).

Acid extrusive and intrusive rocks in northern Dalarna have very similar REE patterns, which is a strong argument for the generally assumed comagmatic relationship between them (Lundqvist 1968). An example is the close REE resemblance between the Bredvad porphyry, the most voluminous ignimbrite of the region, and the Garberg granite that intruded volcanic rocks at a high crustal level and outcrops between Älvdalen and Mora (Fig. 44; Lundqvist & Persson 1999). A close relationship is supported by other trace elements, e.g., Rb, Y and Nb (Fig. 51). Chemically, the Garberg granite is classified as I type

with many A type features by Ahl et al. (1999). The extrusive and subvolcanic porphyries of this study are likewise transitional between I and A type. They appear to be closer to A type in the central part of the region (Lundqvist & Persson 1999).

The variation diagrams for certain elements are smooth curves (e.g., TiO_2 and FeO), but there is a break in the diagrams for other elements that is consistent with the existence of both basic and acid magmas (Fig. 52). The break is best seen for Ba, Zr, and Eu/Eu*; see also total alkali in Figure 46. The scatter in the variation diagrams is remarkably small. Samples responsible for the largest scatter are mainly from feldspar-rich lavas and the mixed ignimbrite. The lavas from Orsa finmark (three samples at 52–55 wt% SiO_2 in Fig. 52) differ from the Älvdalen lavas only by

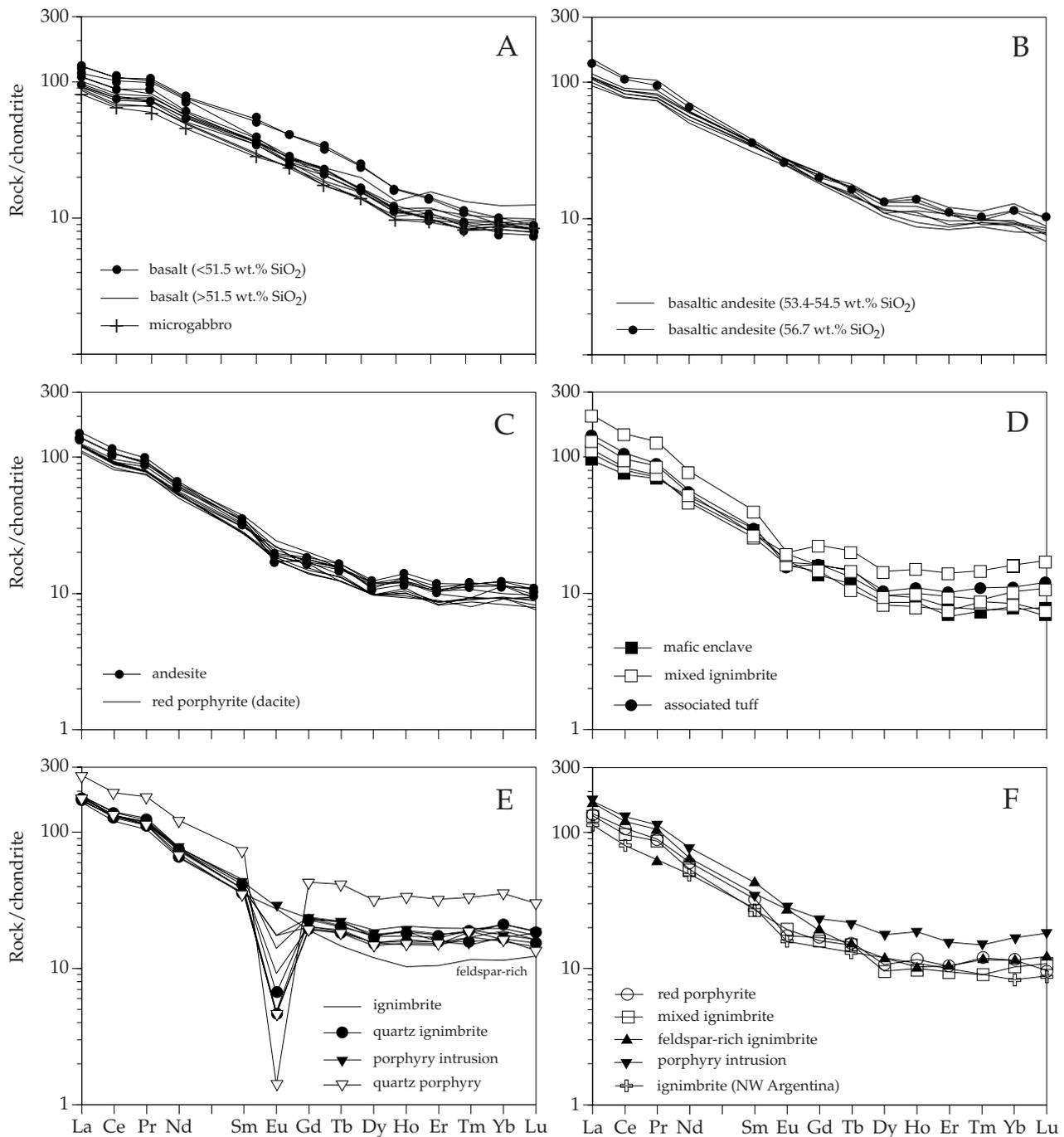


Fig. 50. Chondrite-normalised REE patterns for Dala volcanites and associated subvolcanic rocks: (A) basaltic rocks, (B) basaltic andesites, (C) andesites and dacites, (D) mixed ignimbrites, (E) acid rocks; the two samples without Eu anomaly have dacitic composition, all the others are rhyolitic, and (F) different dacitic rock types, including an average for eleven ignimbrites associated with shoshonites in the inner volcanic arc of the Central Andes (from Schreiber & Schwab 1991).

their high contents of Cr, Ni and Co; this is a real anomaly and not an artefact (Nyström 1999). Of possible relevance is that Ni and Co minerals occur in Orsa finmark, in rocks stratigraphically below and northeast of the Dala volcanites (the element nickel was discovered 1751 in ore from Los).

For rocks of basic to intermediate compositions the variation diagrams (Fig. 52) are consistent with very early crystallisation of olivine and Cr-bearing pyroxene (inferred from the diagrams for Ni, Mg and Cr, and the cores of Cr-diopside in the most basic sample). Absence of plagioclase and occurrence of Cr-diopside are consistent with

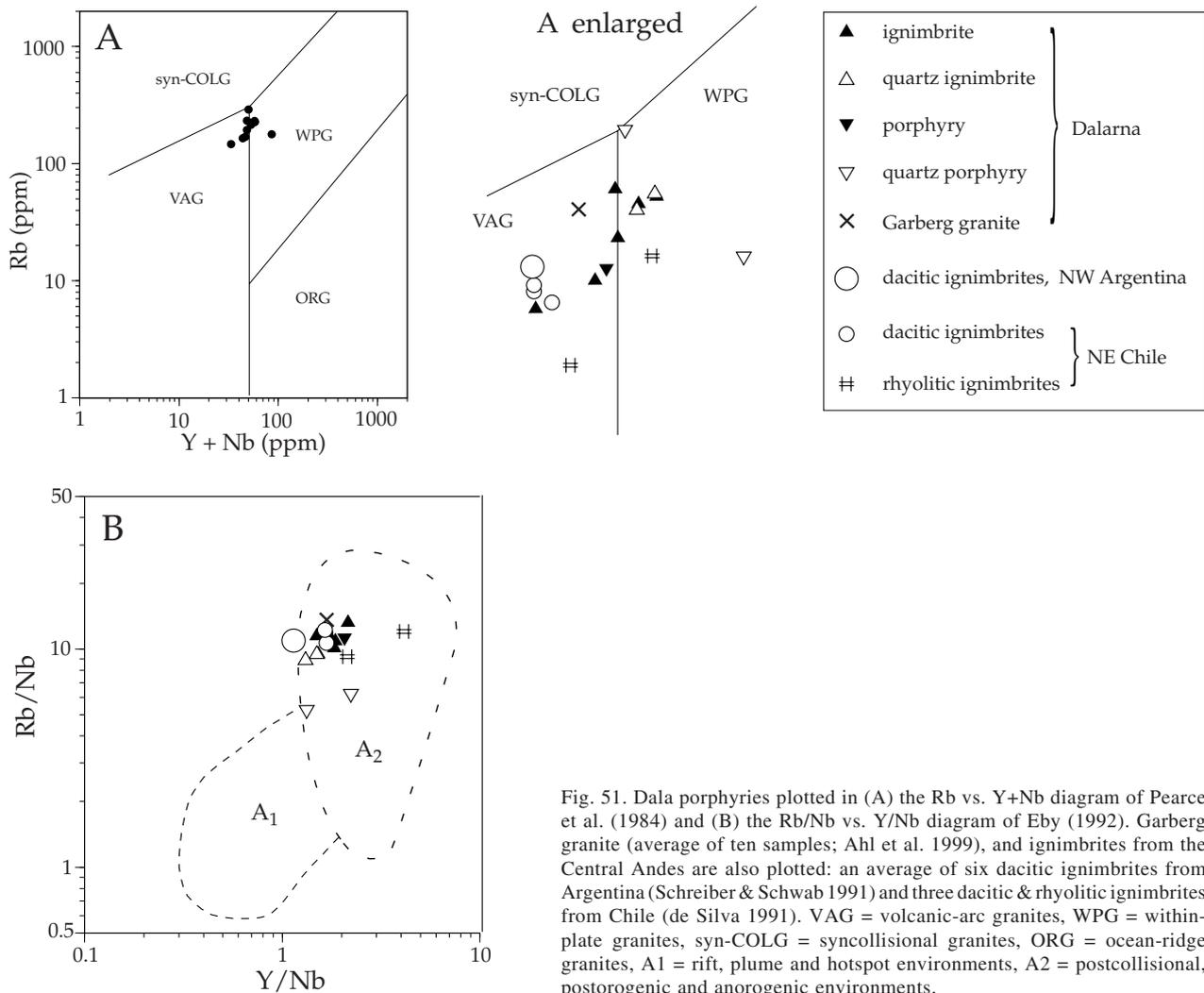


Fig. 51. Dala porphyries plotted in (A) the Rb vs. Y+Nb diagram of Pearce et al. (1984) and (B) the Rb/Nb vs. Y/Nb diagram of Eby (1992). Garberg granite (average of ten samples; Ahl et al. 1999), and ignimbrites from the Central Andes are also plotted: an average of six dacitic ignimbrites from Argentina (Schreiber & Schwab 1991) and three dacitic & rhyolitic ignimbrites from Chile (de Silva 1991). VAG = volcanic-arc granites, WPG = within-plate granites, syn-COLG = syncollisional granites, ORG = ocean-ridge granites, A₁ = rift, plume and hotspot environments, A₂ = postcollisional, postorogenic and anorogenic environments.

high pressure, suggesting crystallisation at deep crustal levels. Then followed crystallisation of more olivine, clinopyroxene lower in Cr ± amphibole (diagram for Mg), magnetite (Fe and Ti), and apatite (P), together. At c. 52 wt% SiO₂ in the magma, plagioclase started to crystallise, as is suggested in the Al₂O₃ diagram, in good agreement with the petrography of the lavas. However, the diagrams in the andesite-dacite range could also be explained by mixing of basic and acid magmas as suggested by Lundqvist (1968), with assimilation of acid crustal material in hot basic magmas as a contributing process.

The voluminous sheet of mixed ignimbrite with mafic enclaves demonstrates that mixing of magmas took place on a large scale in at least one case. Magma mixing and hybrid rocks was reported as a common feature in plutons emplaced at a mid-

crustal level in the TIB (Andersson 1989, 1997a), and in younger rapakivi granites (Andersson 1997a). A simple calculation shows that magma mixing is a realistic process for the origin of the andesites: for example, by mixing 63 % of the best preserved basalt with 37 % of corresponding ignimbrite to obtain the SiO₂ content of the best preserved andesite, a REE pattern very similar to the measured pattern is obtained. Magma mixing may lead to unusual mineral assemblages. Such phenocryst assemblages are indeed found: olivine and biotite (+ clinopyroxene-plagioclase) in one andesite, and K-feldspar phenocrysts in other andesites. The widespread occurrence of corroded quartz grains in basaltic andesites and andesites suggests crustal contamination.

Additional evidence for separate basic and acid magmas are the gap in SiO₂ content (Fig. 46), and

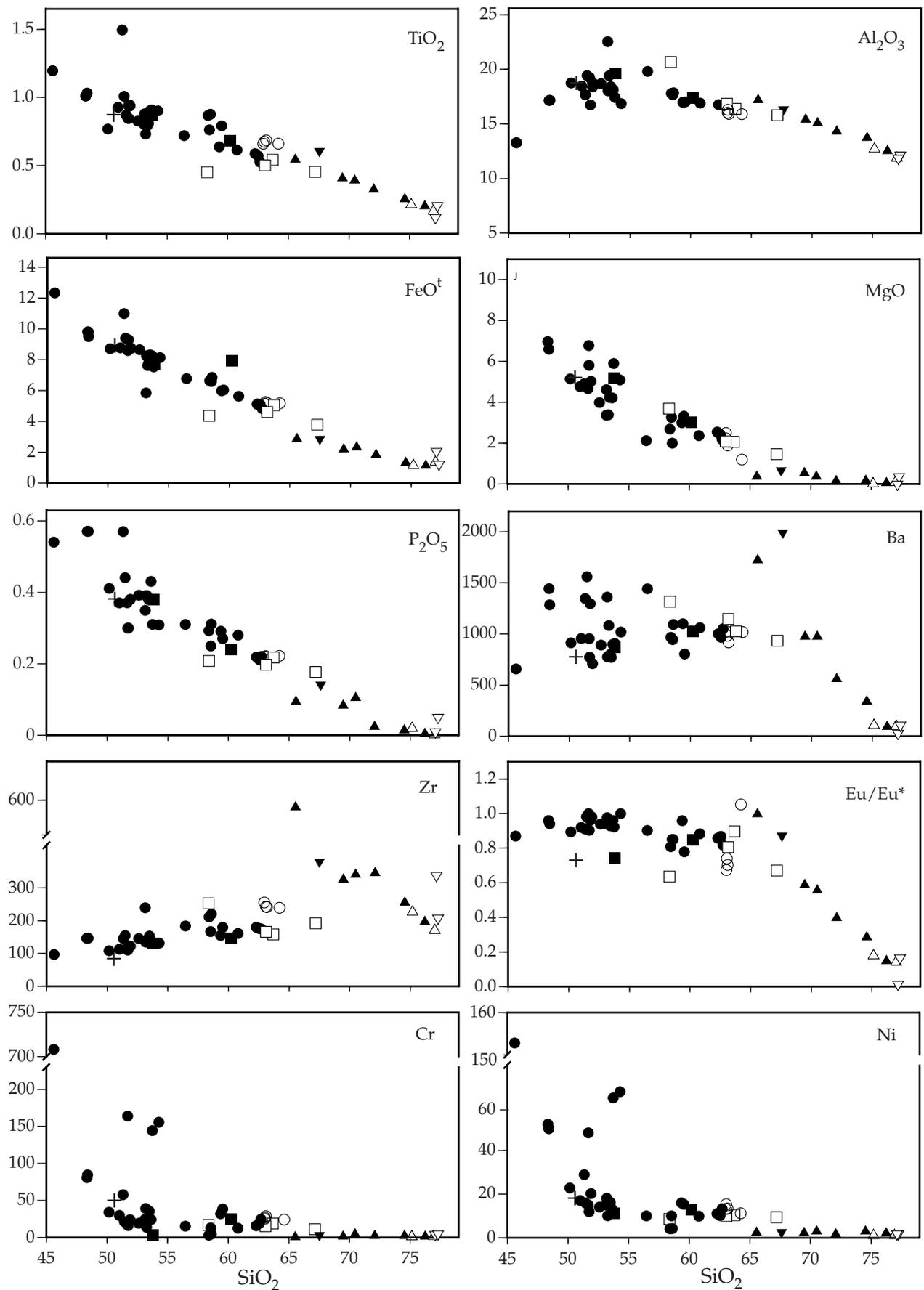


Fig. 52. Variation diagrams for Dala volcanites and associated subvolcanic intrusions (oxides in wt% and elements in ppm). Symbols as in Fig. 46.

Nd isotope data. There is only a small overlap between the ϵ_{Nd} values for basic lavas (range: from +3.0 to +1.2; mean = +1.7) and dacitic to rhyolitic ignimbrites (range: from +1.3 to +0.5; mean = +1.0; Nyström 1999). Seemingly unaltered transparent fragments of pyroxene separated from phenocrysts have very low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Nyström 1999). Their Nd-Sr isotope values plot to the left of the mantle array, probably due to disturbance of the Sr isotopic system during burial metamorphism. No Sr ratios can be given, but if it is assumed for the sake of argument that before alteration the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios plotted in the mantle array, then they would have been in the range 0.7036–0.7045. Dala granites have rather low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (around 0.705) according to Wilson (1980), and Wilson et al. (1986) reported initial ratios from 0.7033 ± 6 to 0.7044 ± 14 for three granitoids in the south-central part of the TIB which have many features in common with Dala granites (Wilson 1980).

3.1.3. The origin of the Dala volcanites

The ϵ_{Nd} values of the basic lavas, around +1.7, indicate a large contribution from the mantle. A mantle source is supported by trace elements like Zr, Hf, Y and HREE for which there is no detectable slab contribution to the source of arc volcanism. For example, the Zr values of the basalts and basaltic andesites define a differentiation trend located only slightly above the MORB array in the Zr/Yb vs. Nb/Yb diagram of Pearce and Peate (1995; Fig. 53). The basic Dala lavas plot to the right of N-MORB, i.e., on the enriched side of this composition, which argues against a depleted mantle source.

The high contents of elements like Sr, K, Rb, Ba, Th and LREE in the Dala basalts (Fig. 49A) indicate a sizeable contribution from subduction-related fluids and/or crustal material to the mantle-derived basic melts that formed the Dala basalts. Part of these elements could have come from the mantle if it was metasomatised or contained mica. This is supported by the discovery by Andersson (1997a) of ultrabasic mantle xenoliths with large amounts of unaltered phlogopite in plutonic rocks at three locations within the south-central TIB.

Fractional crystallisation of basic magmas could

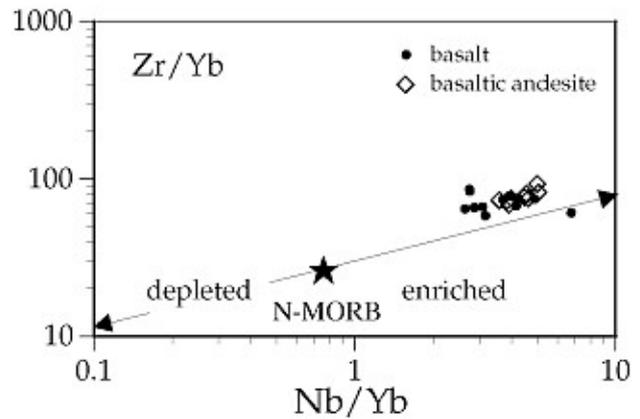


Fig. 53. Zr/Yb vs. Nb/Yb diagram after Pearce and Peate (1995) for basic lavas from Dalarna.

not have played a major role in the formation of the porphyries because the proportion of acid compositions among the Dala volcanites and associated intrusions is by far too high. They must have been generated in a different way, partial melting of crustal rocks being the most likely process. Lower crust of a small isotopic contrast to the Dala rocks, or upper crust dominated by Svecokarelian granitoids and metamorphosed supracrustal rocks like those that constitute the basement for the Dala volcanites in Orsa finmark and outcrop in western Bergslagen are possible sources. Most analysed granitoids and metavolcanic rocks from Bergslagen have ϵ_{Nd} values in the same range as the Dala porphyries: eight samples of Early (1.88 Ga) Svecokarelian granitoids have ϵ_{Nd} values from -1.2 to +2.5 with a mean of +1.3 (only one negative value), six samples of spilite to metarhyolite vary between +0.2 and +1.7 (mean +0.8), and six samples of Late (1.79–1.78 Ga) Svecokarelian granitoids have values from -0.1 to +7.7 (to +2.7 with a mean of +1.1 if one extreme sample is excluded; Patchett et al. 1987, Valbracht et al. 1994).

A comparison between the Dala porphyrites and lavas of the shoshonite series formed in an active continental margin at considerable distance from the trench, using examples from the Central Andes, reveals many mineralogical and chemical similarities. Quaternary shoshonitic lavas in northwestern Argentina described by Déruelle (1991) among others are composed of olivine, clinopyroxene (\pm orthopyroxene), phlo-

gopite and brown pargasite to edenite in a groundmass of plagioclase, sanidine, clinopyroxene and glass. The clinopyroxene is diopside in basaltic lavas and augite in the other lavas; many pyroxenes are Cr-bearing with values up to that recorded for the diopside cores in the most basic Dala sample. Sieve-textured plagioclase and corroded quartz grains are ubiquitous in these and other Andean shoshonites. Moreover, the Dala porphyries are chemically similar to Andean ignimbrites (Figs. 50F and 51) associated with shoshonites in the inner volcanic arc of NW Argentina and associated with high-K calc-alkaline lavas in the main arc of northern Chile, where the crustal thickness is 50–60 km and 70 km, respectively (Déruelle 1991, Schmitz et al. 1997).

The interpretation preferred here for the origin of the Dala volcanites is that the basic magmas were derived by small-scale partial melting of metasomatised upper mantle or phlogopite-bearing mantle peridotite and became modified by subduction-related fluids. Fractional crystallisation at deep crustal levels of mafic minerals, with addition of plagioclase at a later stage,

generated a suite of basalt and basaltic andesite melts, some of which reached the surface. The influx of hot basic magmas resulted in localised partial melting of the lower crust; melting of upper crust could also have taken place. The crustal melts gave rise to the porphyries and granites, and mixed with basic magmas to produce the Dala volcanites of intermediate composition. This explains the conspicuous compositional gap between basaltic andesites and andesites with regard to silica, the unusual mineral assemblages in some andesites, and the voluminous sheet of mixed ignimbrite. Crustal contamination, revealed by corroded quartz grains in many basaltic andesites and andesites, modified the composition, especially at upper-crustal levels, but was probably not the major chemical control. The geological setting, lithology, burial metamorphic pattern, and mineralogical and chemical features of the thick pile of Dala volcanites indicate that they were deposited during extension in a subsiding volcano-tectonic graben within a thick active continental margin.

3.2. The Dala granitoids

Martin Ahl, Ulf B. Andersson, Thomas Lundqvist & Krister Sundblad

3.2.1. Introduction

Northwest of the southern Svecofennian areas, in Dalarna and southern Härjedalen, a major unit of the TIB is exposed; the Dala Province, covering c. 7000 km² (Fig. 54). In the NW this province consists of extensive areas of voluminous basic-intermediate lavas, felsic ignimbrites, and intercalated conglomerates and sandstones (cf. Chapter 3.1), while granitoid plutonics dominate in the SE (Hjelmqvist 1966, Lundqvist 1968, Lundegårdh 1997). The Dala Province appears to form a large-scale graben structure down-faulted relative to the Småland-Värmland belt in the SW and the Rätan Batholith in the NE along two major NW-trending tectonic zones, the kinematics of which are poorly known. SW-side up movements of probable Sveconorwegian, c. 1.0 Ga age, have, however, been observed to dominate along the

SW zone (Magnor et al. 1996). The graben formation made the preservation of the extensive volumes of supracrustal rocks possible. There is also an apparent upward movement in stratigraphy from southeast to northwest, where the oldest and most basic granitoids (Järna type) occur in the SE closest to the Svecofennian margin, suggesting an oblique downfaulting where the NW part was relatively most down-faulted. Deeper levels of emplacement are also indicated from relations in the haplogranite system for the Järna granitoids as compared with the more near-surface Siljan and Garberg types further to the NW (Ahl et al. 1999).

The Dala Province extends into the Trysil area of Norway (Wolff et al. 1995, Heim et al. 1996). The Dala rocks are in the western parts overlain by a 1270 m thick package (Juhlin et al. 1991b) of Jotnian continental-type sandstones covering

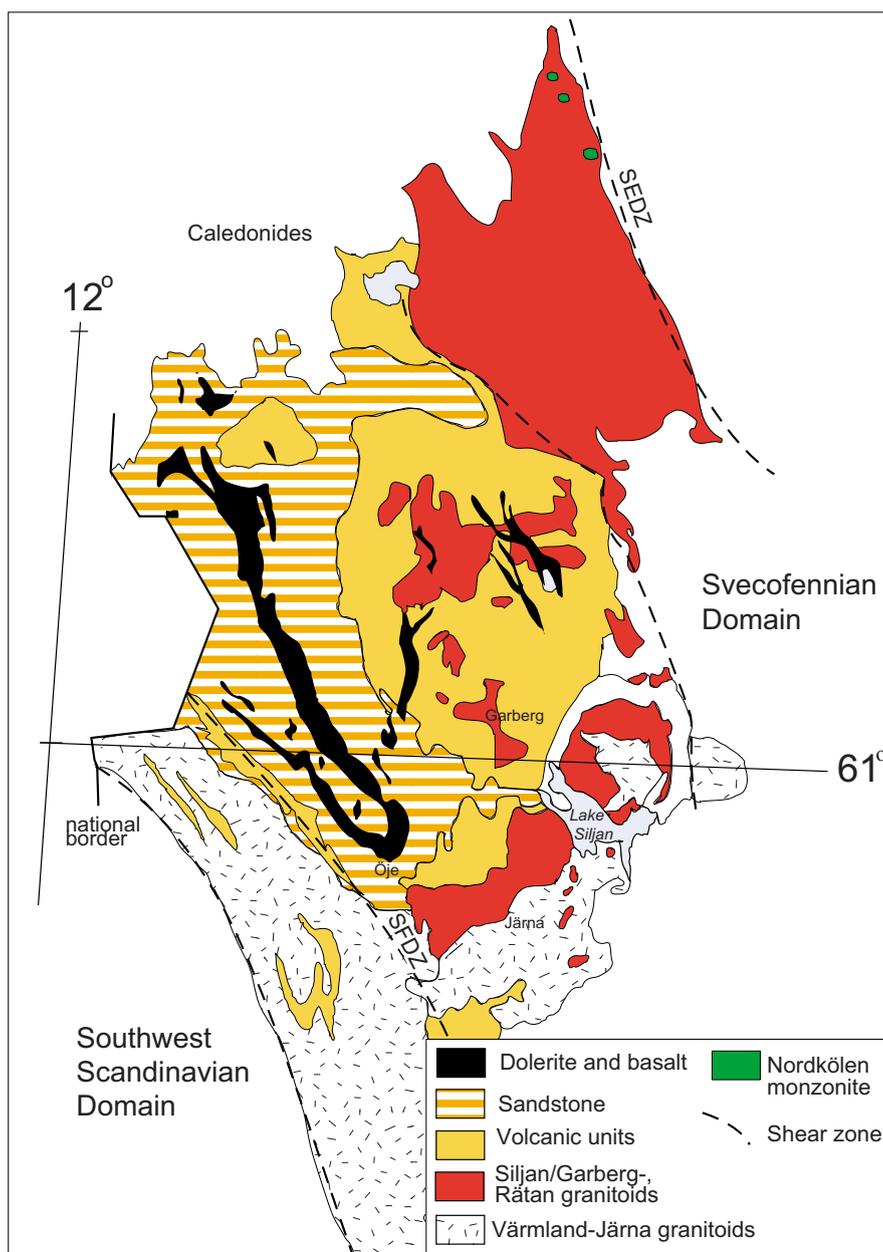


Fig. 54. Simplified geological map of the Dala region. Modified after Hjelmqvist (1966), Lundegårdh et al. (1984), Kresten et al. (1991). SEDZ = Storsjön-Edsbyn Deformation Zone, SFDZ = Sveconorwegian Frontal Deformation Zone.

extensive areas, with minor conglomerates and shales as well as an intercalation of basaltic rocks (Öje basalt) (Hjelmqvist 1966). The time of Jotnian deposition is constrained between an upper age of the underlying Dala rocks (c. 1.70 Ga; Lundqvist & Persson 1999) and the age of cross-cutting dykes and sills of the central Scandinavian dolerite group (CSDG; Gorbatshev et al. 1979, Patchett et al. 1994), referred to as Åsby-type dolerites, with Rb-Sr whole rock ages of 1.25–1.20 Ga (Patchett 1978). Recent U-Pb baddeleyite ages of CSDG in Dalarna, and elsewhere, has yielded

1.27–1.26 Ga, while the lower parts of the Dala sandstone are cut by c. 1.46 Ga old dykes (Söderlund et al. 2004). In the northwesternmost part of the province the rocks of the Dala Province are covered by Caledonian nappes (Fig. 3.11). The intrusion of a small cancrinite-nepheline syenite at 280 Ma (the Särna complex) in a felsic Dala volcanic inlier in the Jotnian sandstones marked the end of magmatic activity in the province (Hjelmqvist 1966, Bylund & Patchett 1977).

3.2.2. The Dala granitoids

The Dala granitoids are found as several generations, where the oldest occur as pebbles in conglomerates intercalated in the Dala volcanites, and the youngest have intruded stratigraphically high in the volcanic pile (Hjelmqvist 1966). Only burial metamorphism has affected the Dala rocks (Nyström 1982), and no anorthosites and very few pegmatites are known associated with the granites. The entire Dala Province is characterised by a positive aeromagnetic anomaly (Riddihough 1972, Dyrelius 1980). Circular and semi-circular magnetic patterns suggest caldera structures in the granites (Nyström 1982). The main types of Dala granitoids, the Järna, Siljan and Garberg granites, were recognised already 100 years ago (Sederholm 1897, Holmquist 1906), but their spatial relations were not clarified until the county map was published (Hjelmqvist 1966).

The Järna granitoids are greyish to greyish red relatively coarse (2–5 mm) rocks, rich in biotite and amphibole, containing also (in excess of quartz) abundant oligoclase, microcline, and euhedral titanite. They are locally enriched in small (a few centimeters in diameter) rounded magmatic enclaves, consisting of mainly plagioclase and amphibole. With decreasing quartz content they gradually become monzonitic or syenitic. In contrast to the other Dala granites, the Järna granitoids are associated with appreciable amounts of cogenetic mafic rocks (Hjelmqvist 1966, Ahl et al. 1999). U-Pb zircon age determinations have yielded ages close to 1.79 Ga (Åberg & Bollmark 1985, Persson & Ripa 1993, Lundqvist & Persson 1999).

The Siljan granites are typically red, leucocratic, medium to coarse (1–5 mm) rocks, containing alkali feldspar, quartz, plagioclase, small amounts of biotite, and muscovite in the most evolved parts. Accessory minerals include magnetite, titanite and fluorite. Age determinations lie in the range 1.70–1.68 Ga (Lee et al. 1988, Juhlin et al. 1991a, Ahl et al. 1999).

A feldspar porphyritic texture is well developed in the likewise leucocratic Garberg granites. Plagioclase-mantled K-feldspar phenocrysts (rapakivi texture) lying in a fine-grained (0.5

mm) groundmass are common. Syenitic and more even-grained varieties do occur. An age of 1710 Ma was reported by Lundqvist and Persson (1999).

Miarolitic cavities and the porphyritic textures with fine-grained matrix in Siljan and Garberg granites suggest that they were emplaced at shallow crustal to subvolcanic levels. Small, polymetallic (Sn-Pb-Zn-Au-Ag-Cu-Mo-Be-F) greisen mineralisations are present within the Siljan and Garberg granites.

3.2.3. Geochemical characteristics of the Dala granitoids

Compositional differences (Ahl et al. 1999) are most marked between the Järna granitoids and the two other types, where the former is consistently more basic showing a spread in SiO₂ between 55 and 71 %. This spread corresponds to a trend from monzodiorite, over monzonite and quartz monzonite into the granite field (Fig. 55a). The Siljan and Garberg granites are evolved granites *s.s.* with SiO₂ between 70 and 78 %.

The less silica-rich composition of the Järna granitoids also corresponds with a lower degree of alumina saturation (average A/CNK=0.97) compared with the other two types (average 1.02; Fig 55b; Ahl et al. 1999). The Siljan and Garberg granites tend to have high total alkali contents (average 8.33 %), but are still classified as subalkaline according to Irvine and Baragar (1971).

With respect to Sr-Ba-Rb variations the Järna granitoids show primitive, relatively Sr- and Ba-rich compositions, while Garberg, and in particular Siljan, granites show a spread towards evolved Rb-rich compositions (Ahl et al. 1999). Further, the Järna granitoids plot generally within I-type and volcanic-arc fields of trace element discrimination diagrams (Figs. 55c, d), while the Garberg granites have transitional characteristics, and the Siljan granites tend to be distinctly A- and within-plate type (Ahl et al. 1999). The Siljan granites also have pronouncedly high FeO*/MgO-ratios.

In addition to enrichment in Rb, Sn, Be, Y, Nb, Ce (and depletion in Ba and Sr) the Siljan and Garberg granites are typically high in fluorine, up to 5500 ppm (average 1980 ppm). Also U and Th tend to be clearly above values for average gran-

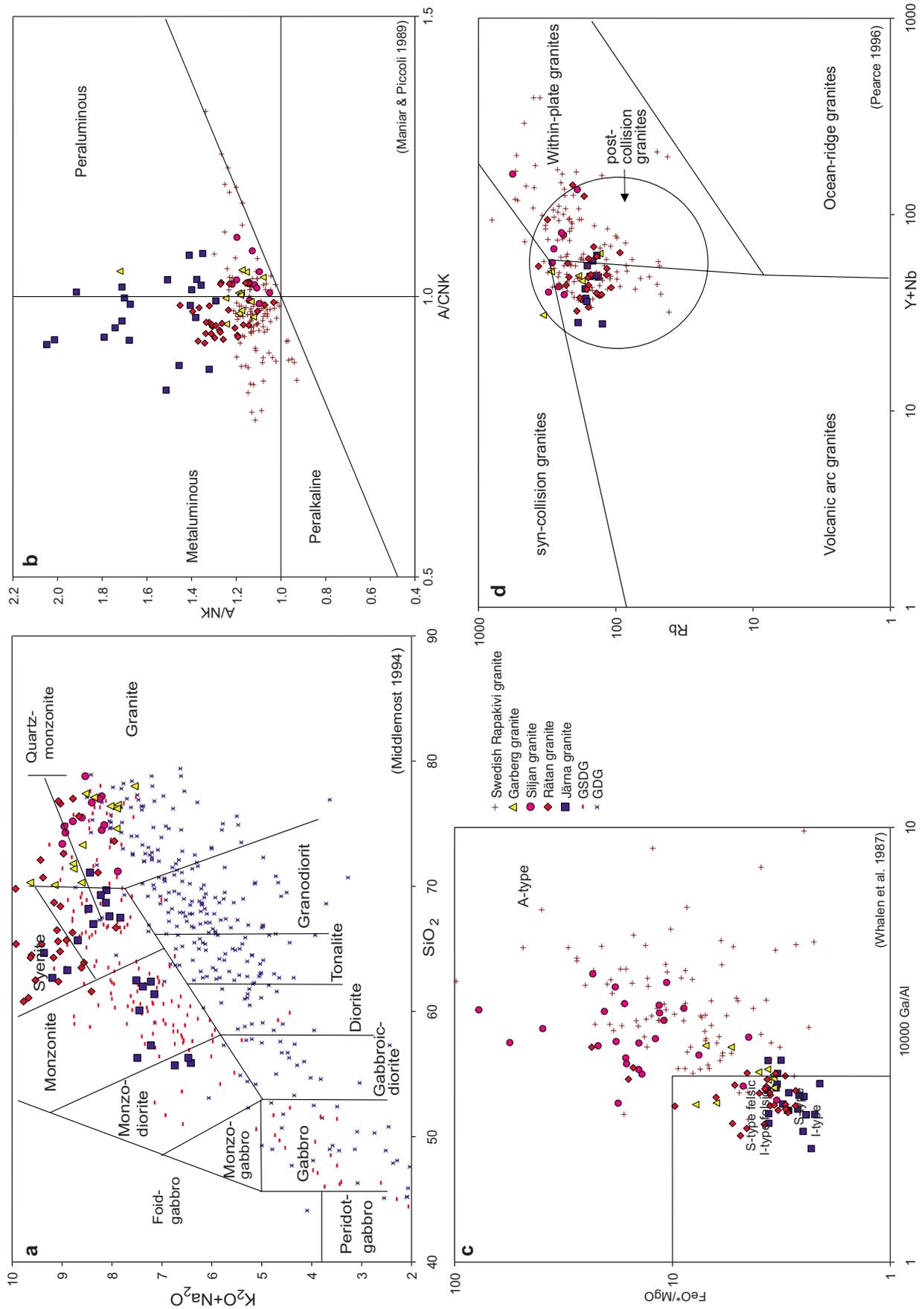


Fig. 55a–d. Geochemical plots of TIB and related rocks from the Dala and Rätan areas. GDG is granitoid-dioritoid-gabbroid rocks from the Bergslagen area. GSDG is granite-syenitoid-gabbroid rocks from the Bergslagen area. For a detailed explanation of the diagrams, see Fig. 5. In a) is basic-ultrabasic rocks also included. In b) A/CNK is molecular $[Al_2O_3]/(CaO+Na_2O+K_2O)$, and A/NK is molecular $[Al_2O_3]/(Na_2O+K_2O)$. Source of data: Ahl et al. (1999), Andersson (1997a), “The Bergslagen project, SGU” Stephens et al. (in prep.).

ite in the Siljan and Garberg granites (cf. Armands & Drake 1978). With respect to REE (Ahl et al. 1999, Lundqvist & Persson 1999), the patterns for all three types of Dala granites are LREE-enriched with relatively flat HREE patterns and La_N/Yb_N ratios from 2 to 12. The Järna granitoids, however, show only small negative Eu anomalies (Sm_N/Eu_N c. 2), while the two others are characterised by more pronounced anomalies (Sm_N/Eu_N around 4). Some highly evolved Siljan granites have extremely deep Eu anomalies (Sm_N/Eu_N up to 55), and elevated contents of both LREEs and HREEs.

The initial ϵ_{Nd} isotopic compositions of the Dala granites range from -1.0 to +1.1 (Patchett et al. 1987, Heim et al. 1996, Andersson & AlDahan, unpubl.), essentially the same as for the associated ignimbrites (± 0 to +1.7; Patchett et al. 1987, Nyström 1999, Lundqvist & Persson 1999; Fig. 6).

3.2.4. Source of granitoid magmas

Geochemical comparison clearly shows a more primitive character for the Järna suite than for the Siljan and Garberg granites. The widespread and common association with mafic rocks including structures indicating mingling and mixing, argues for a significant component of mafic magma that mixed with the originally presumably mainly crustal magmas of the Järna granitoids to account for, at least parts of, the low-silica compositional variation. Restitic source components may also play a significant role in the more mafic Järna types.

The Nd and Sr isotopic data (referred to above) indicate no pre-Svecofennian material in the source regions of the Dala granite/ignimbrite magmas. Although the Dala granitoids have a relatively juvenile character, the isotopic data do not require mantle sources. The Nd isotopic evolution of the Svecofennian (1.91–1.86 Ga) crust encompasses the initial compositions of the Dala rocks (Fig. 6) indicating that the pre-existing crust represents suitable source lithologies, although juvenile (1.8–1.7 Ga) mantle additions

may be significant, particularly in the Järna rocks (cf. elsewhere in TIB; Patchett et al. 1987, Andersson 1991, 1997a).

The Järna granitoids may represent relatively high degrees of melting of calc-alkaline early Svecofennian crust. The small negative Eu anomaly and high Ba and Sr contents show that almost all feldspar in the source was exhausted. The lower contents of Ba and Sr as well as the deeper Eu anomaly in the least evolved members of the Garberg and Siljan suites suggest appreciable amounts of feldspar remaining in the protolith, and thus lower degrees of melting if the source was the same as for the Järna granitoids. The strongly evolved types may represent a very small percentage of melting, or, more likely, volumes of magma that experienced extensive fractionation of particularly feldspars, but not of REE-containing phases (except Eu).

The Garberg and Siljan granites have overlapping geochemical characteristics with the c. 1.5 Ga rapakivi granites of central Sweden (Fig. 55; Andersson 1997c, 2001, Lundqvist & Persson 1999) suggesting similar conditions of formation (Ahl et al. 1999), although the rapakivi granites have old, pre-Svecofennian source components (cf. Andersson et al. 2002). However, the lack of features such as e.g. associated anorthosites and basic dyke swarms suggests that the Garberg and Siljan granites may represent “primitive anorogenic magmatism” (in the sense of Greenberg 1990), which developed during an extensional regime c. 100 Ma after accretion of juvenile crust (Ahl et al. 1999). It is even possible that the c. 100 Ma older Järna suite rocks partly acted as source rocks for the Siljan and Garberg magmas, as is indicated by some c. 1.8 Ga zircon cores in the Siljan granite (Ahl et al. 1999). Moreover, this would provide a model that more easily facilitates the increase in alkalinity in a stepwise fashion to the level of the 1.7 Ga Dala granites, and a shift from compressional (1.8 Ga Järna rocks) to extensional (1.7 Ga Garberg and Siljan rocks) setting (Ahl et al. 1999).

4. THE RÄTAN BATHOLITH AND THE NORDKÖLEN ROCKS

4.1. The Rätan Batholith

Martin Ahl, Roland Gorbatshev & Krister Sundblad

The Rätan Batholith, covering an area of c. 5000 km² (Figs. 3 and 54), is located mainly in the county of Jämtland in central Sweden. It was first described by Högbom (1894) and Svedmark (1895). Major recent publications are those by Lundegårdh et al. (map, 1984) and Gorbatshev (1997). In addition, a number of specific occurrence areas and aspects have also been studied (Blomberg 1895, von Eckermann 1936, Lundqvist 1968, Gorbatshev 1972, Welin & Lundqvist 1977, Delin 1996, Lundegårdh 1997, Mattsson & Elming 2001).

The batholith constitutes a rather homogeneous group of mostly undeformed intrusions, with only a few aplites and pegmatites, and no immediately associated volcanic units. It is mainly composed of fairly coarse-grained, megacryst-bearing granitoid rocks with subordinate amounts of fine- to finely medium-grained equigranular granites, which form dykes and minor, irregular bodies.

All available U-Pb age determinations of the Rätan granitoids (Wilson et al. 1985, Patchett et al. 1987, Delin & Aaro 1992, Ahl et al. in prep.) range from c. 1.70 to 1.68 Ga. While the earliest of these datings have wide error limits, a constraint is imposed by the c. 1.68 Ga age of the cross-cutting main body of the Nordkölen quartz monzodiorite (Gorbatshev & Schöberg, unpubl. data). That limitation, and the absence of distinct boundaries between the various types of coarse-grained Rätan granitoids, indicate that the entire batholith must be considered as one single igneous complex.

Several stocks of quartz monzodiorite and related mafic plutonics are found near Nordkölen in the northeasternmost part of the batholith. Contrary to the microcline-bearing Rätan granitoids, the Nordkölen rocks regularly contain orthoclase. In the present context, they are considered as a separate igneous group and are described in Chapter 4.2. The Rätan Batholith is also cut by the significantly younger (c. 1.2 Ga) dolerites of the Central Scandinavian Group (Gorbatshev et

al. 1979; also described as the “Åsby dolerites”), and is overlain by Phanerozoic cover rocks and Caledonide nappe piles in the north and northwest. A concealed continuation into the granitoids of the Olden tectonic window, c. 200 km farther to the north (cf. Gorbatshev 1985, 1997), is supported by an aeromagnetic anomaly (Fig. 56). In the south and southwest, the batholith is bordered by the volcanic rocks and granites of the Dala igneous complex. Many of these are nearly coeval with the Rätan granitoids (cf. Lundqvist & Persson 1996). Locally (e.g. in the Härjeåsjön area), the Rätan-Dala contact is determined by shear zones. Farther to the north (in the Linsell area), the contact with the Dala igneous complex may be intrusive, but the limited number of exposures hampers an evaluation of these relationships. The northeastern part of the Rätan Batholith is separated from the Ljusdal and Revsund granitoids by a boundary zone nearly coinciding with the NNW-trending Storsjön-Edsbyn Deformation Zone (SEDZ; Bergman & Sjöström 1994; Fig. 64).

The predominant rock type in the Rätan Batholith is a fairly coarse-grained, greyish, greyish-red or red hypersolvus granitoid. The greyish varieties are more common in the north than in the south but always only form minor, diffusely delimited individual occurrences. Normally, this rock type has a somewhat indistinct porphyritic texture, with megacrysts of microcline perthite with exsolved albite mostly 0.5 to 2 and occasionally up to 3 cm in length. The medium-grained matrix consists of plagioclase (oligoclase), quartz, biotite, and hornblende. The latter occasionally carries cores of augite. Magnetite and titanite are also present, as are minor accessories like apatite, ilmenite, fluorite, allanite, zircon, monazite, tourmaline, and pyrite. A much less abundant rock type is an almost equigranular, nearly fine-grained granite with subsolvus textural features and little or no hornblende. That granite commonly forms dykes in the coarser-grained rocks.

The SiO₂ content in the common, coarse-grained, porphyritic type of Rätan granitoids ranges between 61 and 73 wt%. The equigranular, fine-grained granite carries more silica (SiO₂ between 75.6 and 76.8 wt%).

The coarse-grained granitoids follow a syenitic to quartz-monzonitic to granitic magmatic trend in the TAS diagram (Fig. 55a). In the Debon-Le Fort PQ-diagram (Fig. 58), the variation is from the monzonite to the granite field. The molecular Al₂O₃/(Na₂O+K₂O+CaO)-ratio is slightly less than unity, indicating a metaluminous character (Fig. 55b). While the contents of K₂O range between c. 4.5 and slightly less than 6 %, the Na₂O/K₂O wt% ratios are commonly close to 1, in some rocks even with a slight predominance of Na₂O (Fig. 59). As a result, the overall alkali oxide contents are extremely high, approaching 10 % (Fig. 55a). Particularly in the northeastern part of the batholith there is substantial variation in the quartz content, which locally decreases to 5–10 %. In general, the relationship between quartz and feldspars is antithetic, the sum of alkalis decreasing somewhat as silica increases (Fig. 59). In regard to the alkali-lime index acc. to Peacock (1931), all the analyses of the coarsely porphyritic Rätan rocks plot in the alkali-calcic field. The chondrite-normalised REE patterns show a slightly enriched LREE trend, the (La/Yb)_N ratios ranging from 8.0 to 14.3. The Eu-

anomalies are weakly negative with (Sm/Eu)_N = 1.0–5.9, which is a normal granitic signature. Typically, the Rätan rocks are enriched in LIL elements such as Sr, Ba and Rb. HFS elements like Zr, Nb and Y, as well as other incompatible elements (Hf, Th, K and REE except for Eu) also show enrichment. The F contents range from 440 to 2630 ppm with an average of 1237 ppm. The FeO_t/(FeO_t+MgO) ratios vary between 0.73 and 0.87 in terms of wt%.

The equigranular, fine-grained granites plot in the granite field of the TAS diagram (Fig. 55a). Their molecular Al₂O₃/Na₂O+K₂O+CaO varies between 0.98 and 1.02 (Fig. 55b), and the contents of K are high. In the alkali-lime-index diagram (Fig. 60), some of the more siliceous, usually fine-grained dyke rocks are calc-alkaline. The chondrite-normalised REE patterns show rather flat trends, the (La/Yb)_N ratios being c. 2.2. Two analysed samples have strong Eu anomalies with (Sm/Eu)_N ratios of 25.5 and 10.6, respectively. The most evolved sample of felsic granite is depleted in LREE but enriched in HREE. The tectonic discrimination diagrams of Whalen et al. (1987) and Pearce (1996a) demonstrate trends transitional to A-type granitoids (Figs. 55c–d).

The initial ⁸⁷Sr/⁸⁶Sr ratios of the Rätan granitoids are low (c. 0.703), while the ε_{Nd} values vary between +0.2 and +2.0 (Fig. 6; Wilson et al. 1985, Patchett et al. 1987, Ahl et al. in prep.).

4.2. The Nordkölen quartz monzodiorite and associated rocks

Roland Gorbatshev

The Nordkölen quartz monzodiorite with accompanying granite and presumably associated intrusions of monzogabbroic rocks defines a c. 10 km wide belt of minor stocks extending for a distance of about 40 km from the Caledonide Front near Åsarna towards the south-east (Fig. 56). Most of this belt is situated within the Rätan Batholith, but the easternmost extreme appears to cross over into the adjoining Svecofennian country rocks (Gorbatshev 1997). The largest of the Nordkölen stocks comprises a quartz monzodiorite of c. 26 km² in the central part, surrounded by a 0.5 to 2.5 km wide, seemingly coherent but

not yet continuously mapped rim of fine-grained red granite(s). In addition, the Nordkölen belt contains six or seven minor intrusions. One well exposed intrusion and one mostly documented by boulders in till consist of monzodioritic to gabbroic rocks, while the rest are only indicated by near-circular positive magnetic anomalies. A four-fraction U-Pb zircon age of the Nordkölen quartz monzodiorite is 1684±13 Ma, MSWD=0.7 (Gorbatshev & Schöberg, unpubl. data).

Rather few data exist on the composition of the Nordkölen quartz-monzodioritic rocks. Despite quartz contents ranging from c. 5 % to slightly

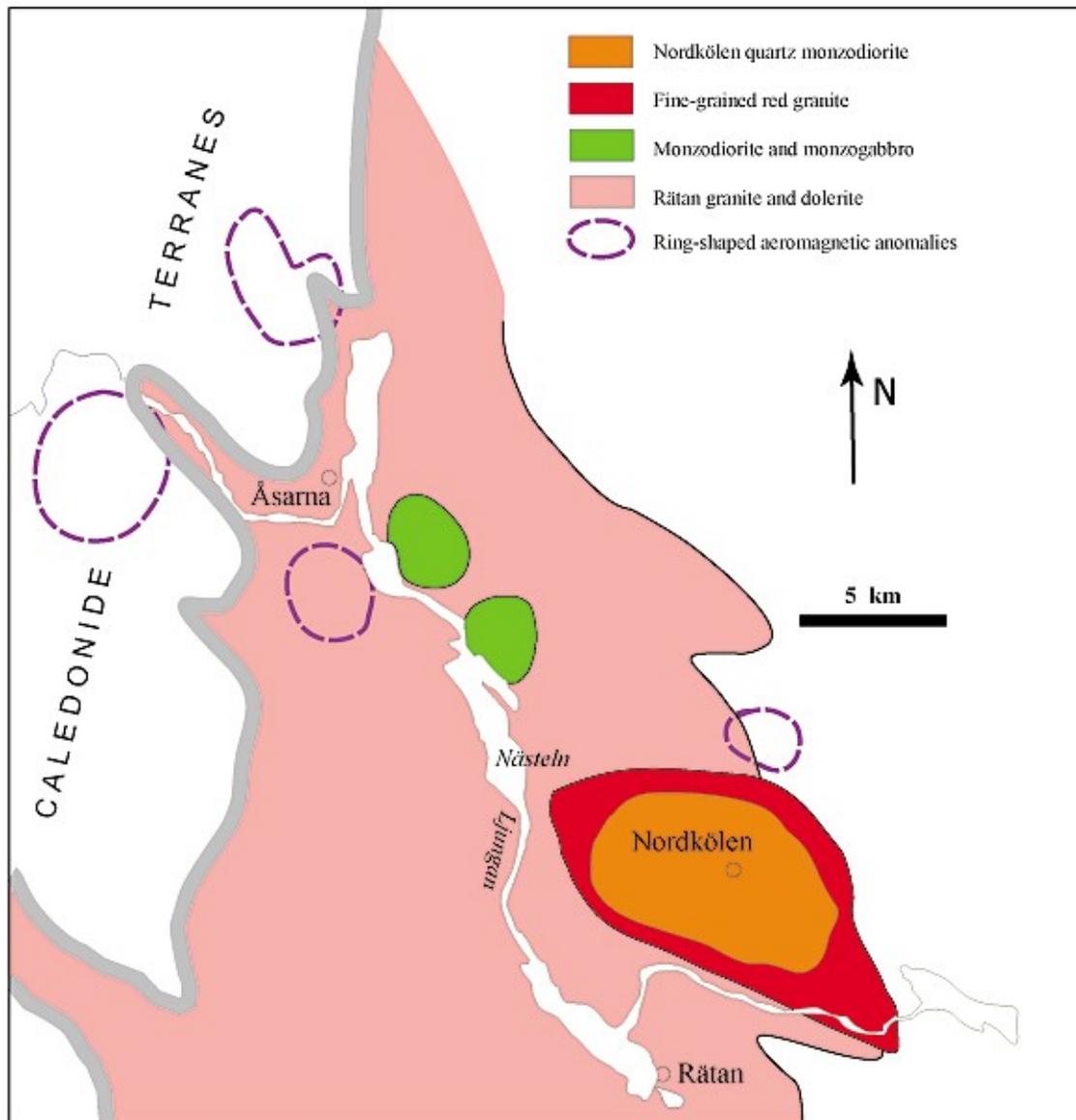


Fig. 56. Sketch-map of the Nordkölen quartz monzodiorite with presumably associated mafic intrusions and semi-circular aeromagnetic anomalies. Modified from Gorbatshev (1997).

less than 20 %, no sharp boundaries between different varieties of the quartz monzodiorite have been observed. The principal minerals are plagioclase, biotite, and pyroxenes; amphibole is relatively subordinate. Altogether, the content of dark minerals is around 25–30 %. Apart from plagioclase and quartz, the light minerals also comprise substantial amounts of orthoclase. The ratios of dark to light minerals vary substantially, likely as the result of cumulation. In terms of weight percentages, the approximate chemical composition of the most common variety of quartz monzodiorite is SiO_2 58–62, TiO_2 1 ± 0.3 , Al_2O_3 c.

15–17, total iron FeO 5.5 to 8.5, MgO <2 to 3.5, Na_2O 3–4 and K_2O c. 3–4.5.

The textures of the quartz monzodiorites are medium-grained, unfoliated, almost even-grained, with only occasional larger crystals of feldspar. The rock colours are brownish medium grey to greenish-greyish brown, the absence of red hues being due to the lack of microcline.

In the two partly exposed mafic massifs, the rocks are mostly dark brownish to blackish grey and finely medium-grained. There are abundant pyroxene and, particularly, biotite phenocrysts reaching c. 5 mm across. The matrices mainly

consist of irregularly subhedral dominant ortho- and subordinate clinopyroxene, some late amphibole, and substantial amounts of plagioclase

with An-values around 50. Apatite is very common. Small amounts of orthoclase occur regularly, while quartz may be present sporadically.

5. THE REVSUND GRANITE AND RELATED ROCKS IN JÄMTLAND

5.1. Precambrian crustal provinces and their relationships with Revsund-type granitoids

Roland Gorbatshev

In Jämtland, a tectonic belt called the Storsjön-Baltic Sea Zone in Fig. 57 marks a major crustal province boundary. Generally, that boundary has the same trend as the Hassela Shear Zone (Högdahl & Sjöström 2000, 2001), while its course in the northwest coincides with the Storsjön-Edsbyn Deformation Zone (SEDZ, cf. Chapter 6). Within the Jämtland part of the Storsjön-Baltic Sea Zone and farther to the southwest, the Svecofennian supracrustal rocks are largely metavolcanics belonging to the South Svecofennian Province (the “Bergslagen Province”), where the ages of the crust are between c. 1.9 and 1.87 Ga. To the northeast of the South Svecofennian Province is the Central Svecofennian Province, traditionally also known as the Bothnian Basin. Here, the dominant supracrustal rocks are metagreywackes associated with subordinate argillaceous schists. Both of these contain substantial proportions of Archaean detritus (Patchett et al. 1987, Claesson et al. 1993, Claesson & Lundqvist 1995). In the zone marked in Fig. 57 as the Transition Belt, central- and southern-province Svecofennian lithologies alternate.

The Storsjön-Baltic Sea Zone and the adjoining parts of the Transition Belt are virtually the only parts of the Precambrian region in Jämtland where a massive input of Palaeoproterozoic mafic magma has occurred. The resulting rocks comprise mafic metavolcanics intercalated with other supracrustals, layers of amphibolitised mafic hypabyssals, and plutonic mafic- and even ultramafic intrusions. All these are distinctly linked to the Svecofennian Province boundary and most are obviously of an early, Svecofennian date. Thus they have little to do with the mafic

magmatism related to the formation of the TIB. Within the Jämtland part of the Bothnian Basin, the metavolcanic intercalations in the metasedimentary rocks are always mafic, but their volume does not exceed some few p.c. of the total exposed rock mass.

Similarly to the different supracrustal lithologies in the central and southern Svecofennian provinces, also the TIB rocks exposed in the Jämtland region differ. Within and for some distance to the southwest of the Storsjön-Baltic Sea Zone, the prevalent TIB lithology is the Rätan granite (Chapter 4), a rather typical alkali-calcic TIB-2 rock with a monzonitic-quartz monzonitic-granitic compositional trend (Fig. 58) and ages around 1.69–1.70 Ga.

In the Bothnian Basin, in contrast, the totally dominant plutonic components are granitoids of the Revsund family with ages around 1.8 Ga, comparable to those of the TIB-1 granites farther south (Gorbatshev 1997). These rocks form interconnected batholiths occurring in a vast region with a total north-south extent of nearly 400 km (Fig. 3). In Jämtland, they occupy an area of more than 6000 km². The term Revsund granite was introduced by Högbom (1894) to describe usually massive to submassive granites in Jämtland which carry K-feldspar megacrysts in an even-grained matrix. Based on these characteristics, similar granitic rocks in the entire Bothnian Basin region were classified as belonging to the Revsund suite.

In Jämtland and its immediate neighbourhood, Revsund granites form two large massifs, the Fjällsjö massif in the north and the South Jämtland massif in the south (Fig. 57). At least in the

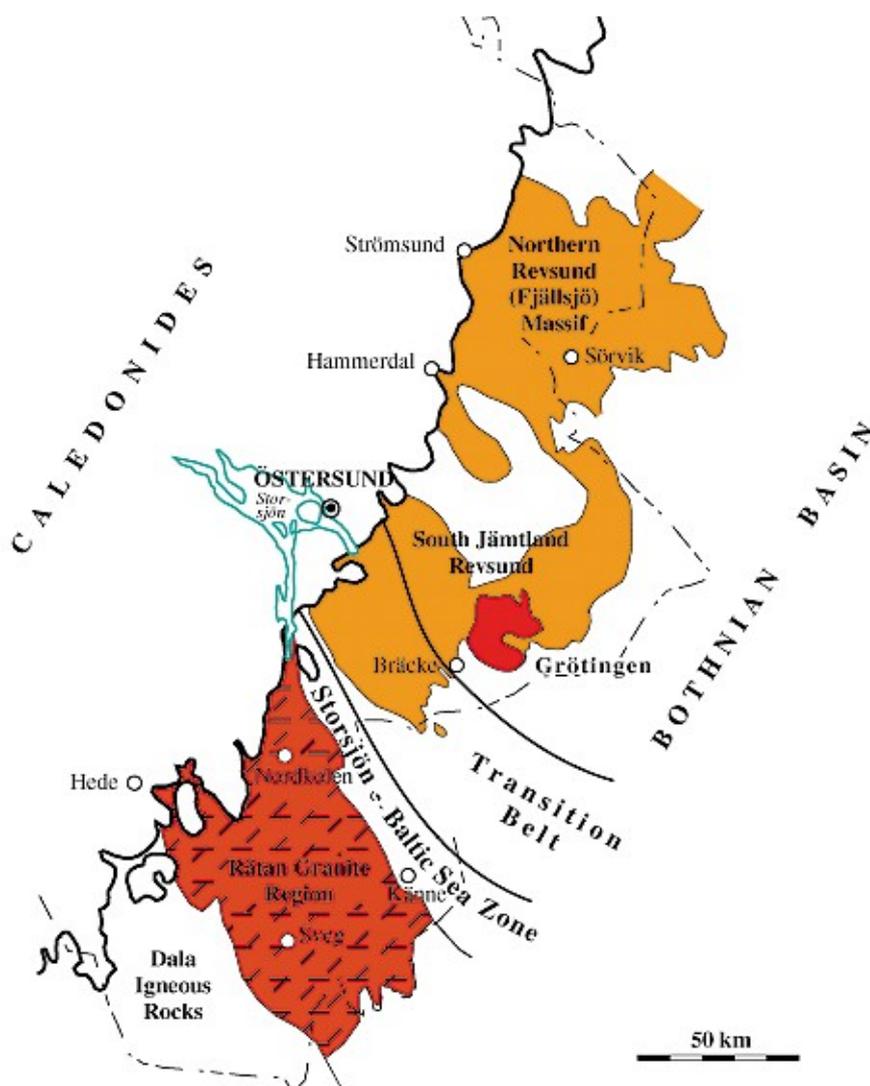


Fig. 57. TIB granitoid massifs in Jämtland and Härjedalen.

western third of the latter massif, however, it has recently been demonstrated that rocks previously classified as Revsund granites have ages of c. 1.85 Ga (Högdahl 2000a, Högdahl & Sjöström 2001). In the present context, it is important that while there exist no U-Pb age determinations from the eastern part of the South Jämtland massif (i.e. the part within the Bothnian Basin in Fig. 57), the Revsund rocks there distinctly cut extensive migmatite terrains and Härnö-type, largely equigranular medium-grained granites with presumable ages close to 1.82 Ga (cf. Lundqvist et al. 1990). At present, therefore, the best “informed guess” may still be that the South Jämtland massif of Revsund granite(s) mostly contains c. 1.8 Ga, not c. 1.85 Ga rocks.

A few dyke- and minor-body intrusions of fine-

to finely medium-grained light grey granite occur in the two Revsund massifs in Jämtland.

In the part of Jämtland southwest of the Storsjön-Baltic Sea Zone there are almost no TIB-type granites with ages comparable to those of the Revsund massifs. The few exceptions are the small intrusion of 1775 ± 7 Ma Känne granite (Delin & Aaro 1992), too small to show in Fig. 57 but in that Figure situated just to the north of the easternmost tip of the “Rätan Granite Region”, and a 1795 ± 7 Ma intrusion (Delin 1996) somewhat farther southeast. These rocks are megacryst-bearing, medium- to coarsely medium-grained, (greyish-) red, and in appearance somewhat recall the Rätan granite. However, the chemical compositions are drastically different with, among other things, higher K/Na-ratios than in the Rätan

(Gorbatshev 1997). Chemically, they thus rather resemble the grey Revsund granite in the eastern part of the South Jämtland massif. Regrettably there still exist no isotopic Nd data for the Känne granite and therefore it cannot yet be assessed whether that rock shares the commonly negative epsilon Nd_(T) values of the grey Revsund varieties.

Within the two Revsund massifs in Jämtland there occur large intrusions of somewhat later rocks, chemically resembling those in the TIB family. In the case of the Fjällsjö massif, these are the c. 1.77 Ga Sörvik granite (Chapter 5.2) and in the South Jämtland massif the c. 1.74–1.75 Ga Grötingen granite (previously referred to as a “Red Revsund”, see Chapter 5.3).

To make the present account nearly complete, a number of minor granite bodies within the Storsjön-Baltic Sea Zone to the southwest of Lake Näkten should also be mentioned. One is the fairly coarse-grained, equigranular, whitish-pinkish Skucku granite of unknown age and dif-

ferent in appearance from everything else seen in Jämtland, another, the rather leucocratic but indistinctly megacryst-bearing, reddish Bingsta granite some distance farther southeast. A third body, finally, is a granite closely west of Gillhov, which has been marked as an “older granite” by Gorbatshev (1997) but as a Revsund rock in the SGU Project-Jämtland maps (Sjöblom 1982). Highly suspect in regard to age and Revsund appurtenance are the megacryst-bearing granites on the isthmus between Lakes Näkten and Storsjön and their extensions east- and southeastwards, as well as numerous elongated, in the maps almost ribbon-like bodies of foliated, megacryst-bearing granite in other places in the area between Lakes Näkten and Revsundssjön (within the “Transition Belt”, Fig 57). By way of technical information for possible future quarrying, these received the Revsund markings in the solid-rocks county map of Jämtland (Lundegårdh et al. 1984).

5.2. The Revsund massifs

Roland Gorbatshev

In regard to the set-up of various rock types and chemical composition, the Fjällsjö (North Jämtland) and the South Jämtland Revsund massifs (the latter probably also including the two tongues of rock SE and ESE of Hammerdal, see Fig. 57) are somewhat different. The Fjällsjö massif is much more diversified. It features both microcline- and orthoclase-bearing grey metaluminous, amphibole-containing granites and quartz monzonites (Fig. 58), reddish granites, and the “Black Revsund” which is a coarse-grained, pyroxene-rich, mostly (quartz-) monzodioritic rock. The latter occupies substantial areas in the southwestern part of the Fjällsjö massif. All these rocks pass gradually into each other, but particularly the “Black Revsund” contains pods and fragments of mafic lithologies, and occasionally distinct indications of magma mixing and mingling. Apparently selectively concentrated to that monzodioritic to quartz monzodioritic rock there occur four major and

several minor, sharply delimited plutons of the somewhat younger, medium-grained, rather leucocratic Sörvik granite. This is an orthoclase-rich, pyroxene-, amphibole- and biotite-bearing rock with very high Fe/Mg ratios and therefore an occasional presence of fayalite. Geochemically, the Sörvik granite resembles, and in regard to major-element chemistry is virtually identical with the Grötingen granite to the east of Bräcke (Fig. 59, cf. Chapter 5.3). The latter, however, is a markedly red, coarse-grained microcline rock while the Sörvik granite, due to its orthoclase contents, is greenish-brownish grey and relatively dark in colour. It is distinctly quartz- and feldspar-porphyrific but lacks large megacrysts. In contrast to the Revsund rocks proper, both the Sörvik and the Grötingen granites feature pegmatites, but in the Sörvik case these are minor dykes and veins, whereas the Grötingen granite contains three major, commercially exploited internal pegmatite bodies. For the Sörvik granite,

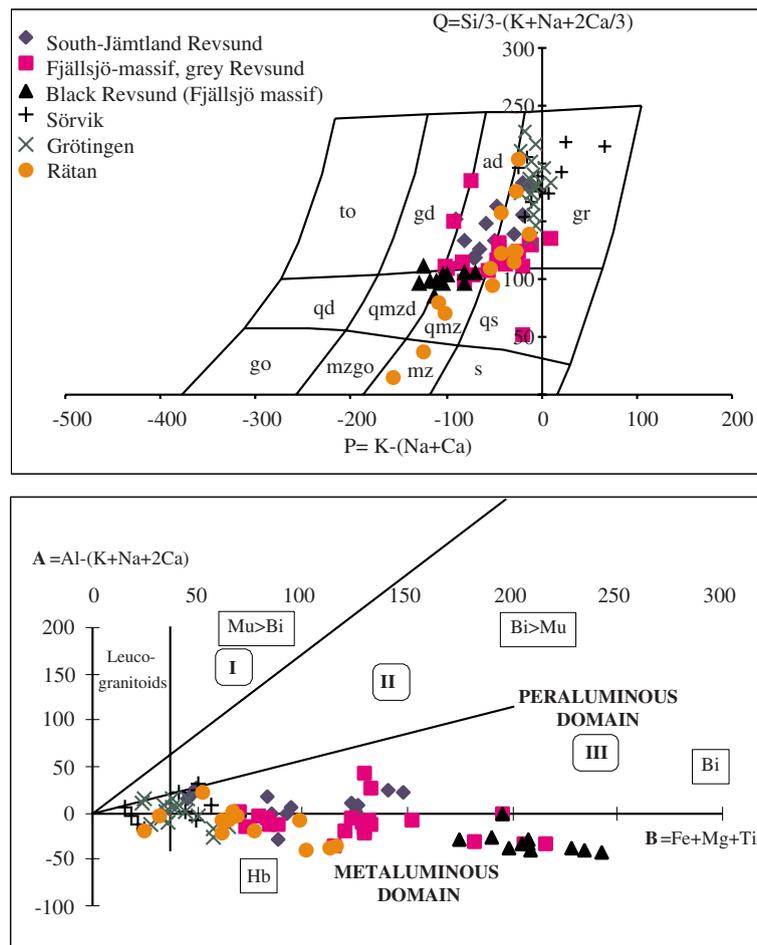


Fig. 58. Debon and Le Fort classification diagrams (1983) for Jämtland TIB rocks. Data from Gorbatshev (1987).

a U-Pb zircon age of 1772 ± 2 Ma, $MSWD=1.2$, has been obtained in a recent study (Gorbatshev & Schöberg, unpubl. data).

As different from the Fjällsjö massif, the South Jämtland massif is dominated entirely by rather light-coloured, coarse to very coarse-grained grey, more often biotite- than biotite plus amphibole-bearing rock varieties, adamellitic to granitic in Debon and Le Fort's (1983) PQ-diagram (Fig. 58), and rich in microcline megacrysts. These are commonly mantled by (unmixed-) plagioclase, and are euhedral to subhedral and often distinctly rectangular. They can reach lengths of 10 cm, but usually vary from 3 to 6 cm, more coarse-grained in the east than in the west, and commonly arranged in flow patterns. Shifts toward reddish-grey colour occur in places, while there are two large areas of more or less pink to red rock. One comprises a well-defined body of coarse-grained,

megacryst-rich granite in the southwest, in the terrain east of Gillhov, the other occurs in the area between Bräcke and Revsund. Within the latter, the most marked reddish-pink colours are found on northern Ammerön Island where the rock features very closely spaced but relatively small megacrysts.

In the Fjällsjö massif and in the eastern part of the South Jämtland massif, foliation is rare, and when present it is often of a flow character rather than caused by tectonic movements. In the area marked the Transition Belt (Fig. 57), however, tectonic foliation is very common, occurring in distinct zones as well as regionally. Previously, it was taken to solely reflect deformation along the various ductile and brittle tectonic zones trending (south-)south-eastwards from the southern tip of Lake Storsjön, but the recent 1.85-Ga ages obtained here by Högdahl (2000a) and Högdahl and Sjöström (2001) indicate otherwise.

In the South Jämtland massif there are very few intermediate to mafic rock components more or less coeval with the granite.

Absorption of country rock probably occurred already soon after the formation of the melts of the Revsund granite, but in the South Jämtland massif, in contrast to the Fjällsjö massif, local contamination by mostly metasedimentary rocks but also by TTG-type Svecofennian plutonics was massive. This is documented by partly resorbed wallrock xenoliths, by the peraluminous geochemistry of the South Jämtland massif and the presence of compositionally different schlieren of rock in some specifically studied localities. Also there are numerous garnet- and/or cordierite-bearing rock varieties, garnet dominating in greywacke-, cordierite in argillaceous-schist settings. In contrast, all samples of Revsund granitoid rocks from the Fjällsjö massif proper are metaluminous. The two apparent exceptions (Fig. 58) derive from the southernmost rock tongues SE and ESE of Hammerdal. These are extensions of the South-Jämtland massif rather than the Fjällsjö Revsund. As already mentioned, the Revsund granites commonly have negative initial epsilon Nd values, possibly lower in the South Jämtland than in the Fjällsjö massif, but there are too few measurements to really establish that distinction (Patchett et al. 1987, cf. Claesson & Lundqvist 1995, Andersson et al. 2002). As discussed above, the chemical differences between these two suites of rocks very probably at least in part depend on different degrees of country-rock interaction, but that still remains to be assessed quantitatively.

Harker diagrams (Fig. 59) show that both massifs of Revsund granite feature high to very high contents of alkali oxides, mostly 6 to 9 wt%, the Fjällsjö Revsund granite being somewhat richer in alkalis than the South Jämtland rock at similar contents of SiO₂. This difference is still more marked than immediately evident from the graphics, the reason being analyses of the two already mentioned peraluminous, relatively alkali-poor rocks from the area SE of Hammerdal. In Figs. 58 through 60, these have received Fjällsjö-massif markings. In terms of weight percentages, there is a distinct prevalence of K over Na.

The South Jämtland Revsund granites are gen-

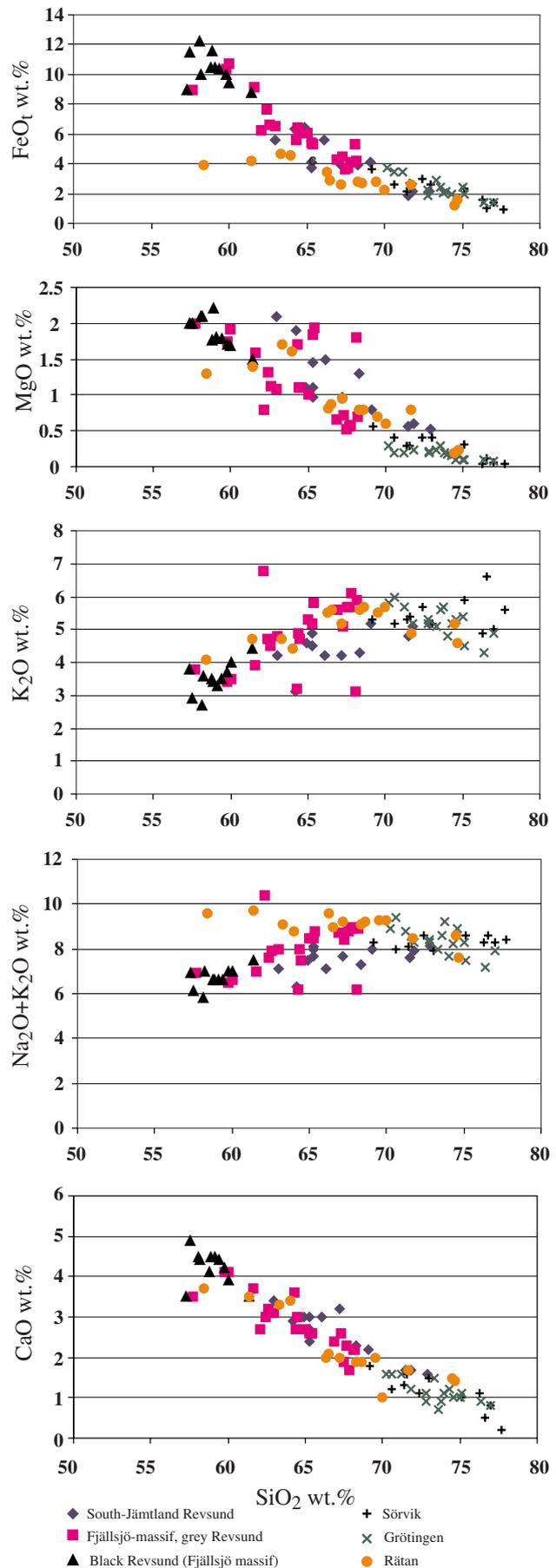


Fig. 59. Harker diagrams for Jämtland TIB rocks. Data from Gorbatshev (1987).

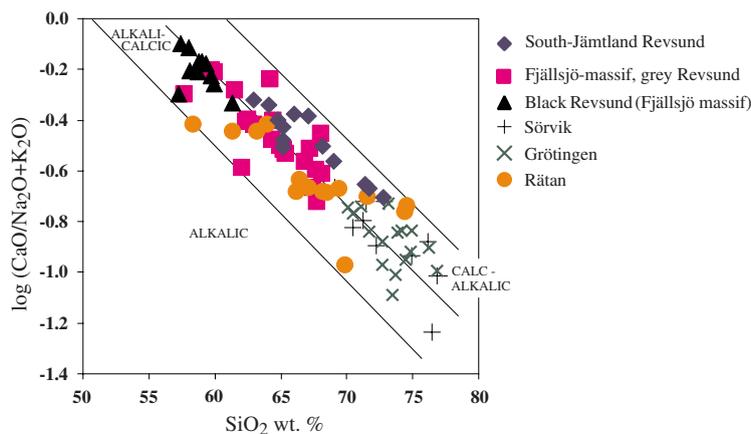


Fig. 60. Alkali-lime index for Jämtland TIB rocks. Data from Gorbatshev (1987).

erally substantially richer in Mg than the Fjällsjö granitoids, this being true in regard to absolute contents (Fig. 59) as well as the $Mg/(Mg+Fe)$ ratios. In terms of atomic proportions, these are between 0.2 and 0.3 throughout the Fjällsjö-massif Revsund granitoids, which applies even to the least siliceous “Black Revsund” monzodiorites. In the South Jämtland massif, in contrast, the named proportions mostly vary between 0.3 and 0.4, which should be compared with values between 0.45 and 0.50 in the Bothnian-Basin greywackes.

In the alkali-lime-index diagram (Fig. 60), almost all granites from the South Jämtland massif (most samples deriving from its eastern, Bothnian-Basin part) and the two samples from the Hammerdal rock tongues plot in the calc-alkalic

field. In contrast, all “Black Revsund” quartz-monzodiorites and monzodiorites, and a majority of granites and quartz-monzonites from the Fjällsjö massif are alkali-calcic. The rest plot close to the line between the alkali-calcic and calc-alkalic fields.

As has been emphasised by Andersson (1997a), the Revsund granites despite certain chemical similarities with rapakivis (cf. Persson 1978) lack the syenitic trend of these rocks. This is evidence of a different mode of origin. In consequence, the monzo-trend observed in the Fjällsjö massif has recently been interpreted as a result of plutonic mixing processes (Andersson 1997a) rather than magma differentiation as suggested by Persson (1978).

5.3. The Grötingen granite

Roland Gorbatshev, Ulf B. Andersson & Sten-Anders Smeds

The Grötingen granite forms two intrusions in Jämtland. One is a sizable massif to the east of Bräcke, c. 20 km across (Fig. 57), the other a much smaller body – not shown in the map-occupying Hebbbergsberget hill, slightly less than 25 km WSW of Bräcke. The latter has not been dated and its correlation with the Grötingen massif is therefore tentative. Because the Grötingen intrusion is largely situated within the South Jämtland massif of Revsund granite, its rock has

also been known as the “Red Revsund”. However, already Högbom (1894) indicated that it may form a distinct, later body. Recent work has demonstrated intrusive contacts all around the Grötingen pluton and shows that previously discussed gradational contacts towards a reddish-greyish rock close to the southern edge of the Grötingen massif (Gorbatshev 1997) represent within-massif Grötingen rock-type variation rather than transition into Revsund granite.

A recent U-Pb dating of the Grötingen granite (Gorbatshev & Schöberg unpubl. data) has yielded ages of c. 1.74–1.75 Ga, varying somewhat in accordance with the inclusion or exclusion of zircon fractions with the highest contents of uranium. The best estimate of crystallisation age is 1744 ± 14 Ma, with MSWD=2.1 at the 95 % confidence level. The absence of visible cores, the morphologies of the zircons, and age overlap between an abraded and the unabraded fractions contradict major admixture of inherited materials. Thus, the Grötingen massif is one of the rare apparently TIB-related rocks that crystallised between the formation periods of the TIB-1 and TIB-2 generations.

The Grötingen granite is a coarse-grained, in places coarsely medium-grained, reddish rock, rich in large microcline crystals. This gives it an appearance much different from that of the chemically similar Sörvik granite (cf. text section 5.2).

The microcline megacrysts locally reach lengths of c. 4 cm but normally are smaller, very numerous and therefore visually relatively subdued. Myrmekitic textures are not very marked, but commonly there are graphic intergrowths between quartz and microcline. The granite is partly leucocratic, the contents of dark minerals (mostly biotite and almost everywhere also amphibole) ranging from less than 5 to c. 12 %. Depending on this variation, the colour is either bright or dull red.

The SiO_2 content of the Grötingen granite varies between 70 and 77 weight % (Fig. 59; Andersson 1997a, Gorbatshev 1997, Smeds & Cerny unpubl. data) and thus the rock is a granite in the strict sense of that term. There is pronounced prevalence of Fe over Mg (Fig. 61c). The molecular $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})$ ratios follow the boundary between the per- and metaluminous fields or plot short distances inside

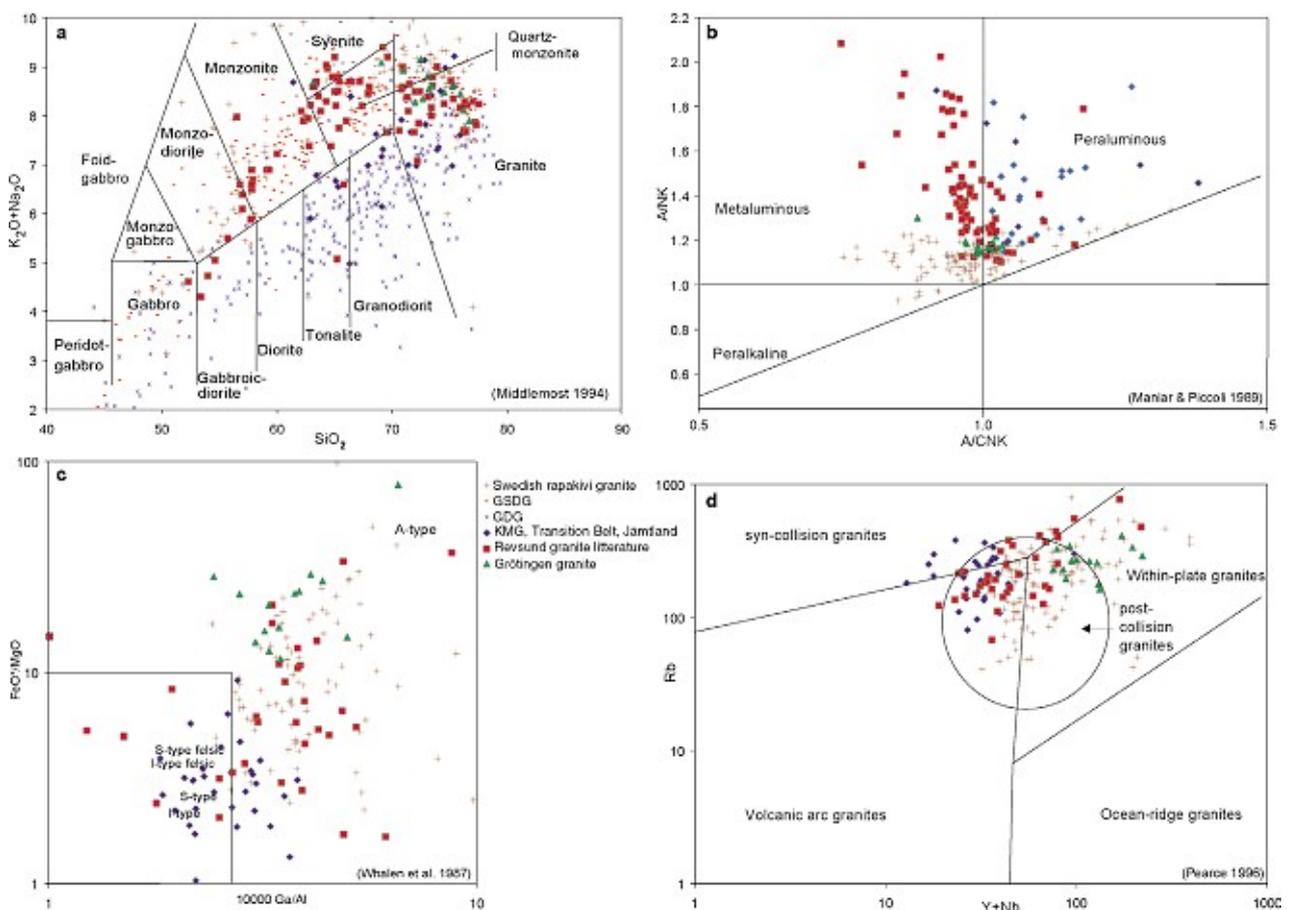


Fig. 61a–d. Geochemical plots of TIB and related rocks from central Sweden. GDG is granitoid-dioritoid-gabbroid rocks from the Bergslagen area, GSDG = Granite-syenitoid-gabbroid rocks from the Bergslagen area, KFM = K-feldspar megacryst-bearing granites. In a) also basic-ultrabasic rocks are included. In b) A/CNK is molecular $[\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})]$, and A/NK is molecular $[\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})]$. Source of data: Ahl et al. in prep, Andersson (1997a, c), “The Norrbotten project, SGU” Bergman et al. (2001), Smeds and Cerny (unpubl. data), “The Bergslagen project, SGU” Stephens et al. (in prep.). For a detailed explanation of the diagrams, see Fig. 5.

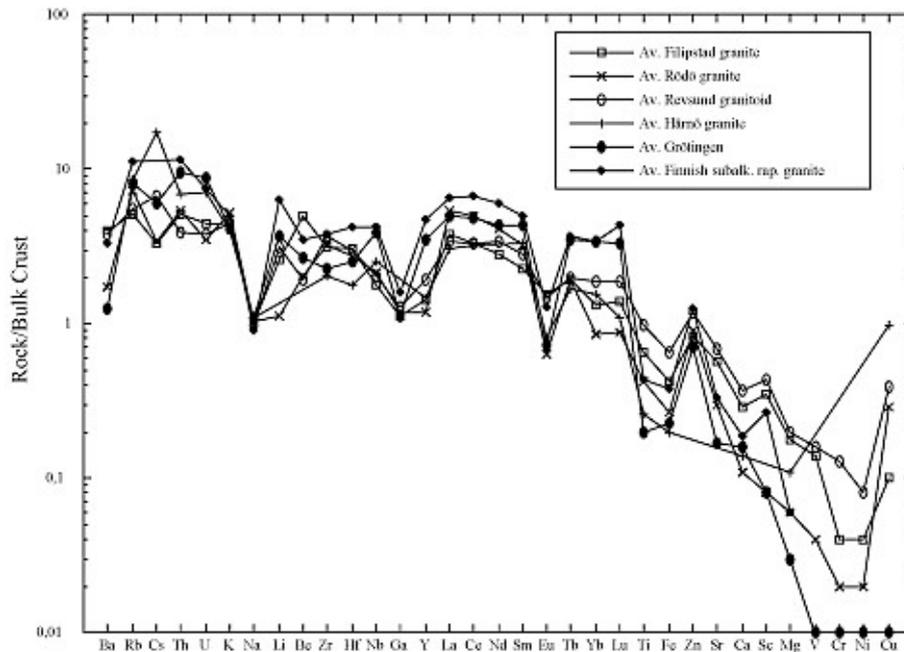


Fig. 62. Bulk crust-normalised (Taylor & MacLennan 1985) spider diagram of average compositions for some TIB and related rocks. Data as compiled in Andersson (1997a,d), except Grötingen granites (Smeds & Cerny unpubl. data). The Grötingen granite has many geochemical similarities with Finnish subalkaline rapakivi granites, and differ more from average Revsund granites or Rödö granites (example of Swedish rapakivi). Note also the close geochemical similarity between the Revsund and Filipstad type (coarse porphyritic Småland-Värmland) granitoids.

the latter (Fig. 61b). In terms of weight percentages, K_2O prevails over Na_2O , the sums of alkali oxides mostly varying between 8 and 9 except in the most siliceous rock varieties where that range is between 7 and 8 (Fig. 59). Fluorite is an important minor component and there are large grains of allanite, zircon and monazite, and less markedly tourmaline. Molybdenite occurs locally. Within internal NYF-type (niobium-yttrium-fluorine) pegmatites, which are fairly common, the fluorite crystals in some cases reach substantial sizes and along with the usual bluish-purple colours are pink, clear green, yellow, light blue or transparent. Topaz has been noted in external pegmatites along the southern margin of the Grötingen pluton. Three of the largest pegmatites have been quarried. Locally, rapakivi-type weathering has caused disintegration of the granite into large fields of reddish rubble.

Strong enrichment of Fe over Mg, high Ga/Al ratios, and elevated HFSE contents in the Grötingen granite correspond to A-type granite characteristics. They overlap those of Swedish rapakivi granitoids and partly also those of silicic Revsund granites from other localities (Fig. 61).

However, in comparison with most of the granites in central Sweden, the Grötingen granite is distinct in its strong enrichment in e.g. U, Th, Nb, Y, and the HREE (but not Zr and Hf), and its low contents of Ba, Sr, and the transition elements. In fact, it is geochemically most closely similar to the Finnish subalkaline rapakivi granites (Fig. 62).

Recent Nd-isotopic work on two coarse-grained Grötingen granites (samples Gr 1 and Gr 3b in Andersson 1997a) has yielded $\epsilon_{Nd(1.75 Ga)}$ values between +0.5 and +1.5 (U.B. Andersson, unpubl. data). This is somewhat more positive than generally obtained from the Revsund-suite granitoids, but is still encompassed by the time-integrated evolution trend of the early Svecofennian felsic metaigneous rocks (cf. Patchett et al. 1987, Wilson et al. 1985, Claesson & Lundqvist 1995, Andersson 1997a). Thus the Grötingen pluton may derive from juvenile early Svecofennian sources. Such an origin is in strong contrast to that of the chemically somewhat similar rapakivi granites of central Sweden. In the latter, the much lower initial $\epsilon_{Nd(T)}$ values require contribution of materials from Archaean sources (Andersson et al. 2002).

5.4 Granite ages and some problems of rock classification

Karin Högdahl & Martin Ahl

5.4.1. Geochronology

The range of emplacement ages of the Revsund granites is usually taken to be c. 1.80–1.77 Ga (Patchett et al. 1987, Skiöld 1988, Billström & Öhlander 1989, Claesson & Lundqvist 1995, Delin 1996, Delin & Aaro 2000). Despite the enormous volumes of these rocks, that estimate is only based on a limited number of analyses with a wide geographical scatter. In addition, a closer examination of the results reveals that most of them are not reliable.

Geochronological data of acceptable analytical quality have been provided solely by Claesson and Lundqvist (1995), Delin (1996), and Delin and Aaro (2000). Claesson and Lundqvist (1995) dated a granite in the eastern part of the Bothnian Basin in Sweden which yielded an age of 1798 ± 8 Ma. An isolated Revsund granite from a site c. 100 km south of Revsund village and a granite occurring in a marginal part of the type area as defined by Högbom (1894) yielded 1795 ± 7 and 1797 ± 4 Ma, respectively (Delin 1996, Delin & Aaro 2000).

The low reliability of the calculated ages from the remaining Revsund granites is due to one or several of the following factors: (1) poor linear fit resulting in high MSWD values (Patchett et al. 1987, Delin 1996), (2) highly discordant data points (Patchett et al. 1987, Skiöld 1988, Billström & Öhlander 1989), (3) high contents of common lead (Billström & Öhlander 1989), and (4) regressions calculated from zircon fractions collected from different rocks (Skiöld 1988).

One of the Revsund granites of Delin (1996) yielded an age of $1803^{+31/-25}$ Ma with a very high MSWD value of 73. That value reflects poor linear fit, and the result suggests a “composite” age.

In the concordia diagram of Skiöld (1988), the upper intercept at 1778 ± 16 was calculated from nine zircon fractions collected from two different rocks in Västerbotten, situated c. 30 km apart. A

regression through the zircon fractions from one of these two rocks yields a Model-2 (Ludwig 1999) age of 1778 ± 100 Ma. All the fractions are rather discordant, while the error of ± 100 Ma conforms with the large scatter of these points. The other rock yields a Model-2 age of 1763 ± 20 Ma. Here, the points are less discordant than in the first case, but the scatter is still substantial. However, the age could probably be accepted as a crystallisation age.

The 1787 ± 9 Ma result of Patchett et al. (1987) from the Fjällsjö massif does not derive from a state-of-the-art zircon dating. That study was only intended to provide estimates for ϵ_{Nd} calculations. Here, three of the four fractions are grouped closely, whereas one is 88 % discordant. Excluding that fraction from the regression, Claesson and Lundqvist (1995) obtained 1817 ± 30 Ma. Calculating a Model-2 age according to Ludwig (1999), however, yields 1816 ± 610 Ma, which can be regarded as geologically meaningless.

The aim of the U-Pb zircon study by Billström and Öhlander (1989) was to date a W-bearing greisen vein in the Joran granite in Västerbotten, i.e. not to obtain the magmatic age of a Revsund granite. The contents of common lead in the analysed zircons were high, with $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of c. 15, and the authors therefore justly concluded that this complicates the interpretation of their data. Due to the high degrees of uncertainty in the data presented by Patchett et al. (1987), Skiöld (1988), Delin (1996) and Billström and Öhlander (1989), these are not recommended for use when assessing the emplacement ages of the Revsund suite. The acceptably dated Revsund granites have all crystallisation ages of c. 1.80 Ga. This is in agreement with the ages of the principal intrusion phases of the TIB-1 rocks (cf. Chapters 1 and 2.1), and those of numerous granitoids in northern Sweden and northern Finland (Huhma 1986, Skiöld et al. 1988, Welin 1987).

5.4.2. K-feldspar megacryst-bearing granites (KFM granites) in the western part of the South Jämtland massif

The South Jämtland Revsund massif can be divided into an eastern and a western part (Gorbatshev 1997). The latter is situated mainly within the Transition Belt of Fig 57. The boundary between the two parts more or less coincides with the junction of two crustal-scale shear zone systems, the Storsjön-Edsbyn Deformation Zone (SEDZ) and the Hassela Shear Zone (HSZ), respectively (Bergman & Sjöström 1994, Högdahl & Sjöström, 2001, Högdahl et al. 2001b, cf. Chapter 6). In the Transition Belt, these tectonic zones dominate the regional structure and form a pattern of anastomosing shear zones and shear pods in a c. 50 km wide belt. They truncate the early orogenic rocks as well as younger, K-feldspar megacryst-bearing granites (KFM granites). Most commonly, the shear zones are a few metres up to c. 100 m wide, but there exists at least one km-wide zone (Lundqvist 1996, Högdahl & Sjöström 2001). Along that zone, elevated contents of uranium and thorium have been noted (Lundqvist & Antal 2000). Outside the shear zones, most of the KFM granites are generally undeformed but feature occasional magmatic flow structures.

In contrast to the eastern part of the South Jämtland massif, where major relics of older rocks are not very common, the western part hosts a number of very large xenoliths striking northwest-southeast. These often exhibit diffuse contacts with the Revsund granite (Gorbatshev 1997) and consist of early Svecofennian lithologies such as primitive greenstones (Sundblad 1994), calc-alkaline metavolcanic rocks (Mansfeld et al. 1998), metasedimentary rocks, and metagranitoids. All these rocks have been affected by deformation and metamorphism during the Svecokarelian orogeny. Commonly, they have a variably strong gneissic fabric, and migmatites are not unusual. However, early orogenic rocks with well preserved primary igneous textures and/or sedimentary structures occur occasionally.

The dominant rock type in central Jämtland east of the Caledonide front are KFM granites which

have mostly been described as Revsund granites (Lundegårdh et al. 1984, Gorbatshev 1997). Normally, these rocks have a distinct field appearance, they carry K-feldspar megacrysts and are texturally isotropic (Fig. 63). However, varieties lacking megacrysts also occur (Lundqvist & Antal 2000) and magmatic flow structures may be present (Lundqvist et al. 1990, Gorbatshev 1997). Locally, the rocks have even been affected by plastic shearing and attendant foliation. In addition, granitic rocks of various other ages and origins occasionally resemble Revsund granites. Some of the late Svecofennian S-type granites (e.g. the Härnö granites) thus sporadically carry K-feldspar megacrysts larger than normal for these rocks (Lundqvist et al. 1990). At the contacts towards the Revsund granites and some other younger granites, the early Svecofennian granitoids have sometimes been recrystallised. As a consequence, the previous gneissic fabrics have been texturally overprinted and secondary feldspar megacrysts have occasionally been formed (Lundqvist et al. 1990, Gorbatshev 1997). These features complicate the field classification of the KFM granitic rocks in the Svecofennian Domain.

Some of the different types of KFM rocks, previously classified as either Revsund granites or early orogenic granitoids in the Transition Belt (Lundegårdh et al. 1984, Lundqvist & Antal 2000), have similar U-Pb zircon and titanite ages between 1849 ± 14 and 1859 ± 11 Ma (Högdahl 2000a, Högdahl & Sjöström 2001). Consequently, a previously unknown major c. 1.85 Ga batholith of megacryst-bearing granitoids is present, and some of the Transition-Belt granites originally classified as part of the Revsund suite (Gorbatshev 1997, Lundqvist & Antal 2000) are considerably older than the c. 1.80 Ga Revsund granites occurring elsewhere (Claesson & Lundqvist 1995, Delin 1996, Delin & Aaro 2000).

The KFM granites in the Transition Belt of Jämtland are associated with minor pegmatites and fine- to medium-grained granitic dykes. The maximum and minimum ages of these rocks are constrained by their relationships with plastic shearing. While the fine-grained dykes have been affected by the 1816–1794 Ma plastic shearing (Högdahl & Sjöström 2001, Högdahl et al. 2001b,



Fig. 63. Red (a) and grey (b) varieties of K-feldspar megacryst-bearing granites from the Transition Belt in Jämtland. Diameter of lens cap is 52 mm.

cf. Chapter 6), the coarser-grained varieties and the pegmatites cut the shear fabric.

5.4.3. Geochemical characteristics of the KFM granites in the Transition Belt

The SiO_2 contents in the KFM granites and associated rocks in the Transition Belt range between 65 and 72 wt%, and plot in the fields of granite and granodiorite in the TAS diagram (Fig. 61a). These rocks are mostly peraluminous as shown by molecular $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})$ ratios above unity (Fig. 61b) as well as by moderate to high normative corundum values of 0–2.2 %. The relationships between SiO_2 and K_2O (Gill 1981) indicate that they are granites with ultra-high potassium contents. According to the

alkali-lime index (Peacock 1931), the compositions are calc-alkaline. In that regard, the Transition Belt rocks are mostly I-type granites similar to the rocks in the eastern part of the South Jämtland massif (Whalen et al. 1987) (Fig. 61c). The rare-earth element patterns show weak enrichment in LREE, depletion in HREE (La_N/Yb_N ratio from 5.9 to 23.0), and slightly negative Eu anomalies (Sm_N/Eu_N ratio from 1.7 to 3.6). The initial ϵ_{Nd} -values range from –1.6 to +1.7 (Ahl et al. in prep). In the tectonic discrimination diagram employing Rb versus Y+Nb (Pearce 1996a), the Transition Belt granites plot in the VAG/post-COLG to syn-COLG fields, while the other South Jämtland Revsund rocks also extend into the WPG field (Fig. 61d).

5.4.4. Origin of the KFM granites in the Transition Belt

During the last five decades, several models for the origin of the rocks of the Revsund suite have been proposed. Previously, these were described as ser- (or late-) orogenic with respect to the Svecokarelian orogeny, and were thought to have originated from *in situ* granitisation (Gavelin & Kulling 1955, Svensson 1970) or anatexis of greywackes to produce S-type granites (Wilson & Åkerblom 1980, Armands & Xeftaris 1987, Patchett et al. 1987). More recently they have been classified as post-orogenic (Lundqvist et al. 1990, Claesson & Lundqvist 1995), or as parts of the TIB suite (Gorbatshev & Bogdanova 1993, Gorbatshev 1997, Andersson 1997a). Their geochemical signatures indicate that they are predominantly I-type but have some S- to A-type signatures (Wilson, 1980, Lundqvist et al. 1990, Ahl & Sundblad 1994, Claesson & Lundqvist 1995, Andersson 1997a).

In regard to their appearance in outcrop, the KFM granites in the Transition Belt form a rather heterogeneous group. Nevertheless, their geochemical signatures show striking similarities. The major-element compositions resemble those of early Svecofennian granitoids, the rocks have calc-alkaline trends and belong to the magnetite series (Ahl et al. in prep), but the ϵ_{Nd} -values are slightly lower than those of the early Svecofennian granitoids. These features and the overall

geochemical signatures (Figs. 61a–d) suggest that the KFM granites have originated from re-worked older, mainly early Svecofennian igneous rocks with a minor component from an older source. The scatter of the data in the tectonomagmatic diagrams (VAG, syn-COLG to post-COLG, Fig. 61d) may indicate multiple reactivation of an igneous source.

The deviating geochemical signatures and the older emplacement ages of the granitic rocks in the Transition Belt, as compared to the rocks of the Revsund suite proper, indicate that they might not be a constituent of that suite. They could, however, represent an earlier phase of Revsund-type magmatism, with a different magma source. It is also possible that the 1.86–1.85 Ga KFM granites in Jämtland are part of the 1.85–1.84 Ga Ljusdal Batholith (Fig. 66, cf. Chapter 7.1) located further south (Delin 1993, Welin et al. 1993). However, in contrast to the generally coeval KFM granites in the Transition Belt of Jämtland, the Ljusdal granitoids are mostly folded and foliated (Lundegårdh 1967). They are also to a large extent metamorphosed in the amphibolite facies, locally even in the granulite facies (Lundegårdh 1967, Lundqvist et al. 1990, Delin & Aaro 1992, Bergman & Sjöström 1994, Sjöström & Bergman 1998). This indicates that they have experienced a tectonic and metamorphic event which escaped the Transition-Belt KFM granitoids.

6. SHEAR ZONES IN THE RÄTAN AND SOUTHERN REVSUND AREAS

Stefan Bergman, Karin Högdahl & Håkan Sjöström

6.1. The Storsjön-Edsbyn Deformation Zone

The Storsjön-Edsbyn Deformation Zone (SEDZ) extends from Lake Storsjön to Village Edsbyn in central Sweden (Fig. 64). On the magnetic anomaly map it is outlined as a conspicuous, 10–20 km wide and >200 km long, NNW-SSE or N-S (southern part) complex belt with banded and lenticular patterns discordantly cutting the regional magnetic pattern. East of the zone, E-W

form lines and folds rotate clockwise as the SEDZ is approached, which suggests that dextral shearing was superimposed on the pre-existing Svecokarelian structures. Conservative estimates of the displacement that caused this rotation are between 15.5 and 16.9 km in three profiles.

Several narrow, very persistent low-magnetic lineaments truncate the plastic structures indicat-

ing a prolonged history of deformation at different crustal levels. A WNW-ESE oriented lineament terminates the banded pattern of the SEDZ in the Edsbyn area. To the north, the magnetic signature of the SEDZ disappears below the Caledonian front.

The deformation zone broadly coincides with the boundary between the c. 1.7 Ga old Dala-Råtan magmatic rocks to the west and the older Svecofennian/Svecokarelian rocks (c. 1.8–1.9 Ga) to the east. However, most deformation in the zone, recorded at the present level of exposure, occurred east of the crustal province boundary.

Locally, metamorphic patterns developed during regional Svecokarelian deformation and early shearing were significantly disturbed by later movements on mostly steep, greenschist facies deformation zones. Also the shape of the composite Ljusdal Batholith is more or less controlled by shear zones: the SEDZ to the west and the c. E-W Hassela Shear Zone along its northern margin. There are also a number of c. 1.8 Ga old shear zones within the batholith (Sjöström & Bergman 1998, Högdahl 2000b).

Four main phases of deformation have been recognised along the deformation zone; associated mylonites are characterised by their mineralogy, microstructures, kinematic patterns, magnetic signatures and relative ages (Table 1). The two intermediate mylonite types (Types II and

III) are most characteristic for the SEDZ (Fig.65) compared to the entire region, whereas the formation of high-grade mylonites and cataclasites are not obviously linked to the zone.

6.1.1 Southern and central part

Type II mylonites: Plastic mylonites within the SEDZ exhibit a pronounced schistosity defined by quartz plates, preferred orientation of recrystallised grains and aggregates of quartz and mica, and flattened feldspar aggregates. The mylonitic foliation generally strikes oblique to the main shear zone and is locally folded due to progressive shearing. Fold axes and stretching lineations commonly plunge close to the dip direction of the foliation.

Both W-side-up and E-side-up kinematics have been recorded in the mylonites. In the Haverö area most mylonites indicate reverse movement, in other areas this pattern is not as consistent but there is a slight dominance for W-side-up reverse movement in the data set. As the main shear zone bends from NNW-SSE to N-S near Kårböle, the mylonitic foliation also rotates. The orientation of the generally steep stretching lineations also changes along this bend. North of it the plunge of the stretching lineation varies most across and south of it along the shear zone, and most plot in the NW-quadrant.

Table 1. Generalised summary of characteristic features of the different mylonites along SEDZ.

	Type I	Type II	Type III	Type IV
	Plastic, synmetamorphic regionally distributed	Mostly plastic, retrograde typical of SEDZ	Brittle-plastic typical of SEDZ	Brittle regionally distributed
Temperature / metamorphic grade	high, syn-peak metamorphism, pegmatites	medium-low, post-peak metamorphism	low	very low
Deformation mechanisms, textures	crystal plastic, polygonal texture	plastic quartz, mica and locally feldspar	plastic quartz, pressure solution, pseudotachylite	cataclastic
Magnetic susceptibility	commonly high	commonly high	low	low
Common minerals	magnetite in leucosome	chlorite, magnetite	epidote, chlorite	locally laumontite
Kinematic indicators	rotated foliations, porphyro-clast wings	rotated foliations, porphyroclast wings, s-c fabrics, shear bands	rotated foliations, s-c fabrics, quartz fibres, Riedel fractures	displaced markers, Riedel fractures
Estimated age	1.85–1.8 Ga	1.674±5 Ga	<1.6 Ga?	<1.2 Ga?

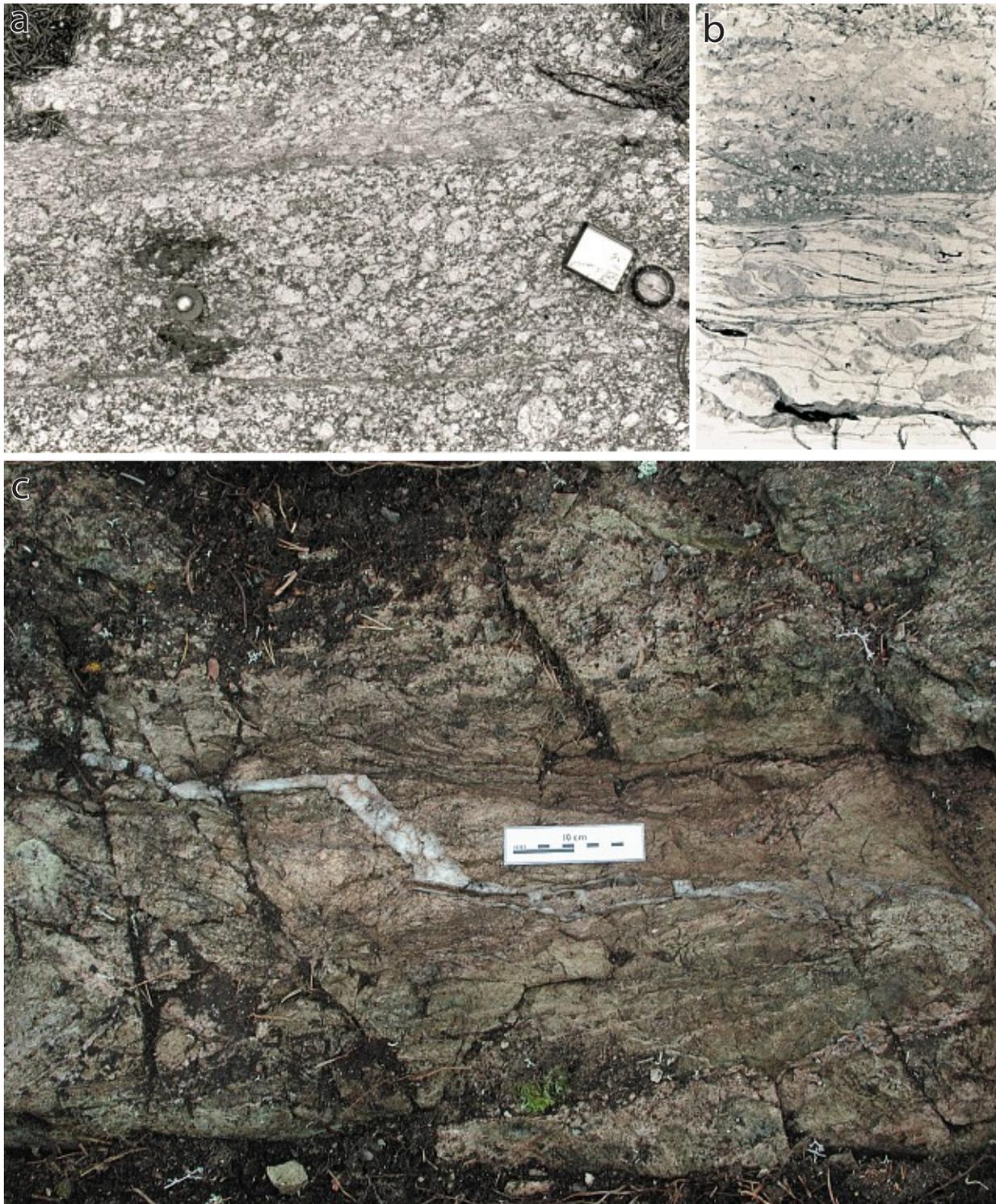


Fig. 65. a) Incipient brittle-plastic (or plastic?) deformation in Revsund granite. The two zones across the picture are the result of intense grain-size reduction. Together with the grain-shape fabric (lower left to upper right) defined by the feldspar phenocrysts, they make up an S-C fabric indicating a dextral strike-slip component. Långviken, 6.7 km east of Hackås. Length of compass is 10 cm.
b) Photomicrograph showing sinistral S-C mylonite cut by cataclasis, in turn cut by discrete contractional microfault. The protolith is a metaarenite. The long dimension of the photograph is 18 mm. Shore of lake Haverö at Löten, 17 km SSE of Haverö. The horizontal size of the picture corresponds to 5.8 mm.
c) Brittle-plastic type-III mylonite in the Storsjön-Edsbyn Deformation zone. Quartz-epidote-chlorite rock with dextral shear indicated by tensional quartz veins and pull-apart structures. Mörthålet, 1 km SW of Yttertingen (SNG 6923100/1457550).

A qualitative strain analysis in the Haverö area was made by comparing the orientations and kinematics of mesoscale shear zones with the

results of Gapais and Cobbold (1987). The analysis indicates that the shear zones accommodated a bulk non-coaxial deformation of flattening type

($0 < k < 0.4$) with a subvertical X-axis and a NW-SE striking XY-plane of the strain ellipsoid. The data is asymmetric, indicating SW-side-up movement during bulk transpressive shear.

The textures and mineral assemblages suggest that these mylonites formed under greenschist facies conditions. In thin section quartz grains show undulose extinction and feldspars are fractured and sericitised or more rarely have recrystallised mantles and asymmetric wings. Post-tectonic pinitisation of cordierite and sericitisation of feldspar porphyroclasts is common in mylonites in the Haverö area. Post-tectonic growth of white mica is also common. Biotite is either recrystallised or more or less replaced by chlorite. Secondary magnetite and/or titanite (U-Pb age 1674 ± 5 Ma, Högdahl 2000b) have formed during chloritisation. Magnetite appears as well-shaped post-tectonic porphyroblasts or as porphyroclasts in sheared chlorite. In extreme cases, up to 1 cm thick magnetite (+hematite) veins have formed. The formation of secondary magnetite in mylonites has important implications for the interpretation of magnetic anomaly maps. In many cases the banded pattern on these maps is due to this neomagnetisation associated with mylonitisation, although stretching of already magnetic bodies may also be significant.

Type III mylonites: Brittle-plastic mylonites are associated with persistent low-magnetic lineaments. The magnetic susceptibility is low in almost every measured outcrop. Characteristic epidotisation gives these mylonites a greenish colour. Quartz veins and pods are common along, or at a small angle to a more or less well-developed anastomosing cleavage. The cleavage is heterogeneously developed and the coexistence of curved and offset markers across it suggests mixed brittle and plastic deformation. A gently plunging stretching lineation exists only locally, but steep intersections of Riedel fractures and shears suggest dominantly strike-slip movement. Dextral shear is most common in this type of mylonite.

In thin section quartz shows undulose extinction and recrystallisation, and a well-developed S-C fabric is frequent, whereas feldspar is deformed cataclastically. Microfractures are ubiquitous. Biotite and feldspar are retrogressed to a

chlorite-epidote-carbonate assemblage. The distribution of dextral and sinistral zones, and the orientation of quartz veins constrain a N-S shortening direction. The field relations of these veins and parallel epidote-filled veins corroborate their relation with the brittle-plastic deformation. The average angle between the sinistral and dextral zones is close to 90° , which is typical for this regime of deformation.

Pseudotachylite is often associated with this type of mylonite. Their textures include amygdules (up to 5 mm in size), microlites, included fragments of wall rock, flow banding and intrusive apophyses. The pseudotachylite veins rarely exceed 3 cm in thickness.

6.1.2. Northern part (Svenstavik-Hackås)

The distribution of rocks within the SEDZ in the Svenstavik-Hackås area is essentially controlled by deformation. According to the county map (Lundegårdh et al. 1984) thin slices of NNW-SSE, steeply-dipping gneissose granitoids and amphibolites, with interleaved minor occurrences of supracrustal rocks, characterise a c. 10 km wide zone between the lakes Storsjön and Näkten. The geometry of a strike-slip duplex or the deeper levels of a flower structure is indicated.

An important feature for the field classification of syn- and post-kinematic granitoids is that the latter (e.g. Revsund and Rätan granitoids) are essentially isotropic as they post-date the regional Svecokarelian deformation. However, such a distinction is not possible along the SEDZ, because plastic and brittle-plastic deformation has affected all generations of granitoids. Consequently, post-kinematic granites may be more common within this part of the SEDZ than previously assumed.

The magnetic signature of the SEDZ on regional maps is characterised by SSE-wards converging bands of positive magnetic anomalies. The pattern indicates high strain, but generally lacks the indications of apparent sense of shear which are typical further to the south. On the detailed 1:50 000 magnetic anomaly maps (18E NO and SO), the SEDZ is well defined by a banded magnetic pattern including isoclinal folds. To the west of the deformation zone, a few, some

kilometres long NE-SW and N-S striking shear zones (apparent dextral) are indicated within the Rätan granitoids. In the Revsund granitoids and older Svecofennian rocks, the banded magnetic pattern indicates more pervasive deformation.

High-temperature gneiss zones (Type I in Table 1) appear to be rare in the area between Lakes Storsjön and Näkten, where the SEDZ-deformation is localised, both according to the magnetic signature and direct studies in the field. Composite microstructures in mylonitised rocks show that intense overprinted deformation has obscured the early pattern. In such mylonites strain-free, high-temperature domains with triple points developed between crystals, exist together with lower temperature structures like ribbon- and dynamically recrystallised quartz and cataclastically deformed feldspars. The low-temperature fabrics are often accompanied by the formation of epidote and/or white mica and/or chlorite, and locally pseudotachylite.

The kinematics of plastic mylonites within the deformation zone show no consistent pattern. Both normal and reverse dip-slip components are indicated, possibly with a dominance of the former. Stretching and mineral lineations vary along the strike of the deformation zone, from shallow plunge (large strike slip component) to steep plunge (large dip-slip component). The overall picture indicates a large dip-slip component which is similar to conditions further to the south. South of Hackås, a subhorizontal post-Jotnian (c. 1.25 Ga) dolerite dyke truncates the steep type II-structures within the SEDZ.

Brittle-plastic deformation zones show a relatively simple pattern. Pre-existing foliations in the various early Svecofennian rocks rotate clockwise into dextral, generally steep-dipping NNW-SSE shear zones. Slip-lineations on movement surfaces are shallowly plunging, indicating dominantly strike-slip. Measured and constructed (on stereograms) intersection lineations generally have a steep plunge consistent with strike-slip.

The principal axes of the strain ellipsoid derived from conjugate dextral and sinistral shear zones recorded in eight outcrops indicate NE-trending short axes (Z), vertical intermediate axes (Y) and NW-trending long axes (X). If the orientation of the strain axes are considered to

approximately correspond to the orientation of principal stresses, compression (σ_1) at a high angle across the SEDZ is indicated contemporaneously with dextral shear, i.e. transpression.

An important feature is that σ_1 (maximum compression) bisects the obtuse angle, and σ_3 (maximum tension) the acute angle between conjugate shear zones. This demonstrates that the overall character of the deformation is plastic.

6.1.3. Tectonic significance and relation to the Rätan Batholith

One of the main enigmas with the SEDZ is the combination of a clockwise rotation of foliation in adjacent rocks (which indicates dextral *strike-slip*), and an overwhelming dominance of plastic *dip-slip* mylonites. The dextral brittle-plastic mylonites are unlikely to have caused the rotation of the foliation, so other possibilities must be explored. Either the dextral rotation and the dip-slip mylonites represent separate deformation episodes or they are the expressions, on different scales, of bulk transpressional deformation. This kind of deformation was suggested by the Gapais and Cobbold (1987) analysis above and the interpretation of the SEDZ as a transpressional zone is supported also by theoretical studies (e.g. Tikoff & Teyssier 1994). Applying these results to the SEDZ, the oblique orientation of individual dip-lineated mylonites within the deformation zone would be the result of dextral simple shear and the dip-slip components record pure shear across the zones.

Near the Rätan Batholith (cf. Chapter 4.1) the maximum shear strain in the SEDZ is shifted towards the batholith. This asymmetry, and the fact that the deformation zone broadly follows the boundary of the batholith, suggests causal relationships between the two. That is, either the batholith margin acted as a rigid boundary during shearing, or the emplacement was simultaneous with, and thereby also affected the shearing. Both mechanisms would explain the existence of mylonitised Rätan granitoid. The latter alternative is favoured because it provides a heat source which facilitates strain localisation, and also opens the possibility of ballooning as a mechanism for shortening across the zone. In addition, it is

supported by the partly overlapping ages of titanites (1674±5 Ma, Högdahl 2000b), that formed during type-II deformation along SEDZ,

and the known age range of Rätan intrusives (1702–1679 Ma, referred in Lindström et al. 2000. p 146).

6.2. Plastic shear zones in the southern Revsund Transition Belt

In south-central Jämtland the SEDZ partly join the Hassela Shear Zone (HSZ) (Fig. 66). Together they form a c. 50 km wide network of sub-vertical, NW-SE to N-S trending, shear zones (Högdahl & Sjöström 2001). The HSZ is located to the northeast of SEDZ, and its constituent shear zones are wider, more pervasive and arrested at higher temperatures than the deformation zones further to the south assigned to the SEDZ. The higher temperature zones developed in the dominating K-feldspar megacryst-bearing granitic rocks are characterised by a penetrative, sub-vertical S-C fabric. With increasing strain the S-C fabric is in places transformed into millimetre to metre wide mylonites. Locally the change from S-C fabric to mylonites and ultramylonites is abrupt where the latter cuts the S-C fabric. In the early syn-kinematic rock S-C fabric is rare, probably due to different initial fabric and/or strain variations. The most common structures in these rocks are plane-parallel mylonites and L>S-mylonites. The shear zones form an anastomosing pattern with large tectonic lenses consisting of early syn-kinematic rocks, and have affected the younger K-feldspar megacryst-bearing granite. Occasionally these plastic deformation zones are truncated by felsic dykes and pegmatites which post-date the deformation.

There is a good correlation between the linear magnetic anomalies and the plastic shear zones (Bergman & Sjöström 1994). The linear magnetic anomalies also emphasise the pattern of anastomosing zones, which occasionally envelop tectonic lenses. There is a distinct difference in magnetic signatures between the early syn-kinematic rocks and the K-feldspar megacryst-bearing granite. The former shows an internal banding and the latter a more homogeneous pattern, which reflects both a composite versus homogeneous composition and a difference in strain intensity. That is, the syn-kinematic gneisses were intensely deformed while the younger gran-

ites were essentially undeformed before the development of the tectonic lenses.

Brittle deformation is widespread in the area. It resulted in the formation of cataclastites ranging from millimetres to several centimetres in width, occasionally accompanied by pseudotachylite melts. Open fractures occur mainly in fine-grained granites, but also in the K-feldspar megacryst-bearing granite. These fractures sporadically host large quartz crystals up to several centimetres in size, and in some cases these contain bitumen-rich inclusions. In places the quartz crystals occur together with epidote and fluorite crystals, and occasionally with calcite.

6.2.1. The Forsaån Zone

One of the most conspicuous plastic deformation zones in the area occurs along River Forsaån at the southern end of Lake Lockne (Lundqvist & Antal 2000, Högdahl & Sjöström 2001) (Fig. 67). The zone is c. 1 km wide and can be traced for more than 10 km in a NNW-SSE to NW-SE direction. The deformational fabric is more or less continuous through the width of the zone and the boundaries to undeformed rocks are distinct. Towards the northwest, the deformation zone follows Lake Locknesjön where it affects early Svecofennian metavolcanic rocks (Mansfeld et al. 1998).

The dominating structure is a coarse, penetrative, subvertical S-C fabric (Fig. 68), sometimes grading into pervasively deformed gneiss zones without S-C fabric. With increasing strain, the S-C fabric is transformed into millimetre- to metre-wide mylonites. Locally, the S-C fabric is cut by mylonites indicating that the latter are slightly younger. Subordinate ultramylonites have been recorded, in which the foliation is defined mainly by platy quartz (i. e. recrystallised ribbons) and thin mica-rich bands.

The bulk sense of shear is not obvious in the steep, NE-dipping Forsaån shear zone and kine-

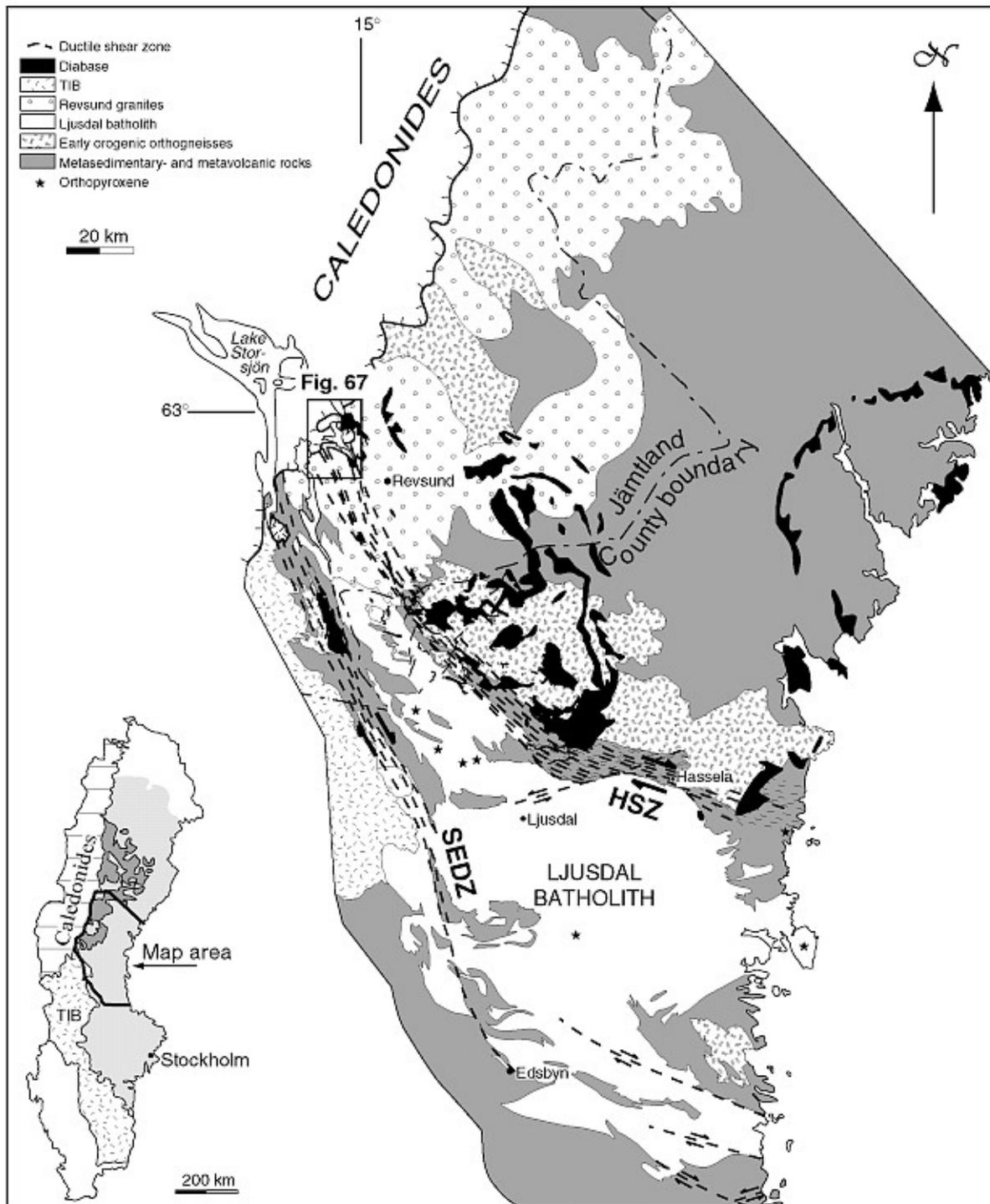


Fig. 66. Geological map of central Sweden (modified after Lundqvist 1987, Bergman & Sjöström 1994 and Högdahl & Sjöström 2001), showing the locations of the HSZ and the SEDZ. These shear zone systems partly join in southern Jämtland where they form a c. 50 km wide pattern of anastomosing deformation zones.

matic indicators are contradictory. Dextral shear zones truncating a sinistral S-C fabric exist, as well as sinistral shear zones truncating a pervasive gneissic foliation, or tensile quartz veins indicating sinistral rotation. Altogether, these examples indicate a sequential formation of sinistral and dextral kinematic patterns.

In pervasively deformed gneissic parts, there is, at least locally, a faint asymmetric pattern indicating dextral sense of shear in sub-horizontal sections. Still, sinistral shear bands and minor shear zones dominate among the data collected. However, more important is that dextral and sinistral shear bands (C') and minor shear zones

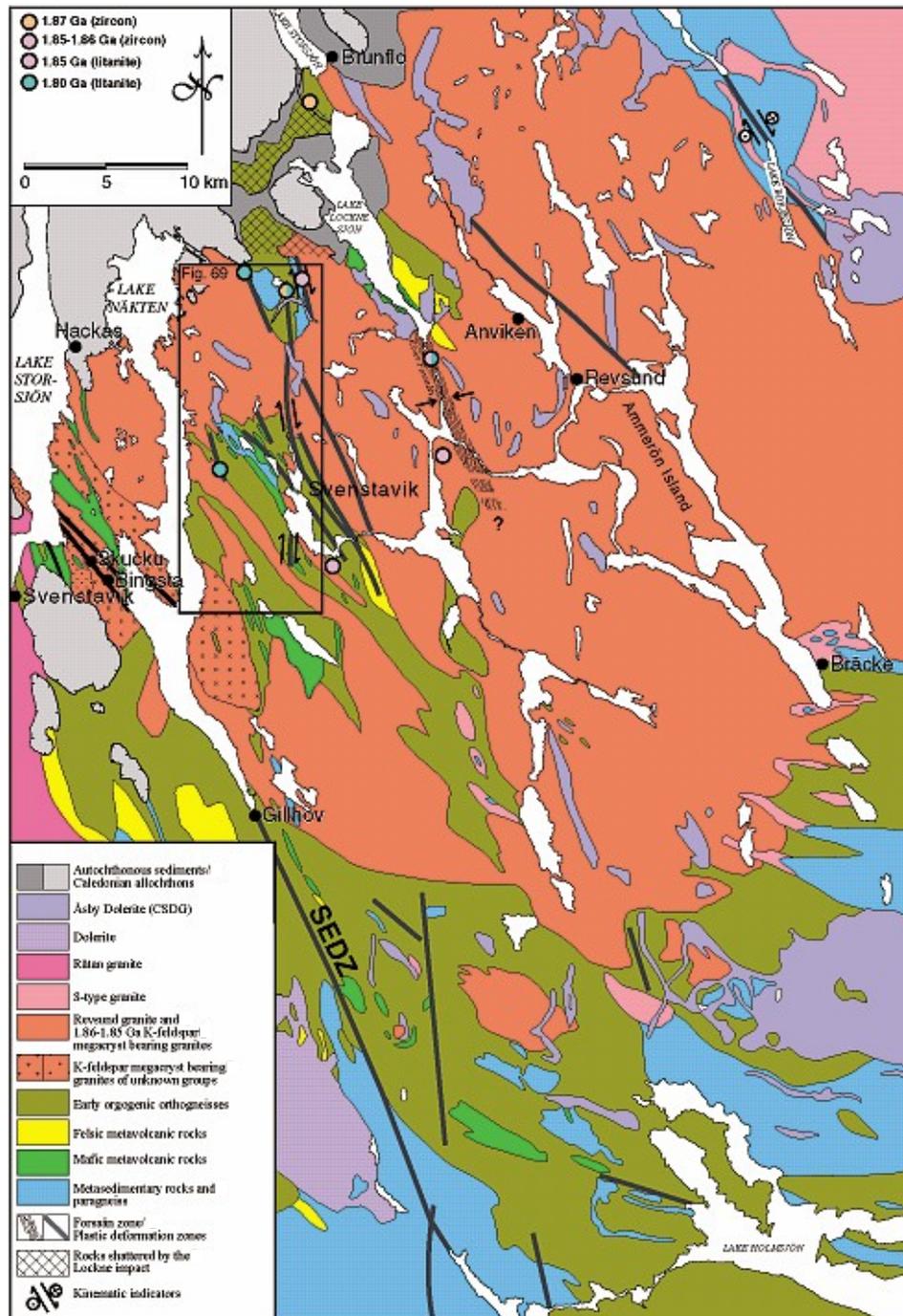


Fig. 67. Simplified geological map over east, central Jämtland and the southwestern part of Västernorrland. The distribution of elongated early Svecofennian rocks are arranged in a large scale dextral C-S pattern consistent with the a clockwise rotation of lithological units in the southeastern part of the area. The filled circles show sample localities which have been dated by Pb-Pb-zircon-, U-Pb zircon- and U-Pb titanite methods (Högdahl 2000a, b, Högdahl & Sjöström 2001, Högdahl et al. 2001) (modified after Lundegårdh et al. 1984, Lundqvist 1987, Lundqvist & Korja 1997).

are symmetrically arranged with respect to the pervasive, partly mylonitic (C) foliation.

Stretching lineations are generally weak and dominated by gentle to moderate plunges. Constructed intersection lineations between minor shear zones or C' and the mylonitic foliation (or C) tend to be perpendicular to the stretching

lineations. The former also shows a variation in plunge from steep to moderate within the mylonitic foliation, comparable in amount to the variation in plunge of the stretching lineations.

The orientations of strain axes, derived from conjugate dextral and sinistral shear zones, are NNW-trending (close to horizontal) X-axes



Fig. 68. Pervasive sinistral C-S-fabric in a 1.85 Ga K-feldspar megacryst-bearing granite along the Forsaån deformation zone. Lens cap for scale is 52 mm.

(stretching), WSW-trending (close to horizontal) Z-axes (shortening) and steep Y-axes. X and Y thus plot in the fields of stretching- and constructed intersection lineations, respectively, and Z close to the field of poles to the mylonitic foliation, i. e. Z is more or less perpendicular to that foliation. In terms of strain axes, the distribution of stretching and intersection lineations indicates that X and Y rotate within the shear plane, while Z is less variable and more or less orthogonal to that plane. This indicates that pure shear predominated during the development of the deformation zone.

Another plastic shear zone occurs c. 20 km NE of the Forsaån zone, at the boundary between the K-feldspar megacryst-bearing granite and the adjacent metasedimentary rocks to the east (Lundqvist 1996, L. Lundqvist, Uppsala, pers. comm. 1997). Within the granitic rock there are steep, metre-wide ultramylonites, which strike NNW-SSE and have a strong, oblique stretching lineation plunging c. 45° to the southeast. Kinematic indicators (shear bands, rotation of gneissosity) verify oblique dextral- and southwest-side-up displacement.

Such kinematic conditions have been recorded also in intensely deformed, very planar, steeply dipping metagreywackes c. 200 m from the contact to the granitic rock. In this case the kinematics are verified by asymmetric boudinage and shear bands (C'), combined with a pronounced

stretching lineation plunging c. 45° to the south-east. A weak, shallow plunging lineation is locally developed in platy quartz.

6.2.2. Plastic deformation zones in the Lockne, Näkten and Pån areas

To the southwest of the Forsaån zone, in the area between the lakes Näkten, Lockne and Pån, several anastomosing, plastic shear zones exist. They envelop two mega-sized tectonic lenses consisting of early syn-kinematic rocks. Less defined tectonic lenses have also formed in the younger, dominantly K-feldspar megacryst-bearing granite (Fig. 69).

One system of moderate-T deformation zones enveloping the tectonic lenses can be traced from the Caledonide front in a SSE direction along topographic lineaments defined by River Gölån and lake Pån. Shear zones in the K-feldspar megacryst-bearing granite are NW-SE to NNW-SSE trending with a steep to moderate dip. These zones are generally several hundreds of meters wide and have often developed a dextral S-C fabric, or appear as gneiss zones. With higher strain, or possibly in finer-grained protoliths, a mylonitic fabric has developed. In the early syn-kinematic rocks the zones are often plane-parallel, which could be due to higher strain or accentuation of pre-existing structures. In these rocks compositionally layered zones occur. The layers

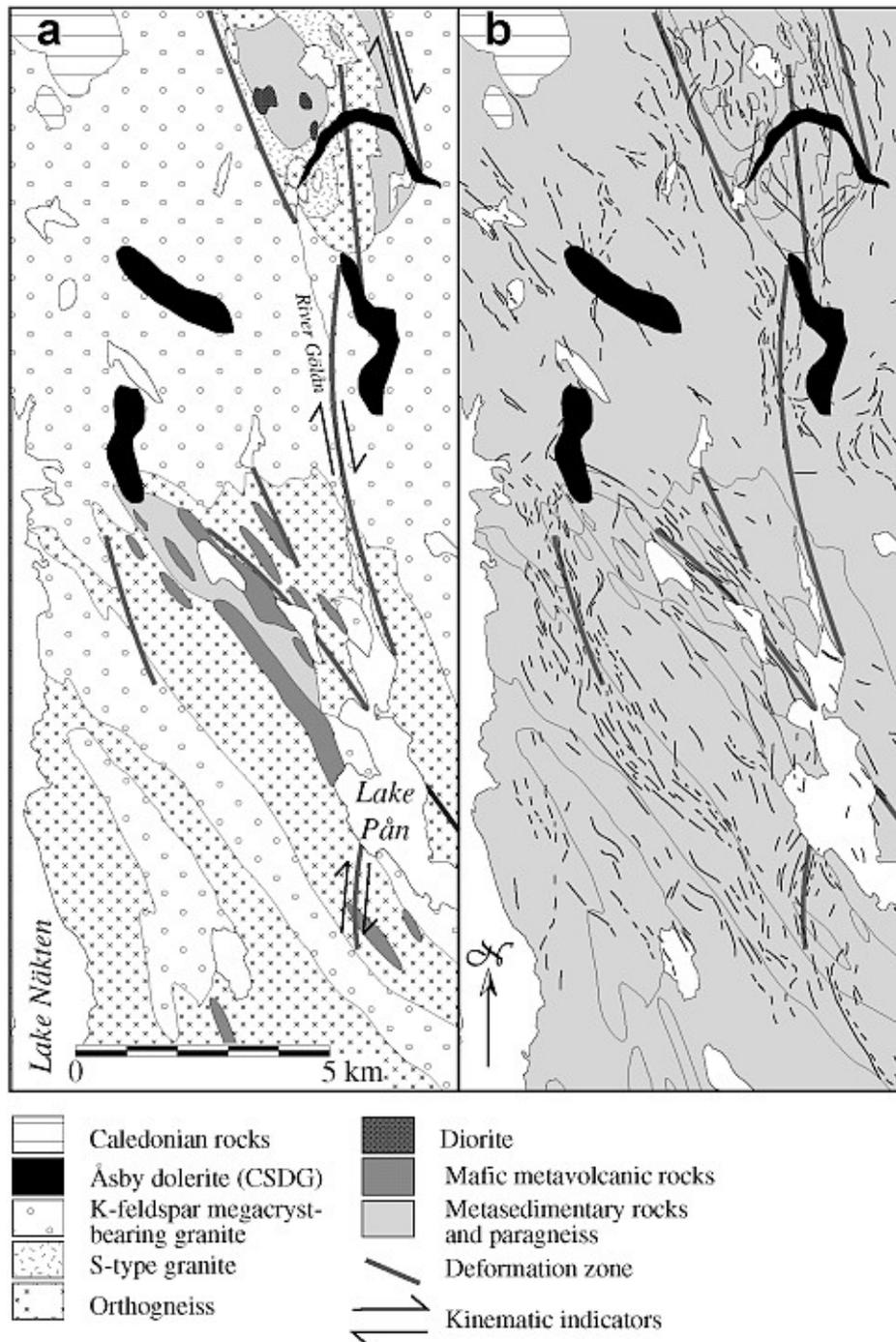


Fig. 69. a) Geological map over the area east of Lake Näkten with deformation zones (modified after Lundegårdh et al. 1984 and Sturkell 1998).

b) Enhanced linear magnetic anomalies interpreted from standard aeromagnetic maps showing that most of the identified deformation zones coincide with magnetic anomalies. Two distinct shear pods are defined by linear anomalies and shear zones to the west of Lake Pån and in the northeastern part of the map. Comparison with Fig. 69a shows that they are lithologically complex.

range from a few millimetres to tens of centimetres in width, and represent different lithologies found outside the deformation zone, which have been juxtaposed during the shearing event. These layered zones occasionally have a pronounced, shallow to moderate, southward plunging stretching

lineation, and when continuing into more homogeneous rocks the foliation is often subordinate compared to lineation.

Near Lake Pån there are two systems of shear zones trending in a NNW-SSE to N-S and a NW-SE direction, respectively. The NNW-SSE to N-

S trending deformation zones are part of the previously described zones in the south Revsund area. North and east of the lake the shear deformation has affected two different types of K-feldspar megacryst-bearing granites as well as a fine-grained, equigranular granite and possibly a felsic metavolcanic rocks. In K-feldspar megacryst-bearing granite the shear zones have a weakly developed, mainly dextral S-C fabric. With higher strain, or possibly in finer grained protoliths, a mylonitic fabric has formed. The dextral kinematics of the zone is further illustrated on a larger scale by the clockwise rotation into the zone of contrasting lithologies in the vicinity.

The NW-SE trending shear zone outlines the eastern margin of the other large-scale tectonic lens which can be traced westward to Lake Näkten. East of Lake Pån deformation has resulted in the development of a L>S zone with a strong sub-horizontal, SE-trending lineation and a steep, weak foliation. The westward continuation of the zone truncates the boundary between partly migmatized supracrustal rocks and early syn-kinematic granitoids. In contrast to the L>S-tectonite found in the plutonic rock a plane parallel (i.e. S>>L) structure has formed in the

supracrustal rocks during the deformation, reflecting the pre-deformational anisotropy of these rocks. The western margin of the tectonic lens is defined by a NNW-SSE trending zone with a well developed planar foliation, with a steep to moderate westward dip. The eastern part of this zone, which affects older, syn-kinematic rocks, has the strongest planar fabric, whereas to the west in the K-feldspar megacryst-bearing granite, the fabric is more gneissic in character.

The geometry of the anastomosing shear zone system in the whole area is dominated by an apparent dextral asymmetry judged from NW-SE trending magnetic anomalies that rotate clockwise into NNW-SSE to N-S zones. In addition, elongate early syn-kinematic rocks to the west are arranged in a large-scale S-C pattern. A dextral horizontal component also dominates in the plastic shear zones. Combined with observed stretching lineations dipping generally to the southeast, the most common kinematics is oblique dextral shear with NE-side down, although dextral horizontal and NE-side up also exists, probably as a result of the development of the tectonic lenses. The difference in kinematic conditions recorded along the zones in the Lockne,

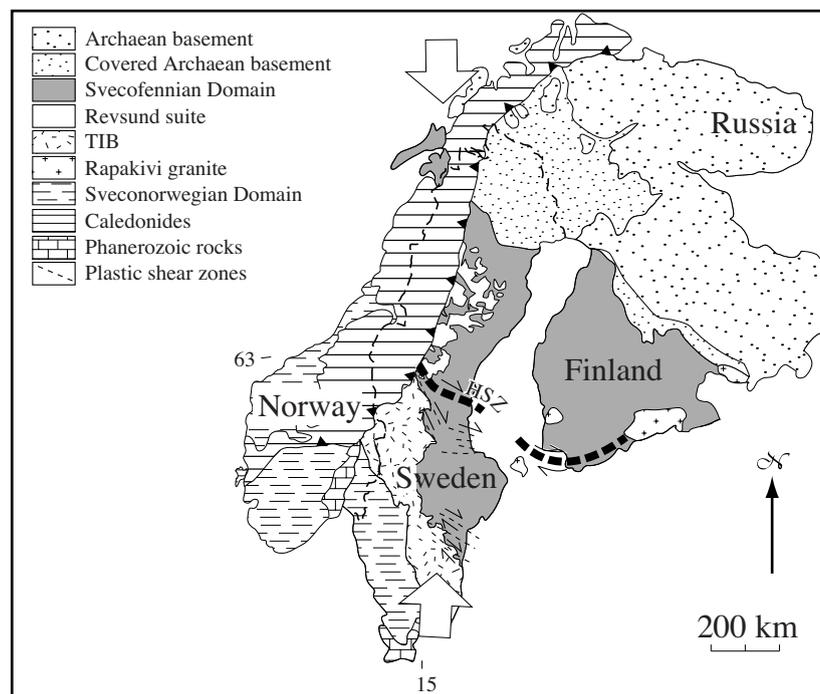


Fig. 70. Simplified geological map of the Fennoscandian Shield (modified after Gaál & Gorbatshev 1987, Bergman & Sjöström 1994, Stephens et al. 1994, Sjöström et al. 2000). The map including the plastic shear zones in central Sweden. Thick broken line shows the inferred continuation of the Hassela Shear Zone (HSZ) towards the shear zone system in southern Finland

Näkten and Pån areas, the zone at the eastern margin of the K-feldspar megacryst-bearing granite (dextral and southwest-side-up) and in the Forsaån section (dominantly pure shear conditions) demonstrates partitioning of strain during their formation.

6.2.3. Regional correlation

U-Pb analyses on brown titanite from three deformation zones in the Näkten, Lockne and Pån areas and from the Forsaån zone yield ages of c. 1.80 Ga and 1.82 Ga, respectively, interpreted to reflect the timing of plastic shearing (Högdahl & Sjöström 2001, Högdahl et al. 2001b). This is accordance with the timing of other shear zones related to the HSZ. The major dextral shearing along the HSZ is late syn-metamorphic with respect to the inferred 1.85–1.80 Ga Svecofennian

regional metamorphism (Sjöström & Bergman 1998). A conjugate sinistral zone and two deformation zones located southeast of the HSZ yield ages between 1.80–1.81 Ga (Högdahl & Sjöström 1999, Högdahl 2000b). The inferred eastward continuation of the HSZ, the Late Svecofennian Granite and Migmatite Zone in southern Finland (Fig. 70) was also active at 1.80 Ga (Ehlers & Skiöld 2001). All these zones were formed due to plastic deformation and indicate major deformational events under approximately the same PT-conditions. The timing, the NW-SE to WNW-ESE orientation and dextral kinematics of these zones, as well as the sinistral kinematics of conjugate ENE-WSW trending zones suggest a roughly SSW-NNE or SSE-NNW contraction late during the plastic evolution (Fig. 70) (Högdahl & Sjöström 2001, Lindroos et al. 1996).

7. THE LJUSDAL BATHOLITH AND LATE SVECOFENNIAN MAGMATISM

7.1. The Ljusdal Batholith

Håkan Sjöström & Karin Högdahl

The c. 130 (N-S) x 100 (E-W) km Ljusdal Batholith is a major unit in the Svecofennian of central Sweden. It is located south of the Bothnian Basin, which is a marine Palaeoproterozoic metasedimentary sequence, and continues eastwards to the coast of the Bothnian Bay (Fig. 66). The northern and western boundaries of the batholith coincide with the Hassela Shear Zone (HSZ) and the Storsjön-Edsbyn Deformation Zone (SEDZ), respectively. To the south, the granitoids of the batholith have a complex boundary to the rocks of the Bergslagen region (Delin 1993). The batholith is composed of different calc-alkaline rocks, ranging in composition from tonalite to granodiorite; granite *sensu stricto* is less common (Delin 1989a, b, Delin & Aaro 1992, Sukotjo 1995). The granitoids vary from fine-grained equigranular to coarse-grained megacryst-bearing types. The latter are referred to as Ljusdal granites and often appear as augen gneisses. Although generally metamorphosed and de-

formed, the Ljusdal granites resembles locally some varieties of the Revsund suite.

The granitoids within the Ljusdal Batholith belong to the synkinematic suite of intrusions, and have emplacement ages of c. 1.85–1.84 Ga (Delin 1993, 1996, Welin et al. 1993). They are the youngest rocks of the suite and their ages overlap those of the oldest TIB intrusives. Intrusive rocks with similar ages have also been found to the north and to the west of the batholith (Delin 1996, Delin & Persson 1999, Högdahl 2000a). Remnants of older Svecofennian supracrustal rocks exist within the batholith and in the vicinity of these rocks garnet porphyroblasts have occasionally formed in the granite. Some of the supracrustal rocks are well-preserved (Los and Hamrånge areas) while others are intensely migmatized, particularly in the granulite grade areas in the east.

A major part of the Ljusdal Batholith has been affected by amphibolite facies metamorphism

(Lundegårdh 1967, Lundqvist et al. 1990, Bergman & Sjöström 1994, Sjöström & Bergman 1998, Delin & Aaro 1992). However, in certain areas granulite facies conditions prevail (Lundegårdh 1967, Sjöström & Bergman 1998). Close to Hudiksvall, monazites indicate a minimum U-Pb age of 1826 ± 2 Ma for that high-grade low-pressure metamorphism (Sjöström & Bergman 1998).

7.2. The late Svecofennian magmatism

Ulf B. Andersson & Björn Öhlander

The late Svecofennian magmatism (Fig. 3) developed within the Svecofennian Domain to the east of the TIB, roughly synchronously with the TIB-1 magmatic activity (e.g. Gaál & Gorbatshev 1987, Andersson 1991, 1997a, b, Öhlander & Romer 1996). It is more or less entirely related to reworking of the pre-existing early orogenic crust in the form of anatexis as local migmatite granites or larger plutons. In different areas this magmatism has been allocated local names which have become established terms. In northernmost Sweden, where the Svecofennian rocks are largely underlain by an Archaean basement (e.g. Öhlander et al. 1993, Mellqvist 1999), the Lina type granites cover extensive areas (Bergman et al. 2001). In the Bothnian basin areas of central Sweden, this group of granites is known as Skellefte (north) and Härnö (south) granites (e.g. Lundqvist et al. 1990, Claesson & Lundqvist 1995). In the southern Svecofennian Bergslagen area two main types are recognised: the Stockholm type, which dominates in the southeast and is a heterogeneous but usually fine-grained greyish granite; and the coarse-porphyrific mainly red Fellingsbro type occurring in the north and west (e.g. Öhlander & Zuber 1988b, Andersson 1991, Öhlander & Romer 1996). Hardly any mafic-intermediate bodies have been observed in association with the late Svecofennian granites.

The *Lina type granites* in northernmost Sweden are essentially reddish, leucocratic, minimum-melt type, migmatite-related granites (Öhlander et al. 1987, Öhlander & Skiöld 1994, Ahl et al. 2001, Bergman et al. 2001), with crystallisation ages of 1.81–1.77 Ga (Skiöld 1981, Öhlander & Schöberg 1991, Wikström & Persson 1997,

The batholith has locally been affected by intense deformation. At least two phases of regional folding has been recorded. It has also been truncated by several WNW-ESE, generally oblique, dextral c. 1.8 Ga old plastic shear zones such as the HSZ (Sjöström & Bergman 1998, Högdahl 2000b).

Bergman et al. 2002). Their protoliths contain large portions of Archaean components mixed with juvenile material, mainly non-pelitic, I-type, in composition (Öhlander et al. 1987, 1999, Skiöld et al. 1988); the latter may comprise early Svecofennian granitoids or metaigneous material which occur in the same general area and have overlapping time-integrated Nd isotope compositions (Öhlander et al. 1987, 1993, Öhlander & Skiöld 1994). The contemporaneous c. 1.80 Ga alkali-rich, more A-type, *Boden-Edefors granitoids* are characterised by much more juvenile sources, with only small Archaean contributions (Öhlander & Skiöld 1994).

The *Skellefte and Härnö suite granitoids* comprise a group of smaller, dominantly S-type intrusions (two-mica granites) in east-central Sweden (Fig. 3) with generally peraluminous compositions (mean A/CNK=1.2) (Claesson & Lundqvist 1995, Weihed et al. 2002). The range of silica content is restricted (70–76 % SiO₂; Lundqvist et al. 1990) and with few exceptions they plot as monzogranites in the diagram of De la Roche (1980). In the Pearce et al. (1984) diagrams they plot in the syn-collision granite field due to high Rb contents (300–400 ppm). The determined crystallisation ages are in the range 1.82–1.80 Ga (Claesson & Lundqvist 1995, Eliasson & Sträng 1997, Weihed et al. 2002)

The Skellefte and Härnö granites vary from finely medium- and even-grained, to coarser types with tabular K-feldspar crystals up to 3 cm long, usually greyish in colour and commonly carrying metasedimentary (restitic) enclaves (Lundqvist et al. 1990). The latter, together with a tendency for grading into migmatites, suggest an origin by

anatexis of metasediments. The isotopic composition of Nd and Sr, and the metaluminous character of some types, however, implies also a contribution from early orogenic metaigneous sources (Claesson & Lundqvist 1995, Weihed et al. 2002). These groups of granites are thus derived from mixed (but sedimentary-dominated) crustal sources, with no detectable mantle component.

Abundant pegmatites are spatially associated with these granite types, partly enriched in Li, Cs, and Ta and related elements (LCT-type), occurring particularly in lower metamorphic (greenschist to low amphibolite facies) areas (Smeds 1994). U-Pb columbite ages of these pegmatites are c. 1.80 Ga in the Bothnian basin area and somewhat lower (1780–1765 Ma) in the Skellefte area (Romer & Smeds 1994, 1997).

In the *Bergslagen area* of southern Sweden numerous late Svecofennian granites (Fig. 3) have ages in the range 1.81–1.75 Ga (Åberg & Bjurstedt 1986, Patchett et al. 1987, Billström et al. 1988, Stephens et al. 1993, Sundblad et al. 1993, Ivarsson & Johansson 1995, Bergman et al. 1995, Öhlander & Romer 1996, Högdahl & Jonsson 2004). A few migmatite granites are somewhat older (c. 1.85 Ga; Romer & Öhlander 1995). This granite generation is thus roughly coeval with the regional metamorphic peak in Bergslagen (Romer & Öhlander 1994, Andersson 1997b) and TIB rocks in the Svecofennian margin (see Chapter 2). Pegmatites of both LCT and NYF (Nb, Y, F) affinity yield overlapping ages in the range 1.82–1.77 Ga (Romer & Smeds 1994, 1997).

The granites occur as two principal types: large, homogeneous plutons of dominantly coarse K-feldspar porphyritic (typically rectangular megacrysts) granites (e.g. Fellingsbro, Lisjö, Örebro and Hedesunda) of relatively restricted compositional variation (mostly 65–77 % SiO₂; Öhlander & Zuber 1988a, b); and small heterogeneous, migmatite-related granites (Zuber & Öhlander 1991, Öhlander & Romer 1996).

The large homogeneous plutons range from metaluminous to peraluminous with increasing silica content, and consistently plot in the within-plate field in the diagrams of Pearce et al. (1984), due to high Nb and Y abundances (Zuber &

Öhlander 1990). This contrasts with the Småland-Värmland Belt (SVB) granites of the TIB, which generally have lower contents of Nb, Y, and other trace elements such as e.g. Th and Rb, but overlapping major element characteristics with the late Svecofennian granites (Zuber & Öhlander 1990, Andersson 1991).

The larger massifs of late Svecofennian granites in Bergslagen mostly occur in areas dominated by early Svecofennian metaigneous lithologies. The higher contents of the generally incompatible trace elements in the large homogeneous plutons, have been related to smaller degrees of partial melting of this composite metaigneous crust as compared with the SVB granites, rather than variation in the protoliths (Andersson 1991). Also available Nd isotope data support derivation from early Svecofennian metaigneous sources for the late Svecofennian granites, with occasional minor mantle contributions (Patchett et al. 1987, Andersson 1991).

However, regional gravity surveys have indicated the existence of a major E-W-trending anomaly of relative gravity (the Central Swedish Gravity Low), spatially correlated with some of the larger late Svecofennian intrusions (Öhlander & Zuber 1988a, Zuber & Öhlander 1990). These intrusions were therefore (and from geochemistry) interpreted to result from extensive melting of lower crustal lithologies, followed by magma rise to form deep-reaching granitic ridges. This was thought to have developed in a tensional environment on the continental side of a subduction zone (Öhlander & Zuber 1988a, b).

The small, heterogeneous granitic bodies have generally been interpreted as local anatectic, minimum-melt type rocks that owe their heterogeneity to variation in the local source lithology and degree of melting (Zuber & Öhlander 1991, Andersson 1991). They could either be related to regional migmatization or local remobilisation due to, e.g., TIB intrusions. The trace element chemistry is variable, but contents of e.g. Nb and Y are usually lower than in the larger intrusions (Öhlander & Romer 1996), and these granites therefore plot in the volcanic-arc or syn-collisional fields of Pearce et al. (1984). The low contents of certain trace elements seem to indicate that important accessory minerals remained

in the sources, most notably zircon. In areas dominated by metasedimentary gneisses (e.g. the Sörmland basin), these small-scale intrusives are peraluminous, S-type, two-mica granites.

The anatectic granite and pegmatite formation in Bergslagen has been related to continental collision and crustal thickening (Romer & Smeds 1994, 1997, Öhlander & Romer 1996). In contrast, the larger intrusions have been interpreted as induced by mafic underplating in response to subduction or lithospheric delamination (An-

dersson 1991, Öhlander & Romer 1996). However, very little, if any, mafic-intermediate magmatism is observed associated with these granites. The general lack of high-pressure regional metamorphic mineral assemblages in Bergslagen (cf. Andersson 1997b) and overlapping ages of both granite types and TIB rocks, seem to support a model of continued subduction, reworking and transpression/transension, rather than collisional thickening for the period 1.85–1.75 Ga (see Chapter 8).

8. THE TRANSSCANDINAVIAN IGNEOUS BELT, EVOLUTIONARY MODELS

Ulf B. Andersson, Håkan Sjöström, Karin Högdahl & Olav Eklund

As outlined in the previous chapters, rocks grouped together under the TIB heading comprise a diverse temporal and spatial collection with a large variation in individual characteristics. The concept of TIB may be used without genetic connotation, including all magmatic rocks representing a transition in time and space between the processes that formed the calc-alkaline, juvenile, arc-related early Svecofennian (1.95–1.86 Ga) crust to the east and the essentially younger calc-alkaline crust to the west (c. 1.70–1.58 Ga) of this belt. In spite of overlaps in ages at both ends (Fig. 71), the TIB granitoids can in most cases be distinguished by their typical alkali-rich geochemistry and/or coarse, mostly porphyritic textures. However, in the last years several transitions into calc-alkaline units have been recognised both among older and younger generations, e.g. in the Transition Belt of the south Jämtland Revsund massif and possibly within the Ljusdal Batholith (1.86–1.84 Ga) (Chapters 5.2 and 7.1, Ahl et al. in prep), in the (c. 1.85 Ga) Tiveden area (Wikström & Karis 1998), in southern Småland and Blekinge (c. 1.77 Ga) (Kornfält & Bergström 1991, Gorbatshev 2001, Lindh et al. 2001a), and in the transition to the gneisses of the Eastern Segment of the Southwest Scandinavian Domain (c. 1.7–1.65 Ga) (Gorbatshev 1980, Berglund & Larson 1997, Gorbatshev & Bogdanova 2003). Furthermore, in the c. 1.7 Ga Dala Province, a transition into alkaline, A-

type granitoids exists (Ahl et al. 1999, Chapter 3.2). The significance of these transitions need to be addressed in any crustal evolution model for the TIB.

There is a temporal and partly spatial overlap between the late tectonomagmatic processes within the Svecofennian Domain and the emplacement of the earliest TIB generations (1.86–1.80 Ga). From the previous descriptions (Wikström et al. 1997, Chapter 2.3) it is clear that several of the earliest (1.86–1.84 Ga) intrusions of TIB affinity along the Svecofennian margin were subjected to Svecokarelian plastic deformation (1.85–1.80 Ga). Moreover, the granitoids of the Ljusdal Batholith and the coeval K-feldspar megacryst-bearing (KFM) granitoids in the Transition Belt (1.86–1.84 Ga) appear to reflect a change from TTG to more alkali-calcic compositions, approaching TIB chemical affinity (Fig. 61; Ahl et al. in prep). However, most of the Ljusdal Batholith is affected by deformation and metamorphism in amphibolite-, locally up to granulite facies, which has not affected the KFM granitoids (Lundegårdh 1967, Bergman & Sjöström 1994, Sjöström & Bergman 1998).

The TIB-1 magmatism overlap in time with the late Svecofennian granitic magmatism that intruded the early Svecofennian lithologies east of the TIB in the period 1.82–1.75 Ga (Chapter 7.2, and ref. therein). The small volume of the latter intrusions compared to the TIB, and the apparent

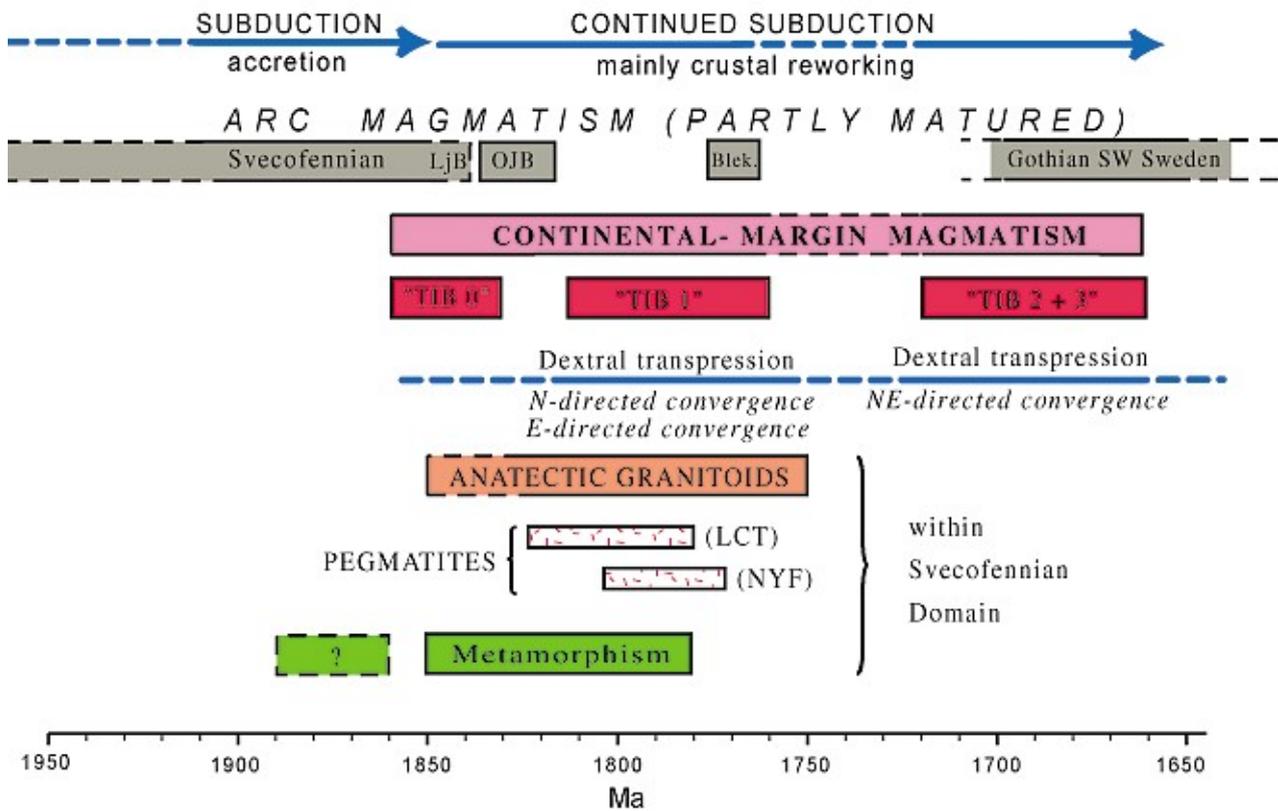


Fig. 71. Time-evolution diagram showing the duration and tectonic setting of TIB-related geological processes. See Fig. 4 for abbreviations.

control of their chemistry by the local country rocks (generally peraluminous S-type in metasedimentary- and metaluminous I-type granites in metaigneous-dominated areas; Chapter 7.2) support the interpretation of a local, anatectic magmatism in areas of lower heat flow due to less extensive mafic underplating during subduction (Andersson 1991, Öhlander & Romer 1996).

The variation in crustal thickness and composition along the TIB and neighbouring areas has profound implications for the understanding of the crustal development. Several interpretations of reflection and refraction seismic data along the FENNOLORA, BABEL and Coast profiles (e.g. Clowes et al. 1987, Guggisberg & Berthelsen 1987, Guggisberg et al. 1991, BABEL-group 1993, Abramovitz et al. 1997, 2002, Korja & Heikkinen 2000, Lund et al. 2001) yield roughly similar results for crustal sections from Blekinge in the south to the Skellefte district in the north. The thinnest crust (c. 35 km) is present in the south, south of the Oskarshamn-Jönköping belt (OJB), with a stepwise thickening of the mafic lower crust from c. 20 km in the south to a maximum thickness of c. 30 km in the transition

zone between the TIB and the Svecofennian of southern Bergslagen. In the Lake Mälaren area, there is a rapid change of total crustal thickness from c. 50 km in the south to c. 40 km in the north (northern Bergslagen). The thinning is entirely within the mafic lower crust, while the felsic upper crustal rocks here extend deeper than 20 km. Northwards, below the Ljusdal Batholith the crustal thickness increases again to more than 50 km, followed by a gentle decrease across the Bothnian Basin/Revsund granitoid areas to around 40 km in the Skellefte juvenile arc area. In the area of the Bothnian Basin, the uppermost crust consists of a c. 8 km thick layer of especially low-velocity crust, which terminates just south of the Skellefte district (Guggisberg et al. 1991).

In the west, there is a general shallowing of Moho depth that approximately coincides with the Sveconorwegian frontal deformation zone (SFDZ; Wahlgren et al. 1994) (cf. BABEL working group 1993, Korja et al. 1993). This may be correlated with an uplift of the southern part of the Eastern Segment of SW Sweden in late Sveconorwegian time (c. 0.96 Ga), as determined from P-T-t considerations (e.g. Johansson et al.

1991, 2001, Johansson 1992). The shallowing of Moho continues northwards below the Caledonides up to the Norwegian coast, with an abrupt crustal thinning in the northernmost TIB areas of the Lofoten Islands (cf. Korja et al. 1993).

Concerning the formation of the juvenile calc-alkaline Svecofennian crust, most authors agree that it was formed as a series of island arc systems, successively accreted to the Archaean craton in the NE, with a sedimentary basin (the Bothnian Basin) in between (e.g. Hietanen 1975, Nurmi & Haapala 1986, Gaál 1986, Berthelsen 1987, Gaál & Gorbatshev 1987, Lahtinen 1994, Nironen 1997, Korsman et al. 1999, Väisänen 2002, and ref. therein). The earliest arc crust appears to have formed during 2.1–1.9 Ga (e.g. Huhma 1986, Patchett & Arndt 1986, Patchett et al. 1987, Valbracht et al. 1994, Lahtinen & Huhma 1997), of which only remnants exist (Wasström 1993, 1996, Skiöld et al. 1993, Welin et al. 1993, Lahtinen & Huhma 1997, Lundqvist et al. 1998). In addition, abundant inherited zircons of 2.1–1.87 Ga are found in 1.9–1.86 Ga Svecofennian rocks (Claesson et al. 1993, Kumpulainen et al. 1996, Andersson et al. 2000, 2004, Lahtinen et al. 2002, Sultan et al. 2004). Due to the pronounced bimodality of especially the volcanic rocks, several workers invoke rifting and almost complete reworking of the earliest arc crust at 1.9–1.86 Ga (e.g. Vivallo & Claesson 1987, Baker et al. 1988, Lagerblad 1988, Vivallo & Willdén 1988, Gaál 1990, Allen et al. 1996).

Regional metamorphism occurred earlier in central and eastern Finland (at c. 1.88–1.87 Ga; Koistinen et al. 1996, Korsman et al. 1999, and ref. therein), than in southern Finland and Sweden (1.85–1.78 Ga; Romer & Öhlander 1994, 1995, Andersson 1997b, Sjöström & Bergman 1998, Väisänen 2002, Väisänen et al. 2002, 2004, and ref. therein); in the latter areas overlapping with early stages of TIB formation (TIB-0,1). Areas of lower grade metamorphism (e.g. northern Bergslagen) represent shallower crustal levels (pressures 2–4 kbar and temperatures <600°C; Rickard 1988, Stålhös 1991, Sjöström & Bergman 1998, Ripa 1994).

Three different main scenarios have been proposed after the arc-accretion stage and onset of TIB magmatism: 1) a convergent continental

margin setting of Andean type (Wilson 1982, Nyström 1982, 1999, Andersson 1991, Åhäll & Larson 2000); 2) an ensialic tensional setting (Wilson et al. 1985, Johansson 1988, Öhlander & Zuber 1988b); and 3) or post-collisional extensional collapse after overthickening of the crust (Korja et al. 1993, Korja & Heikkinen 1995). The latter two models are faced with some objections:

- 1) There is no intermediate to high pressure metamorphism documented so far in the Svecofennian Domain recording overthickened continental crust, which would be expected to be exhumed after post-collisional extensional collapse (cf. e.g. Ruppel & Hodges 1994, Davies & von Blanckenburg 1995, Chemenda et al. 2000, 2001, Borghi et al. 2003). Variations in the Moho depth are essentially related to an uneven thickness of the lower, high velocity (density) crust, which tends to be thick below high grade, low P-high T domains such as the Ljusdal Batholith and the Sörmland Basin of southern Bergslagen. Moreover, low to intermediate pressures (4–6 kbar) are typical for amphibolite-granulite terrains over the entire Svecofennian area up to the Archaean margin (Rickard 1988, Andersson 1997b, Koistinen et al. 1996). Korsman et al. (1999, 2000) related the low P/high T metamorphism in the Svecofennian to mafic underplating shown by the thickening of the lower high-velocity seismic crust. Accretion of mafic material to the lower crust would not promote gravitational instability and collapse to the same extent as a major thickening of silicic crust by continent-continent collision.
- 2) The geochemical signatures of essentially all mafic TIB rocks studied so far are of subduction-related continental-margin type (Chapter 2.5, Nyström 1999, Claesson 2001, Claesson & Andersson 2000). This could be related to an entirely inherited signature from previous subduction event/s, e.g. by postcollisional asthenospheric upwelling, resulting in thinning and melting of the enriched continental lithosphere (e.g. Väisänen 2002). However, the large volumes of magmas involved along an essentially linear belt, as well as transitions to calc-alkaline units, is reminiscent of conti-

mental-margin type belts (e.g. Cordani et al. 2000, and ref. therein).

- 3) The lack of related extensional or transtensional structures and scarcity of dyke generations coeval with the TIB argues against an extensional collapse setting.

In fact, the southern TIB (the Småland-Värmland belt; SVB) seems to represent a massive post-accretionary reworking of the juvenile early Svecofennian crust along a newly established apparently (N)NW-(E)SE-oriented continental margin in the SW. This reworking started around 1.86–1.84 Ga (TIB-0), due to northward subduction, with possibly slightly oblique convergence (Fig. 72). Abramovitz et al. (1997) traced a north(east) dipping suture through the crust and into the upper mantle below southern Bergslagen which they interpreted as a fossil trace of c. 1.86 Ga subduction. Lund et al. (2001) also recognised this suture, but added the aspect of a continuing episodic southwards accretionary and collisional growth of the crust across the entire TIB (SVB) area down to Blekinge during 1.84–1.77 Ga. See also Korja & Heikkinen (2001), who considered the Sörmland Basin of SE Bergslagen to represent an accretionary prism of this subduction. However, new calc-alkaline crust was apparently still being produced by 1.86–1.84 Ga in the Ljusdal Batholith/KFM granitoid transitional area, presently located further north between the Bothnian Basin and the Bergslagen area. This magmatism probably included some reworking of the slightly older juvenile crust, as indicated by its transitional calc-alkaline – alkali-calcic geochemistry (cf. Fig. 5.5; Chapter 5.4).

Around 1.81–1.80 Ga a transpressional regime seems to have dominated the overall tectonic setting for the TIB and southern/central Svecofennian Domain (Figs. 71, 72). Large-scale dextral and minor conjugate sinistral plastic shear zones become predominant features both within the TIB marginal areas in Östergötland and NE Småland (Beunk & Page 2001), as well as within the adjoining Svecofennian areas of southern Bergslagen (Stephens et al. 1994). Concurrently, major shear zones bounding and within the Ljusdal Batholith and in the KFM granitoids in the Transitional area further north were active with a

corresponding dextral kinematics due to c. N-S convergence (cf. Chapter 6, Bergman & Sjöström 1994, Sjöström & Bergman 1998, Högdahl et al. 2001, Högdahl & Sjöström 2001). Some of these shear zones seem to have a continuation in southern Finland (Ehlers et al. 1993, Lindroos et al. 1996, Högdahl & Sjöström 2001, Ehlers & Skiöld 2001). The displacements along the dextral shear zones are not known. However, assuming onset of shearing at c. 1.82 Ga (Högdahl & Sjöström 2001), the pre-1.82 Ga position of each crustal block south of the Bothnian Basin should be stepwise increasingly eastwards compared to their current positions (Fig. 72 inset). A north-, or even northnorthwestward (cf. Ehlers et al. 1993), convergence would account for the transpressive shear resulting in the present-day geometry.

From magnetic structures and lithologies it is also possible to discern an apparent clockwise rotation of the magmatic flow in TIB-1 magmas from essentially E-W to N-S around the SW Svecofennian Bergslagen Province (cf. Fig. 4 in Andersson 1991, Fredén 1994, Koistinen et al. 2001), indicating that dextral horizontal movements were active during TIB-1 intrusion, i.e. long before the western continuation of TIB was pervasively overprinted by the 1.2–0.95 Ga Sveconorwegian orogeny. The development of the transpressional shear zones in the older crust could, in fact, have been instrumental in the localisation of TIB magma flow and emplacement in accordance with the models of e.g. Brown & Solar (1998a,b). Most of these plausible zones are now obliterated by the TIB intrusions, with a possible exception associated with the Gåsborn pluton (Chapter 2.4.3.3; Cruden et al. 1999).

The present geometry of the lower crust most likely developed essentially during the time of TIB formation (1.85–1.65 Ga). The thick section of mafic lower crust in the northern SVB and southern Bergslagen could be related to voluminous mafic underplating (cf. Lund et al. 2001) with a related strong reworking of the pre-existing juvenile crust, that in southern Bergslagen resulted in amphibolite to granulite facies metamorphism, as well as anatexis that produced both TIB intrusions and late Svecofennian magmatism.

To the south, the 1.84–1.82 Ga OJB in central Småland represents a sliver of younger, post-

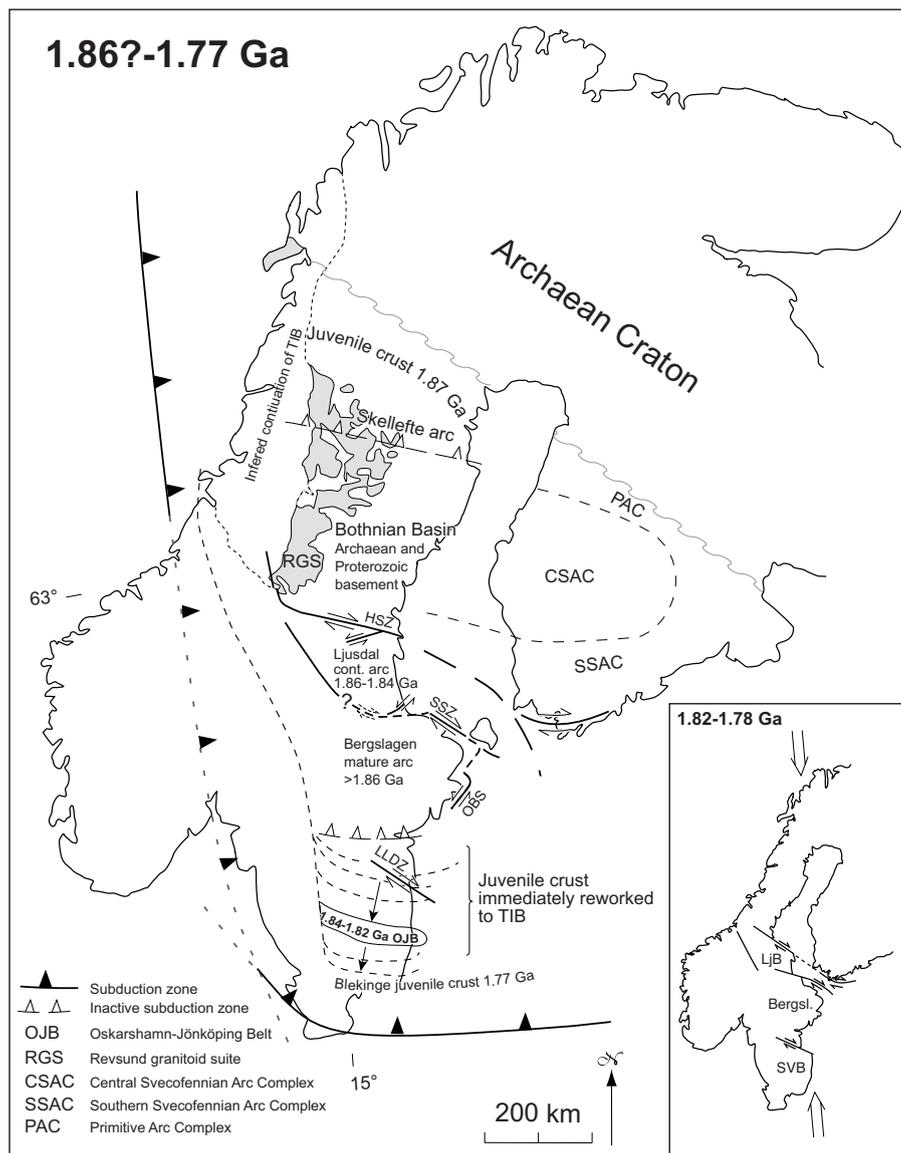


Fig. 72. Sketch showing the proposed palaeotectonic environment during early TIB time (TIB 0-1; c. 1.86-1.77 Ga), characterised by eastward subduction in the north and northward subduction in the south. The coeval shear zone kinematics in southern Sweden is in accordance with c. N-S convergence. Arrows in SE Sweden indicate retreating subduction associated with a southwards progressing continental margin growth and reworking. HSZ = Hassela Shear Zone, SSZ = Singö Shear Zone, OBS = Ornö Band Series Shear Zone and LLDZ = Linköping-Loftahammar Deformation Zone. Inset: LjB = Ljusdal Batholith, Bergsl. = Bergslagen area, SVB = Småland-Värmland Belt.

Svecofennian, juvenile crust, indicating that island-arc accretion continued oceanward from the continental margin, while reworking occurred concurrently further north. Continuous retreat of the continental margin reworking south(south-west)wards resulted in a progressive consumption of the recently accreted crust (Fig. 72).

The marked thinning of the mafic lower crust south of OJB, and particularly in Blekinge, may be partly a post-TIB feature associated with the 'anorogenic' Blekinge-Bornholm magmatism at

c. 1.45 Ga. However, the increase in calcic character of TIB rocks southwards (Gorbatshev 2001), and particularly so in the uplifted block in Blekinge (Lindh et al. 2001a), suggests that an area of juvenile crust-production is encountered here by c. 1.77 Ga. Strong NE-dipping crustal reflectors in the Blekinge-Bornholm block (BABEL working group 1993, Abramovitz et al. 1997) may represent remnants of accreted subduction structures (cf. Korja & Heikkinen 2000), most likely later reactivated as normal faults in

association with the Blekinge-Bornholm magmatism. However, Abramovitz et al. (1997) suggest that the lower crustal sections below southern TIB and the Blekinge-Bornholm Province consists of a triangular area, “the intermediate terrane”, of suppressed early Svecofennian crust, overthrust from the south by c. 1.70–1.58 Ga Gothian crust. The presence of this intermediate terrane was questioned by Lund et al. (2001).

The increased thickness of felsic upper crust and thinning of the mafic lower crust in northern Bergslagen suggest that this is a crustal block that moved down relative to the adjoining areas to the south and north. This is supported by lower T and, in particular, lower P of the metamorphism in this block (Stålhös 1991, Sjöström & Bergman 1994, Ripa 1994, U.B. Andersson unpubl. data), but questioned by the kinematics of the conjugate Singö and Ornö band series shear zones (Persson 2002, and ref. therein). However, in the north the metamorphic break follows a major E-W shear zone (cf. Kresten & Aaro 1987) (cf. Fig. 3), of still unknown kinematics.

Beneath the Ljusdal Batholith the mafic lower crust thickens considerably again, presumably as a result of a major episode of mafic underplating, syn- to post-batholith emplacement in age, causing high-grade metamorphism in many areas (Sjöström & Bergman 1998, and ref. therein). Based on existing geochemical data (including isotopes), the Ljusdal Batholith appears to consist of dominantly calc-alkaline components (cf. Chapter 7.1). This suggests that relatively juvenile arc crust was still forming by 1.84 Ga somewhere in between the (proto)continents (or microcontinents of Nironen et al. 2002) of the early Svecofennian Bergslagen area in the south and the Bothnian Basin in the north, the latter underlain partly by Archaean basement (Andersson et al. 2002). Whether it formed in situ or was transported to its present position shortly after formation from a previous position further east, as is indicated by shear zone kinematics (Sjöström & Bergman 1998), is not known.

Further north in the Bothnian Basin regional metamorphic reworking of the Svecofennian crust is bracketed between the youngest affected supracrustals and oldest unaffected late Svecofennian granites (c. 1865–1820 Ma; Kousa

& Lundqvist 2000, Weihed et al. 2002). However, crustal reworking in this region continued with the formation of late Svecofennian anatectic, mostly S-type granites (1.82–1.80 Ga Härnö/Skellefte type) and the voluminous, more deeply derived, I- to A-type, TIB-1 Revsund granitoid magmatism (RGS) (1.81–1.77 Ga) (Claesson & Lundqvist 1995, Chapter 7.2), where at least the RGS is associated with significant contact metamorphism (c.f. Lundqvist et al. 1990). The RGS is essentially elongated N-S and associated TIB-1 rocks continue northwards as basement rocks of the Caledonides up to the Lofoten area of northern Norway (Romer et al. 1992, Corfu 2000, Skår 2002, Rehnström 2003, and ref. therein). This N-S trend is oblique to Svecofennian lithologies, and appear to be related to N-S oriented shear zones active c. 1.8 Ga and associated with E-W compression in the area of the Skellefte district (Bergman Weihed 2001, Weihed et al. 2002). Weihed et al. (2002) proposed an Andino-type continental-margin setting with E-directed subduction for the RGS and related rocks, including the anatectic S-type suites, in central Sweden and Norway. Moreover, this subduction scenario could then also apply to the generation of the coeval intrusive rocks inland further to the northeast transgressing across and into the Archaean craton nucleus, e.g. the roughly 1.8 Ga Lina and Edefors suites and corresponding rocks in Finland (cf. Chapter 7.2). However, little is yet known about the tectonic regimes in these areas, as well as the nature of the transition from N-S to E-W compression across the Bothnian Basin.

The coeval (1.81–1.77 Ga), partly bimodal, ‘post-collisional’ intrusive complexes stretching from SW Finland to Russian Karelia (Eklund et al. 1998, Konopelko et al. 1998, Rutanen 2001), appear to represent increasingly continent-ward magmatic expressions related to the overall tectonic regime associated with the TIB in the west, and where the mafic magmatism shows evidence of strongly increasing mantle enrichment character eastwards towards the Archaean craton margin (Eklund et al, in prep).

At c. 1.71 Ga (TIB-2), extensive igneous activity commenced in the central provinces of TIB (Dala and Rätan, Chapters 3 and 4, Lundqvist & Persson 1999). This magmatism tends to be more

alkaline in character than the earlier TIB generations (e.g. Ahl et al. 1999), but is associated with calc-alkaline subduction-related mafic rocks (Nyström 1999). The graben and horst environment represented by the large volumes of well-preserved supracrustal rocks in the Dala Province, and the lack of such rocks in the Rätan Batholith, may be the result of post-TIB block movements. However, the more alkaline character of these rocks argues for an extensional setting already at the time of magmatism, possibly in an overall dextral transpressional regime which caused a NW-SE extensional environment for the Dala and Rätan Provinces (Fig. 73) as indicated by the kinematics in the coeval Storsjön-Edsbyn Deformation Zone (Bergman & Sjöström 1994,

Bergman et al. *subm.*). The increased alkalinity and occurrence of some of c. 1.8 Ga zircons imply that the TIB-2 rocks, at least some of the c. 1.7 Ga Dala granites, may in part represent a reworking of the earlier TIB-1 crust (Ahl et al. 1999, Chapter 3.2). The very large positive aeromagnetic and gravity anomalies associated with the Dala Province, and in particular the Rätan Batholith (cf. Korhonen et al. 2002a,b), suggest that these areas are underlain by large volumes of mafic-intermediate rocks, possibly representing the heat source for the crustal magmatism by mafic underplating.

West of the Dala Province, and to the south along the western margin of the TIB-1 magmatism (1.81–1.76 Ga), 1.71–1.65 Ga alkali-rich granitoids of TIB-2 and 3 generations were

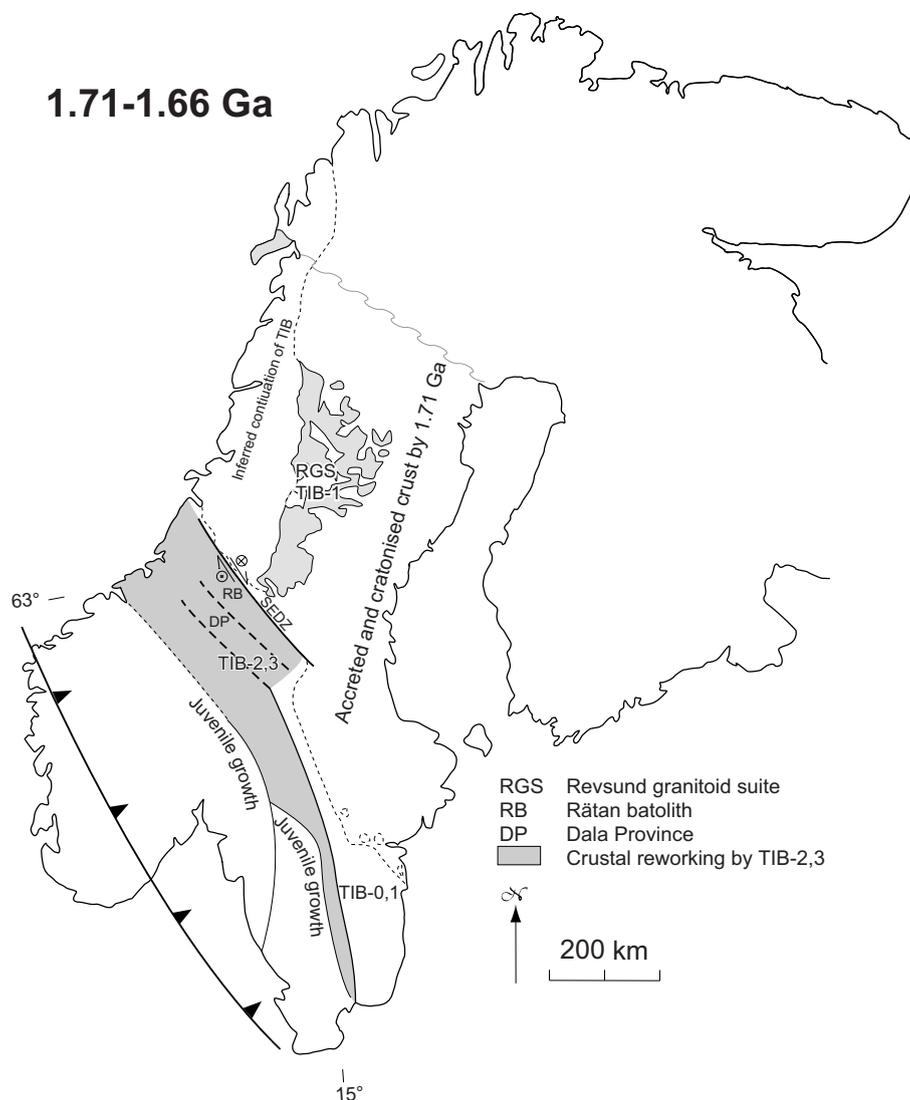


Fig. 73. Sketch showing the proposed palaeotectonic setting during late TIB time (TIB 2–3; c. 1.71–1.66 Ga), characterised by northeastward subduction, complete reworking of the earlier crust in the shaded areas, and juvenile growth further southwest. SEDZ = Storsjön Edsbyn Deformation Zone, which was active by dextral transpression during this stage.

emplaced (cf. Koistinen et al. 2001). In Värmland, this magmatism seems to cover the whole area up to the Mylonite Zone in the west (Lindh & Gorbatshev 1984, Lindh & Persson 1990, Söderlund et al. 1999), while south of Lake Vänern a westward transition into more calc-alkaline rocks is recorded (Gorbatshev 1980, Berglund & Larson 1997, Gorbatshev & Bogdanova 2003). The latter represents a transition from TIB into juvenile 'Gothian' arc-related crust-forming rocks overlapping in time (cf. Åhäll & Larson 2000). In contrast, the alkali-rich TIB-2 and 3 rocks represent reworking of earlier rocks in a continental margin setting, where the precursors were probably both calc-alkaline and alkali-calcic.

Synthesis of tectonomagmatic models: The distribution of lithologies and ages among TIB-assigned rocks mark a shift from the last calc-alkaline arc-related crust formation (1.86–1.84 in central Sweden, and 1.84–1.82 Ga in southern Sweden) to partly coeval and successively younger (1.85–1.65 Ga) remelting of the crust. Massive mafic underplating in a convergent continental-margin setting caused remelting of this juvenile crust and produced the alkali-calcic, I- (to A-) type, crustal magmas of the TIB (1 to 3). The coeval development of minor metaluminous and late Svecofennian intrusions within the Svecofennian interior represents areas of comparatively (to TIB) less extensive underplating and accompanying heat flow. A similar development of subduction-related metaluminous (I-type) and peraluminous (S-type) granitoids within the continental interior of western North America, east of the coeval to somewhat older, more juvenile, Cordilleran batholiths was described by Miller & Barton (1990). Both types of the Jurassic to Tertiary interior plutonic suites are, like TIB, crustally derived, but from much older, Proterozoic crust. In agreement with the model presented here for TIB development, Karlstrom et al. (2001) concluded that long-lived continental-margin subduction of Andean type best explains the 1.8–1.0 Ga magmatism along the southern margin of Laurentia-Baltica.

During 1.86–1.83 Ga northwards (to north-northeast) convergence was probably dominant, resulting in the earliest reworking and magma formation along the early Svecofennian margin

of south Bergslagen (TIB-0). Whether the simultaneous formation of the calc-alkaline Ljusdal Batholith further north was the result of a separate subduction in this area is unclear, although seismic data suggests remnants of south-dipping (Guggisberg et al. 1991), or north-dipping (Heikkinen & Luosto 2000) slabs. During 1.81–1.76 Ga roughly N-S convergence continued and produced TIB-1 magmatism with a general younging of SVB-rocks (and protoliths) southwards, from southern Bergslagen to Blekinge. In the south the geochemistry of the TIB-crust changes in character to more calc-alkaline and juvenile (Lund et al. 2001). The retreating, northward subduction thus created new, juvenile, calc-alkaline crust just prior to its reworking and consumption while forming TIB-1 in SE Sweden. The general tectonic regime was dextral tranpressional, as recorded by several major plastic, 1.82–1.78 Ga, shear zones within the Svecofennian rocks, from the 1.86–1.82 Ga marginal TIB-0 and coeval rocks in the south to at least the Hassela Shear Zone in the north (e.g. Högdahl & Sjöström 2001, Högdahl et al. 2001b, Beunk & Page 2001). Partly, the early stages of this deformation may have been accommodated by magmatic flow in the TIB (or coeval) intrusions.

However, between 1.81–1.76 Ga, east-directed subduction appears to have been active in the north to generate the northward continuation of TIB-1 rocks, particularly the extensive RGS and the TIB continuation below the Caledonides to northwestern Norway (cf. e.g. Gaál 1990, Nironen 1997, Weihed et al. 2002, Skår 2002). The northern TIB rocks represent a similar, mainly alkali-calcic reworking of early Svecofennian crust as is recorded for the SVB further south. These simultaneously active subduction directions may represent two intersecting plates (Fig. 72), as in the areas of present subduction in southeastern Asia (cf. e.g. Hall et al. 1995, Lee & Lawver 1995, Milsom 2001).

At c. 1.76 Ga the northwards convergence was inactivated and during 1.76–1.71 Ga little magmatic activity is recorded. After c. 1.71 Ga the continental margin subduction shifted and resumed with a direction essentially northeastwards, causing renewed crustal reworking and alkali-

rich TIB activity (TIB-2 and 3) along the western margin of TIB-1. Further north, the dextral transpressive shearing resulting in NW-SE extension enhanced the voluminous, alkaline TIB-2 magmatism in the Dala-Rätan Provinces (Bergman et al. *subm.*). The end of TIB

magmatism is marked by the transition to more juvenile, 1.70–1.65 Ga, calc-alkaline rocks further to the west, in the southern part of the Eastern Segment of the Southwest Scandinavian Domain.

9. REFERENCES

- Åberg, G. 1978.** Precambrian geochronology of south-eastern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 100, 125–154.
- Åberg, G. & Bjurstedt, S. 1986.** Radiometric dating of the serotogenic Svecofennian Enkullen and Fjällberg granites, south central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 108, 73–77.
- Åberg, G. & Bollmark, B. 1985.** Retention of U and Pb in zircons from shocked granite in the Siljan impact structure, Sweden. *Earth and Planetary Science Letters* 74, 347–349.
- Åberg, G. & Wikström, A. 1982.** Radiometric dating of the postorogenic Graversfors granite, south central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 104, 225–230.
- Åberg, G. & Wikström, A. 1985.** Radiometric dating of the Finspång augen gneiss, south central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 107, 7–10.
- Abramovitz, T., Berthelsen, A. & Thybo, H. 1997.** Proterozoic sutures and terranes in the southeastern Baltic shield interpreted from BABEL deep seismic data. *Tectonophysics* 270, 259–277.
- Abramovitz, T., Thybo, H. & Perchuc, E. 2002.** Tomographic inversion of seismic P- and S-wave velocities from the Baltic shield based on FENNOLORA data. *Tectonophysics* 358, 151–174.
- Åhäll, K.-I. & Gower, C.F. 1997.** The Gothian and Labradorian orogens: variations in accretionary tectonism along a late Paleoproterozoic Laurentia-Baltica margin. *GFF* 119, 181–191.
- Åhäll, K.-I. & Larson, S.Å. 2000.** Growth-related 1.85–1.55 Ga magmatism in the Baltic shield; a review addressing the tectonic characteristics of Svecofennian, TIB 1-related, and Gothian events. *GFF* 122, 193–206.
- Åhäll, K.-I. & Larson, S.Å. 2001.** Growth-related 1.85–1.55 Ga magmatism in the Baltic shield; a review addressing the tectonic characteristics of Svecofennian, TIB 1-related, and Gothian events – A reply. *GFF* 123, 59–61.
- Åhäll, K.-I., Connelly, J.N. & Brewer, T.S. 2002.** Transitioning from Svecofennian to Transscandinavian Igneous Belt (TIB) magmatism in SE Sweden: implications from the 1.82 Eksjö tonalite. *GFF* 124, 217–224.
- Ahl, M. 1989.** Zn-Pb-Cu-mineraliseringarna vid Ramnebo, sydöstra Sverige, och deras genetiska relation till Smålandsgraniten. Unpublished master's thesis, Stockholm university. 25 p.
- Ahl, M. & Sundblad, K. 1994.** Geology and geochemistry of the Råtan batholith, central Sweden. Program and abstracts. Joint meeting IGCP # 290 ad #315, Mc Gills University, Montreal, Canada, p. 1.
- Ahl, M., Andersson, U.B., Lundqvist, T. & Sundblad, K. (eds.), 1997.** Rapakivi granites and related rocks in central Sweden. *Sveriges Geologiska Undersökning C* 87. 99 p.
- Ahl, M., Sundblad, K. & Schöberg, H. 1999.** Geology, geochemistry, age and geotectonic evolution of the Dala granitoids, central Sweden. *Precambrian Research* 95, 147–166.
- Ahl, M., Bergman, S., Bergström, U., Eliasson, T., Ripa, M. & Weihed, P. 2001.** Geochemical classification of plutonic rocks in central and northern Sweden. *Sveriges Geologiska Undersökning, Rapporter och meddelanden* 106. 82 p.
- Allen, R.L., Lundström, I., Ripa, M., Simeonov, A. & Christofferson, H. 1996.** Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. *Economic Geology* 91, 979–1008.
- Andersson, J. 2001.** Sveconorwegian orogenesis in the southwestern Baltic Shield. Zircon geochronology and tectonothermal setting of orthogneisses in SW Sweden. Lund University. 28 p. (dissertation)
- Andersson, U.B. 1989.** Evidence of plutonic magma-mixing, southern Sweden. *Rendiconti della Società Italiana di Mineralogia e Petrologia* 43, 831–839.
- Andersson, U.B. 1991.** Granitoid episodes and mafic-felsic magma interaction in the Svecofennian of the Fennoscandian shield, with main emphasis on the ~1.8 Ga plutonics. *Precambrian Research* 51, 127–149.
- Andersson, U.B. 1997a.** Petrogenesis of some Proterozoic granitoid suites and associated basic rocks in Sweden (geochemistry and isotope geology). *Sveriges Geologiska Undersökning, Rapporter och meddelanden* 91. 216 p.
- Andersson, U.B. 1997b.** The late Svecofennian, high-grade contact and regional metamorphism in southwestern Bergslagen (central southern Sweden). *Sveriges Geologiska Undersökning, project 03-819/93, Final report* 970519. 36 p.
- Andersson, U.B. 1997c.** The sub-Jotnian Strömsbro granite complex at Gävle, Sweden. *GFF* 119, 157–165.
- Andersson, U.B. 1997d.** An overview of the Fennoscandian rapakivi granite complexes, with emphasis on the Swedish occurrences. In: Ahl, M., Andersson, U.B., Lundqvist, Th. & Sundblad, K. (eds.) *Rapakivi granites and related rocks in central Sweden. Sveriges Geologiska Undersökning C* 87, 33–49.
- Andersson, U.B. & Eklund, O. 1994.** Cellular plagioclase intergrowths as a result of crystal-magma mixing in the Proterozoic Åland rapakivi batholith, SW Finland. *Contributions to Mineralogy and Petrology* 117, 124–136.
- Andersson, U.B. & Harlov, D.E. 2001.** Charnockite patches

- in a granite from central southern Sweden: a case of prograde charnockitization followed by rehydration to granite. European Union of Geosciences, Strasbourg, France, Journal of Conference Abstract 6, p. 564.
- Andersson, U.B. & Wikström, A. 2001.** Growth-related 1.85–1.55 Ga magmatism in the Baltic shield; a review addressing the tectonic characteristics of Svecofennian, TIB 1-related, and Gothian events – A discussion. *GFF* 123, 55–58.
- Andersson, U.B., Larsson, L. & Wikström, A. 1992.** Charnockites, pyroxene granulites and garnet-cordierite gneisses at a boundary between Early Svecofennian rocks and Småland-Värmland granitoids, Karlskoga, southern Sweden. *GFF* 114, 1–15.
- Andersson, U.B., Högdahl, K., Sjöström, H. & Bergman, S. 2000.** Geochronologic constraints on metamorphic, intrusive and detrital ages of rocks from the Bergslagen area, southern Sweden. Sveriges Geologiska Undersökning, report, July 2000, contract nr 03-1025/97. 12 p. + figures.
- Andersson, U.B., Neymark, L. & Billström, K. 2002.** Petrogenesis of Mesoproterozoic (Subjotnian) rapakivi complexes of central Sweden: implications from U-Pb zircon ages, Nd, Sr, and Pb isotopes. *Transactions of the Royal Society of Edinburgh, Earth Sciences* 92, 201–228.
- Andersson, U.B., Högdahl, K., Sjöström, H. & Bergman, S. 2004.** Magmatic, detrital, and metamorphic ages in metamorphic rocks from south-central Sweden. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. *GFF* 126, 16–17.
- Andresen, A. 1980.** The age of Precambrian basement in western Troms, Norway. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 291–298.
- Annertz, K. 1984.** En petrografisk karakteristik av en sent postorogen mafisk intrusion i östra Värmland. Unpublished masters thesis, Lund University. 21 p.
- Armands, G., & Drake K.-M. 1978.** Litho-geochemical ore exploration, with particular reference to tin, tungsten and molybdenum in Swedish granitoids. STU (Styrelsen för Teknisk Utveckling), Stockholm, Report 77-41–70.
- Armands, G. & Xeferis, A. 1987.** Swedish granitoids of S- and I-type and their lithophile element distribution. *Geologiska Föreningens i Stockholm Förhandlingar* 109, 177–195.
- Asklund, B. 1923.** Berggrunden. In: Asklund, B. & Sandegren, R. *Beskrivning till kartbladet Torönsborg*. Sveriges Geologiska Undersökning Aa 153, 11–45.
- Asklund, B. 1925.** Petrological studies in the neighbourhood of Stavsjö at Kolmården. Granites and associated basic rocks of the Stavsjö area. Sveriges Geologiska Undersökning C 325. 122 p.
- Asklund, B. 1928.** Berggrunden. In: Asklund, B., Ekström, G. & Assarsson, G. *Beskrivning till kartbladet Gusum*. Sveriges Geologiska Undersökning Aa 159, 13–57.
- BABEL Working Group, 1993.** Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. *Geophysical Journal International* 112, 325–343.
- Baker, J.H. 1985.** The petrology and geochemistry of 1.8–1.9 Ga granitic magmatism and related sub-seafloor hydrothermal alteration and ore-forming processes, W. Bergslagen, Sweden. University of Amsterdam, GUA Papers of Geology, Series I, (21). 224 p. (dissertation)
- Baker, J.H., Hellinwerf, R.H. & Oen, I.S. 1988.** Structure, stratigraphy and ore-forming processes in Bergslagen: implications for the development of the Svecofennian of the Baltic Shield. *Geologie en Mijnbouw* 67, 121–138.
- Barbarin, B. 1990.** Granitoids: main petrogenetic classifications in relation to origin and tectonic setting. *Geological Journal* 25, 227–238.
- Berglund, J. & Larson, S.-Å. 1997.** Granitoids across the Gothian front, SW Sweden; age and characteristics. In: Berglund, J. *MidProterozoic evolution in south-western Sweden*. Gothenburg University, 1–21. (dissertation)
- Bergman Weihed, J. 2001.** Palaeoproterozoic deformation zones in the Skellefte and Arvidsjaur areas, northern Sweden. In: Weihed, P. (ed.) *Economic geology research 1, 1999–2000*. Sveriges Geologiska Undersökning C 833, 46–68.
- Bergman, S. & Sjöström, H. 1994.** The Storsjön-Edsbyn Deformation Zone, central Sweden. Research Report, Sveriges Geologiska Undersökning. 46 p.
- Bergman, S., Kübler, L. & Martinsson, O. 2001.** Description of regional geological and geophysical maps of northern Norrbotten county (east of the Caledonian orogen). Sveriges Geologiska Undersökning Ba 56. 110 p.
- Bergman, S., Persson, P.-O. & Kubler, L. 2002.** U-Pb titanite and zircon ages of the Lina granite at the type locality NW of Gällivare, northern Sweden. In: Bergman, S. (ed.) *Radiometric dating results*. Sveriges Geologiska Undersökning C 834, 12–17.
- Bergman, S., Sjöström, H. & Högdahl, K.** Palaeoproterozoic transpressive shear and arc magmatism: the Storsjön-Edsbyn deformation zone, central Sweden. *Tectonics* (submitted).
- Bergman, T., Schöberg, H. & Sundblad, K. 1995.** Geochemistry, age and origin of the Högberget granite, western Bergslagen, Sweden. *GFF* 117, 87–95.
- Bergström, U. & Sträng, T. 1999.** Berggrundskartorna 23I Malå. Sveriges Geologiska Undersökning Ai 114–117.
- Bergström, U. & Triumpf, C.-A. 2002.** Berggrundskartorna 24I Storavan. Sveriges Geologiska Undersökning Ai 156–159
- Bergström, U., Juhojuntti, N., Kero, L., Lundqvist, L., Stephens, M.B., Sukotjo, S., Wik, N.G. & Wikman, H. 2002.** Projekt Småland, regional berg. In: Delin, H. (ed.) *Regional berggrundsgeologisk underökning*. Sammanfattning av pågående undersökningar 2001. Sveriges Geologiska Undersökning, Rapporter och meddelanden 110, 65–83.
- Berthelsen, A. 1980.** Towards a palinspastic tectonic analysis of the Baltic Shield. In: Cogné, J. & Slansky, M. (eds.) *Geology of Europe from Precambrian to Post-Hercynian Sedimentary Basins*. International Geological Congress Colloquim C6, Paris 1980, 5–21.
- Berthelsen, A. 1987.** A tectonic model for the crustal evolution of the Baltic shield. In: Schaer, J.-P. & Rogers, J. (eds.) *The anatomy of mountain ranges*, Princeton University Press, Princeton, 31–57.
- Beunk, F.F. & Page, L.M. 2001.** The structural evolution of a deeply eroded, accretional continental margin in the Palaeoproterozoic Svecofennian orogen in southern Sweden. *Tectonophysics* 339, 67–92.
- Beunk, F.F., Page, L.M., Wijbrans, J.R. & Barling, J. 1996.** Deformational, metamorphic and geochronological constraints from the Loftahammar-Linköping Deformational Zone (LLDZ) in SE Sweden: implications for the development of the Svecofennian Orogen. *GFF* 118 Jubilee Issue, p. A 9.
- Billström, K. & Öhlander, B. 1989.** U-Pb zircon age of the Rostberget W-occurrence, northern Sweden. *Geologiska Föreningens i Stockholms Förhandlingar* 111, 121–126.
- Billström, K. & Weihed, P. 1996.** Age and provenance of host rocks and ores in the Paleoproterozoic Skellefte district, northern Sweden. *Economic Geology* 91, 1054–1072.
- Billström, K., Åberg, G. & Öhlander, B. 1988.** Isotopic and

- geochemical data on the Pintstaber Mo-bearing granite in Bergslagen, south central Sweden. *Geologie en Mijnbouw* 67, 255–263.
- Björk, L. 1986.** Beskrivning till berggrundskartan Filipstad NV. Sveriges Geologiska Undersökning Af 147. 110 p.
- Björklund, L. & Claesson S. 1992.** Geochemical character and preliminary Sm-Nd data on basic metavolcanic rocks in the Tiveden area, south Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 114, 340–341.
- Blomberg, A. 1895.** Praktiska geologiska undersökningar inom Gefleborgs Län. Sveriges Geologiska Undersökning C 152. 209 p.
- Blomberg, A. 1909.** Beskrifning till kartbladet Linköping. Sveriges Geologiska Undersökning Aa 141. 43 p.
- Bogdanova, S.V., Gorbatshev, R. & Stephenson, R.A. 2001.** EUROBRIDGE: Palaeoproterozoic accretion of Fennoscandia and Sarmatia. *Tectonophysics* 339, VII–X.
- Borghi, A., Castelli, D., Lombardo, B. & Visonà, D. 2003.** Thermal and baric evolution of garnet granulites from the Kharta region of S Tibet, E Himalaya. *European Journal of Mineralogy* 15, 401–418.
- Brown, M. & Solar, G.S. 1998a.** Shear-zone systems and melts: feedback relations and self-organization in orogenic belts. *Journal of Structural Geology* 20, 211–227.
- Brown, M. & Solar, G.S. 1998b.** Granite ascent and emplacement during contractional deformation in convergent orogens. *Journal of Structural Geology* 20, 1365–1393.
- Bylund, G. & Patchett, P.J. 1977.** Paleomagnetic and Rb-Sr isotope evidence for the age of the Särna alkaline complex, western central Sweden. *Lithos* 10, 73–79.
- Cabanis, B. & Lecolle, M. 1989.** Le diagramme La/10–Y/15–Nb/8: un outil pour la discrimination des series volcaniques et la mise en evidence des processus de melange et/ou de contamination crustale. *Comptes Rendus Academie de Sciences, Paris, Series II*, 309, 2023–2029.
- Chappell, B.W. 1996.** Magma mixing and the production of compositional variation within granite suites: evidence from the granites of southeastern Australia. *Journal of Petrology* 37, 449–470.
- Chappell, B.W., White, A.J.R. & Wyborn, D. 1987.** The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* 28, 1111–1138.
- Chemenda, A.I., Burg, J.-P. & Mattauer, M. 2000.** Evolutionary model of the Himalaya-Tibet system: geopoem based on new modelling. *Earth and Planetary Science Letters* 174, 397–409.
- Chemenda, A.I., Yang, R.-K., Stephan, J.-F., Konstantinovskaya, E.A. & Ivanov, G.M. 2001.** New results from physical modelling of arc-continent collision in Taiwan: evolutionary model. *Tectonophysics* 333, 159–178.
- Claesson, D.T. 1998.** Coronas, reaction rims, symplectites and emplacement depth of the Rymmen gabbro, Transscandinavian Igneous Belt, southern Sweden. *Mineralogical Magazine* 62, 743–757.
- Claesson, D.T. 1999.** Geochronology of the Rymmen gabbro, southern Sweden; implications for primary versus inherited zircon in mafic rocks and rheomorphic dykes. *GFF* 121, 25–31.
- Claesson, D.T. 2001.** Investigation of gabbroic rocks associated with the Småland-Värmland granitoid batholith of the Transscandinavian Igneous Belt. Gothenburg University, XI p. (dissertation)
- Claesson, D.T. 2002.** Stability of REE-bearing minerals in a metaluminous leucotonalite from the Eriksberg gabbro, Transscandinavian Igneous Belt, Sweden. *Neues Jahrbuch für Mineralogie Abhandlungen* 177, 277–291.
- Claesson, D.T. & Andersson, U.B. 2000.** The 1.85 Ga Nygård pluton, central southern Sweden: an example of early Transscandinavian igneous belt (TIB) noritic magmatism. 24:e Nordiska Geologiska Vintermöte, Trondheim 6–9.1. 2000. *Geonytt Nr 1*, p. 50.
- Claesson, D.T. & Meurer, W.P. 2002.** An occurrence of igneous orthorhombic amphibole, Eriksberg gabbro, southern Sweden. *American Mineralogist* 87, 699–708.
- Claesson, S. 1987.** Nd isotope data on 1.9–1.2 Ga old basic rocks and metasediments from the Bothnian basin, central Sweden. *Precambrian Research* 35, 115–126.
- Claesson, S. & Lundqvist, Th. 1995.** Origins and ages of Proterozoic granitoids in the Bothnian Basin, central Sweden; isotopic and geochemical constraints. *Lithos* 36, 115–140.
- Claesson, S., Huhma, H., Kinny, P.D. & Williams, I.S., 1993.** Svecofennian detrital zircon ages – for the Precambrian evolution of the Baltic Shield. *Precambrian Research* 64, 109–130.
- Clowes, R.M., Gens-Lenartowicz, E., Demartin, M. & Saxov, S. 1987.** Lithospheric structure in southern Sweden – results from FENNOLOGRA. *Tectonophysics* 142, 1–14.
- Connelly, J.N., Berglund, J. & Larson, S.Å. 1996.** Thermotectonic evolution of the eastern segment of southwestern Sweden: tectonic constraints from U-Pb geochronology. In: Brewer, T.S. (ed.) *Precambrian crustal evolution in the north Atlantic Region*. Geological Society of London, Special Publication 112, 297–313.
- Cordani, U.G., Milani, E.J., Thomaz Filho, A. & Campos, D.A. (eds.) 2000.** Tectonic evolution of South America. Brazil 2000, 31st International Geological Congress, Rio de Janeiro, Brazil, August 6–17 – 2000. 856 p.
- Corfu, F. 2000.** U-Pb zircon geochronology of the Lofoten-Vesterålen AMCG-complex, northern Norway. *Geonytt 1*, p. 53.
- Cruden, A.R. 1998.** On the emplacement of tabular granites. *Journal of the Geological Society, London* 155, 853–862.
- Cruden, A.R., Sjöström, H. & Aaro, S. 1999.** Structure and geophysics of the Gåsborn granite, central Sweden: an example of fracture-fed asymmetric pluton emplacement. In: Castro, A., Fernández, C. & Vigneresse, J.L. (eds.) *Understanding granites: Integrating new and classical techniques*, Geological Society of London, Special Publications 168, 141–160.
- Davies, J.H. & von Blanckenburg, F. 1995.** Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters* 129, 85–102.
- Debon, F. & Le Fort, P., 1983.** A chemical-mineralogical classification of common plutonic rocks and associations. – *Transactions of the Royal Society of Edinburgh, Earth Sciences* 73, 135–149.
- De la Roche, H., LeTerrier, J., Grand Claude, P. & Marchal, M. 1980.** A classification of volcanic and plutonic rocks using R1–R2 diagrams and major element analyses – its relationship with current nomenclature. *Chemical Geology* 29, 183–210.
- Delin, H. 1989a.** Berggrundskartan 16 G Ljusdal NV. Sveriges Geologiska Undersökning Ai 33.
- Delin, H. 1989b.** Berggrundskartan 16 G Ljusdal NO. Sveriges Geologiska Undersökning Ai 34.
- Delin, H. 1993.** The radiometric age of the Ljusdal granodiorite of central Sweden. In: Lundqvist, Th. (ed.) *Radiometric dating results*. Sveriges Geologiska Undersökning C 823, 13–16.
- Delin, H. 1996.** U-Pb zircon ages of granitoids in the Kårböle region, central Sweden. In: Lundqvist, Th. (ed.) *Radiometric dating results 2*. Sveriges Geologiska Undersökning C 828, 6–14,

- Delin, H. & Aaro, S. 1992.** Berggrundskartorna 16 F Kårböle. Sveriges Geologiska Undersökning Ai, 56–59.
- Delin, H. & Aaro, S. 2000.** Kartbladen 17F Ånge NV, NO. Sveriges Geologiska Undersökning, Rapporter och meddelanden 102, 40–50.
- Delin, H. & Persson, P.-O. 1999.** U-Pb zircon ages of three Palaeoproterozoic igneous rocks in the Loos-Hamra area, central Sweden. In: Bergman, S. (ed.) Radiometric dating results 4. Sveriges Geologiska Undersökning C 831, 21–31.
- DePaolo, D.J. 1981.** Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. *Nature* 291, 193–196.
- Déruelle, B. 1991.** Petrology of Quaternary shoshonitic lavas of northwestern Argentina. In: Harmon, R.S. & Rapela, C.W. (eds.) Andean magmatism and its tectonic setting. Geological Society of America, Special Paper 265, 201–216.
- de Silva, S.L. 1991.** Styles of zoning in central Andean ignimbrites; insight into magma chamber processes. In: Harmon, R.S. & Rapela, C.W. (eds.) Andean magmatism and its tectonic setting. Geological Society of America, Special Paper 265, 217–232.
- Dobbe, R.T.M., Oen, I.S. & Verdurmen, E.A.T. 1995.** U-Pb zircon ages of metatuffites and Older Granite from the Tunaberg area, SE Bergslagen, Sweden. *Geologie en Mijnbouw* 74, 129–136.
- Dyrelius, D. 1980.** Aeromagnetic interpretation in a geotransverse area across the central Scandinavian Caledonides. *Geologiska Föreningens i Stockholms Förhandlingar* 102, 421–438.
- Eby, G.N. 1992.** Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* 20, 641–644.
- von Eckermann, H. 1936.** The Loos-Hamra region. *Geologiska Föreningens i Stockholm Förhandlingar* 58, 130–341.
- Ehlers, C. & Skiöld, T. 2001.** SIMS-dating of ductile shearing in SW Finland. European Union of Geosciences, Journal of Conference Abstract 6, Strasbourg, France, p. 624.
- Ehlers, C., Lindroos, A. & Selonen 1993.** The late Svecofennian granite-migmatite zone of southern Finland – a belt of transpressive deformation and granite emplacement. *Precambrian Research* 64, 295–309.
- Eklund, O., Konopelko, D., Rutanen, H., Fröjdö, S. & Shebanov, A.D. 1998.** 1.8 Ga Svecofennian post-collisional shoshonitic magmatism in the Fennoscandian shield. *Lithos* 45, 87–108.
- Eklund, O., Konopelko, Andersson, U.B., Korja, A. & Fröjdö, S. 2000.** 1.8 Ga Svecofennian post-collisional shoshonitic magmatism in the Fennoscandian shield: Evidence of mantle enrichment and detachment of the lithospheric mantle. 24. Nordiske Geologiske Vintermøte, Trondheim 6–9.1. 2000. *Geonytt* 1, p. 61.
- Elbers, F.J. 1971.** Evolution of the Svecofennian orogeny in the northeastern part of the Västervik area, southeastern Sweden, with special reference to deformation, metamorphism and magmatism. Vrije Universiteit, Amsterdam. (dissertation)
- Eliasson, T. & Sträng, T. 1997.** Kartbladen 23H Stensele. In: Wahlgren, C.-H., (ed.) Regional berggrundsgeologisk undersökning. Sammanfattning av pågående undersökningar 1996. Regional bedrock mapping. Summary of ongoing activities 1996 with an introduction in English. Sveriges Geologiska Undersökning, Rapporter och meddelanden 97, 41–46.
- Eriksson, L. & Henkel, H. 1994.** Geofysik. In: Fredén, C. (ed.) Berg och jord, 76–101. Sveriges Nationalatlas. Sveriges Nationalatlas Förlag. 208 p.
- Estifanos, B., Johansson, L., Ståhl, K. & Wroblewski, T. 1998.** A mineralogical and synchrotron X-ray Rietveld study of dark-clouded plagioclase from Bjärnum, southern Sweden. *GFF* 120, 337–340.
- Fredén, C. (ed.) 1994.** Berg och jord. Sveriges Nationalatlas. Sveriges Nationalatlas Förlag. 208 p.
- Fröjdö, S., Andersson, U.B. & Claesson, S. 1996.** Nd isotope geochemistry of some mafic rocks and minerals associated with the Mesoproterozoic Åland and Nordingrå rapakivi batholiths, Fennoscandian shield. International conference on Proterozoic evolution in the North Atlantic realm, Goose Bay, Labrador, 29/7–2/8 1996, Abstracts, 62–63.
- Gaál, G. 1986.** 2200 million years of crustal evolution: the Baltic shield. *Bulletin of the Geological Society of Finland* 58, 149–168.
- Gaál, G. 1990.** Tectonic styles of early Proterozoic ore deposition in the Fennoscandian shield. *Precambrian Research* 46, 83–114.
- Gaál, G. & Gorbatschev, R. 1987.** An outline of the Precambrian evolution of the Baltic shield. *Precambrian Research* 35, 15–52.
- Gapais, D. & Cobbold, P.R. 1987.** Slip system domains. 2. Kinematic aspects of fabric development in polycrystalline aggregates. *Tectonophysics* 138, 289–309.
- Gavelin, A. 1904.** Beskrifning till kartbladet Loftahammar. Sveriges Geologiska Undersökning Aa 127. 91 p.
- Gavelin, A. 1905.** Till frågan om berggrunden på kartbladet Loftahammar. *Geologiska Föreningens i Stockholm Förhandlingar* 27, 190–215.
- Gavelin, A. 1910.** Om relationerna mellan graniterna, grönstenarna och kvartsit-leptitserien inom Loftahammarområdet. Sveriges Geologiska Undersökning C224. 116 p.
- Gavelin, S. 1984.** The Västervik area in southeastern Sweden. Studies in Proterozoic sedimentation, high-grade metamorphism and granitization. Sveriges Geologiska Undersökning Ba 32. 172 p.
- Gavelin, S. & Kulling, O. 1955.** Beskrivning till berggrundskarta över Västerbottens län. Sveriges Geologiska Undersökning Ca 37. 296 p.
- Gill, J. 1981.** Orogenic Andesites and Plate Tectonics. New York: Springer-Verlag. 390 p.
- Gorbatschev, R. 1971.** Age relations and rocks of the Svecofennian-Gothian boundary, Linköping, south central Sweden. Sveriges Geologiska Undersökning C 664. 62 p.
- Gorbatschev, R. 1972.** The X-ray obliquity of potassic feldspar in the granites of Jämtland, northern central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 94, 213–228.
- Gorbatschev, R. 1975.** Beskrivning till berggrundskartan Linköping SO. Sveriges Geologiska Undersökning Af 113. 76 p.
- Gorbatschev, R. 1980.** The Precambrian development of southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 102, 129–136.
- Gorbatschev, R. 1985.** Precambrian basement of the Scandinavian Caledonides. In: Gee, D.G. & Sturt, B.A. (eds.) The Caledonide orogen – Scandinavia and related areas. New York: J. Wiley, 197–212.
- Gorbatschev, R. 1987.** Chemistry and geotectonic position of Proterozoic granites in the Baltic Shield. Abstracts of the Lund Meeting of IGCP-217 “Proterozoic Geochemistry”, June 3–6, 1987. Lund University, Department of Geology, 37–38.
- Gorbatschev, R. 1997.** Den prekambiska berggrunden i Jämtlands län – Bergartsbeskrivningar – Översikter och sammanfattningar – Summary: An outline of Precambrian geology in the County of Jämtland. Sveriges Geologiska

- Undersökning Ca 53:1, 18–174.
- Gorbatshev, R. 2001.** Rock complexes, timing and geodynamic significance of TIB magmatism: new experience from southern Sweden. In: Högdahl, K., Andersson, U.B. & Eklund, O. (eds.) TIB-2001. Workshop about and excursion to the Transscandinavian Igneous Belt. Geocenter informerar (Turku), Report nr. 18, 4–5.
- Gorbatshev, R. & Bogdanova, S. 1993.** Frontiers in the Baltic Shield. *Precambrian Research* 64, 3–21.
- Gorbatshev, R. & Bogdanova, S. 2003.** The boundary zone between SW- and SE-Sweden south of lake Vättern: new insight and implications for applied geology. *Sveriges Geologiska Undersökning – rapport 2003:4*, 30–31.
- Gorbatshev, R., Fromm, E. & Kjellström, G. 1976.** Beskrivning till berggrundskartan Linköping NO. *Sveriges Geologiska Undersökning Af 107*. 111 p.
- Gorbatshev, R., Solyom, Z. & Johansson, I. 1979.** The Central Scandinavian Dolerite Group in Jämtland, central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 177–190.
- Greenberg, J.K. 1990.** Anorogenic granite associations as products of progressive continental evolution. In: Gower, C.F., Ryan, A.B. & Rivers, T. (eds.) *Mid-Proterozoic Laurentia-Baltic*. Geological Association of Canada, Special Paper 38, 447–457.
- Griffin, W.L., Taylor, P.N., Hakkinen, J.W., Heier, K.S., Iden, I.K., Krogh, E.J., Malm, O., Olesen, K.I., Ormaasen, D.E. & Tveten, E. 1978.** Archaean and Proterozoic evolution in Lofoten-Vesterålen, N Norway. *Journal of the Geological Society of London* 135, 629–647.
- Guggisberg, B. & Berthelsen, A. 1987.** A two-dimensional velocity model for the lithosphere beneath the Baltic shield and its possible tectonic significance. *Terra Cognita* 7, 631–638.
- Guggisberg, B., Kaminski, W. & Prodehl, C. 1991.** Crustal structure of the Fennoscandian shield: a travelttime interpretation of the long-range FENNOLORA seismic refraction profile. *Tectonophysics* 195, 105–137.
- Gyllencreutz, R. & Sundblad, K. 1999.** Geophysical character of the Precambrian basement underneath Gotland, Baltic Sea region. *European Union of Geosciences, Journal of Conference Abstracts* 4, Strasbourg, France, p. 132.
- Hall, R., Ali, J.R., Anderson, C.D. & Baker S.J. 1995.** Origin and motion history of the Philippine Sea plate. *Tectonophysics* 251, 229–250.
- Hedström, 1908.** Om Sveriges naturliga byggnads- och ornamentstenar jämte förteckning öfver viktigaste svenska stenindustriidkande firmorna. *Sveriges Geologiska Undersökning C 209*. 64 p.
- Hegardt, A.E. 2000.** A Sveconorwegian crustal subduction and exhumation model for the Eastern Segment, southwestern Sweden. Unpublished masters thesis, Earth Sciences Centre, Gothenburg University, Publication B220. 38 p.
- Heikkinen, P. & Luosto, U. 2000.** Review of some features of the seismic velocity models in Finland. *Lithosphere 2000*, Institute of Seismology, University of Helsinki, Report S-41, 35–41.
- Heim, M., Skiöld, T. & Wolff, F.C. 1996.** Geology, geochemistry and age of the “Tricolor” granite and some other proterozoic (TIB) granitoids at Trysil, southeast Norway. *Norsk Geologisk Tidsskrift* 76, 45–54.
- Henkel, H., Lee, M.K., Lund, C.-E. & Rasmussen, T. 1990.** An integrated geophysical interpretation of the 2000 km Fennolora section of the Baltic Shield. In: Freeman, R., Giese, P. & Mueller, St. (eds.) *The European Geotraverse: integrative studies*. European Science Foundation, Strasbourg, 1–47.
- Hibbard, M.J. 1995.** *Petrography to petrogenesis*. Englewood Cliffs, NJ: Prentice-Hall. 587 p.
- Hietanen, A. 1975.** Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian of Finland. *Journal of Research of the U.S. Geological Survey* 3 (6), 631–645.
- Hjelmqvist, S. 1966.** Beskrivning till berggrundskarta över Kopparbergs län. Summary: Description to map of the Kopparberg County, Central Sweden. With map to the scale of 1:200 000. *Sveriges Geologiska Undersökning Ca 40*. 217 p.
- Högbom, A.G. 1894.** *Geologisk beskrifning öfver Jemtlands län*. Sveriges Geologiska Undersökning C 140. 107 p.
- Högdahl, K. 2000a.** 1.86–1.85 Ga intrusive ages of K-feldspar megacryst-bearing granites in the type area of the Revsund granite in Jämtland County, central Sweden. *GFF* 122, 359–366.
- Högdahl, K. 2000b.** Late-orogenic, ductile shear zones and protolith ages in the Svecofennian Domain, central Sweden. *Meddelanden från Stockholms Universitets Institution för Geologi och geokemi* 309. 21 p. (dissertation)
- Högdahl, K. & Jonsson, E. 2004.** U-Pb geochronology of Hyttjö granites in the Långban-Nordmark ore district, western Bergslagen. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. *GFF* 126, 23–24.
- Högdahl, K. & Sjöström, H. 1999.** Timing and kinematics of Paleoproterozoic shear zones in central Sweden. *European Union of Geosciences, Strasbourg, France, Journal of Conference Abstract* 4, p. 828.
- Högdahl, K. & Sjöström, H. 2000.** Timing of emplacement and shearing of a post-orogenic Revsund (?) granitoid in central Jämtland, Sweden. 24. *Nordiske Geologiske Vintermøte, Trondheim 6–9.1. 2000*. *Geonytt* 1, p. 88.
- Högdahl, K. & Sjöström, H. 2001.** Evidence for 1.82 Ga transpressive shearing in a 1.85 Ga granitoid in central Sweden: implications for the regional evolution. *Precambrian Research* 105, 37–56.
- Högdahl, K., Andersson, U.B. & Eklund, O. 2001a.** TIB-2001. Workshop about and excursion to the Transscandinavian Igneous Belt 13–19.8 2001. *Geocenter tiedottaa – Geocenter informerar, Report 18, Turun yliopisto/ Åbo Akademi*. 97 p.
- Högdahl, K., Gromet, L.P. & Broman, C. 2001b.** Low P-T Caledonian resetting of U-rich Paleoproterozoic zircons, central Sweden. *American Mineralogist* 86, 534–546.
- Holmquist, P.J. 1905a.** Behandlingen av berggrunden i “Geologiska kartbladet Loftahammar”. *Geologiska Föreningens i Stockholm Förhandlingar* 27, 153–161.
- Holmquist, P.J. 1905b.** Loftahammarbladet och urbergsproblemen. *Geologiska Föreningens i Stockholm Förhandlingar* 27, 237–253.
- Holmqvist, P. J. 1906.** Studien über die Granite von Schweden. *Bulletin of the Geological Institute of Upsala, Vol. VII*, 81–256.
- Hooper, P.R. & Hawkesworth, C.J. 1993.** Isotopic and geochemical constraints on the origin and evolution of Columbia River Basalts. *Journal of Petrology* 34, 1203–1246.
- Huhma, H. 1986.** Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the early Proterozoic Svecokarelian crust in Finland. *Bulletin of the Geological Survey of Finland* 337, 1–48.
- Irvine, T.N. & Baragar, W.R.A. 1971.** A guide to the chemical classification of the common volcanic rocks: *Canadian Journal of Earth Sciences* 8, 523–548.
- Ivarsson, C. & Johansson, Å. 1995.** U-Pb zircon dating of

- Stockholm granite at Frescati. GFF 117, 67–68.
- Jarl, L.-G. 2002.** U-Pb zircon ages from the Vaggeryd syenite and the adjacent Hagshult granite, southern Sweden. GFF 124, 211–216.
- Jarl, L.-G. & Johansson, Å. 1988.** U-Pb zircon ages of granitoids from the Småland-Värmland granite-porphyrty belt, southern and central Sweden. Geologiska Föreningens i Stockholm Förhandlingar 110, 22–28.
- Johansson, Å. 1988.** The age and tectonic setting of the Småland-Värmland granite-porphyrty belt. Geologiska Föreningens i Stockholm Förhandlingar 110, 105–110.
- Johansson, Å. 1990.** Age of the Önnestad syenite and some gneissic granites along the southern part of the Protogine Zone. Geological Association of Canada, Special Paper 38, 131–148.
- Johansson, Å. & Larsen, O. 1989.** Radiometric age determinations and Precambrian geochronology of Blekinge, southern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 111, 35–50.
- Johansson, L. 1992.** The late Sveconorwegian metamorphic discontinuity across the Protogine zone. Geologiska Föreningens i Stockholm Förhandlingar 114, 350–353.
- Johansson, L. & Johansson, Å. 1990.** Isotope geochemistry and age relationships of mafic intrusions along the Protogine zone, southern Sweden. Precambrian Research 48, 395–414.
- Johansson, L., Lindh, A., & Möller, C. 1991.** Late Sveconorwegian (Grenville) high-pressure granulite facies metamorphism in southwestern Sweden. Journal of Metamorphic Geology 9, 283–292.
- Johansson, L., Möller, C. & Söderlund, U. 2001.** Geochronology of eclogite facies metamorphism in the Sveconorwegian province of SW Sweden. Precambrian Research 106, 261–275.
- Johansson, S. 1999.** Fältrelationer och U/Pb zirkonålder på en variant av Småländsk gångporfyr vid Axebosjön, SO om Virserum, Småland. Unpublished masters thesis, Department of Geology and Geochemistry, Stockholm University. 30 p.
- Juhlin, C., Aldahan, A.A., Castaño, J., Collini, B., Gorody, T. & Sandstedt, H. 1991a.** Scientific Summary Report of the Deep Gas Drilling Project in the Siljan Impact Structure. Vattenfall, Swedish State Power Board, U(G) 1991/14. 257 p.
- Juhlin, C., Lindgren, J. & Collini, B. 1991b.** Interpretation of seismic reflection and borehole data from Precambrian rocks in the Dala Sandstone area, central Sweden. First Break 9 (1), 24–36
- Juhlin, C., Wahlgren, C.-H. & Stephens, M.B. 2000.** Seismic imaging in the frontal part of the Sveconorwegian orogen, south-western Sweden. Precambrian Research 102, 135–154.
- Karlstrom, K.E., Åhäll, K.-I., Harlan, S.S., Williams, M.L., McLelland, J. & Geissman, J.W. 2001.** Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. Precambrian Research 111, 5–30.
- Kerrick, R. & Wyman, D.A. 1996.** The trace element systematic s of of Igneous rocks in Mineral Exploration: An Overview. In: Wyman, D.A. (ed.) Trace element Geochemistry of volcanic rocks: Applications for Massive Sulphide Exploration. Geological Association of Canada. Short Course Notes Volume 12, 1–51.
- Kleinhanns, I., Hansen, B.T. & Vollbrecht, A. 1999.** Geochronological and geochemical investigations on the Öro-Hamnö massif and its surrounding rocks, Västervik area, SE-Sweden. European Union of Geosciences, Strasbourg, France, Journal of Conference Abstracts 4, p. 809.
- Koistinen, T., Klein, V., Koppelmaa, H., Korsman, K., Lahtinen, R., Nironen, M., Puura, V., Saltykova, T., Tikhomirov, S. & Yanovskiy, A. 1996.** Paleoproterozoic Svecofennian orogenic belt in the surroundings of the Gulf of Finland. Geological Survey of Finland, Special Paper 21, 21–57.
- Koistinen, T., Stephens, M.B., Bogatchev, V., Nordgulen, Ö., Wennerström, M. & Korhonen, J. 2001.** Geological map of the Fennoscandian shield. Scale 1 : 2 000 000. Geological Surveys of Finland, Norway, Sweden and the North-West Department of Natural Resources of Russia.
- Konopelko, D.L. 1997.** Postorogenic intrusions of the NW Ladoga region with special references to apatite-bearing potassium ultramafic rocks. St. Petersburg University, 200 p. (dissertation) (in Russian)
- Konopelko, D.L., Eklund, O. & Ivanikov, V.V. 1998.** 1.8 Ga phosphorous-rich lamprophyre-granitoid complexes in the Fennoscandian shield: parental magmas and fractionation paths. Proceedings of the International Conference: Genetic significance of phosphorous in fractionated granites. Acta Universitatis Carolinae Geologica 42 (1), 51–54.
- Kontak, D.J., Clark, A.H., Farrar, E., Pearce, T.H., Strong, D.F. & Baadsgaard, H. 1986.** Petrogenesis of a Neogene shoshonite suite, Cerro Moromoroni, Puno, Southeastern Peru. Canadian Mineralogist 24, 117–135.
- Korhonen, J.V., Aaro, S., All, T., Nevanlinna, H., Skilbrei, J.R., Säävuori, H., Vaher, R., Zhdanova, L., Koistinen, T. 2002a.** Magnetic anomaly map of the Fennoscandian Shield. Scale 1 : 2 000 000. Geological Surveys of Finland, Norway, Sweden and the North-West Department of Natural Resources of Russia.
- Korhonen, J.V., Aaro, S., All, T., Elo, S., Haller, L.-Å., Kääriäinen, J., Kulinich, A., Skilbrei, J.R., Solheim, D., Säävuori, H., Vaher, R., Zhdanova, L. & Koistinen, T. 2002b.** Bouger anomaly map of the Fennoscandian Shield. Scale 1 : 2 000 000. Geological Surveys of Finland, Norway, Sweden and the North-West Department of Natural Resources of Russia.
- Korja, A. & Heikkinen, P.J., 1995.** Proterozoic extensional tectonics of the central Fennoscandian Shield: Results from the Baltic and Bothnian Echoes from the Lithosphere experiment. Tectonics, 14, 503–517.
- Korja, A. & Heikkinen, P. 2000.** The accretionary Svecofennian orogen – in the light of seismic BABEL lines. Lithosphere 2000, Institute of Seismology, University of Helsinki, Report S-41, 165–171.
- Korja, A. & Heikkinen, P. 2001.** Crustal structure of the southern Svecofennides. In: Högdahl, K., Andersson, U.B. & Eklund, O. (eds.), TIB-2001, Workshop about and excursion to the Transscandinavian Igneous Belt 13–19/8 2001. Geocenter informerar, Report S-18, Turku University, p. 6.
- Korja, A., Korja, T., Luosto, U. & Heikkinen, P. 1993.** Seismic and geoelectric evidence for collisional and extensional events in the Fennoscandian shield-implications for Precambrian crustal evolution. Tectonophysics 219, 129–152.
- Kornfält, K.-A. 1975.** Beskrivning till berggrundskartan Norrköping NV. Sveriges Geologiska Undersökning Af 108. 54 p.
- Kornfält, K.-A. 1993.** U-Pb zircon ages of three granite samples from Blekinge county, south-eastern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. Sveriges Geologiska Undersökning C 823, 17–23.
- Kornfält, K.-A. 1996.** U-Pb zircon ages of six granite samples from Blekinge County, southeastern Sweden. In:

- Lundqvist, Th. (ed.) Radiometric dating results 2. Sveriges Geologiska Undersökning C 828, 15–31.
- Kornfält, K.-A. & Bergström, J. 1991.** Beskrivning till provisoriska översiktliga berggrundskartan Karlskrona. Sveriges Geologiska Undersökning Ba 44. 33 p.
- Kornfält, K.-A., Persson, P.-O. & Wikman, H. 1997.** Granitoids from the Åspö area, southeastern Sweden – geochemical and geochronological data. GFF 119, 109–114.
- Korsman, K., Korja, T., Pajunen, M., Virransalo, P. & the GGT/SVEKA Working group. 1999.** The GGT/SVEKA transect: structure and evolution of the continental crust in the Paleoproterozoic Svecofennian orogen in Finland. International Geology Review 41, 287–333.
- Korsman, K., Hölttä, P. & Korja, A. 2000.** Granulite metamorphism and formation of the lower crust in Finland. Lithosphere 2000, Institute of Seismology, University of Helsinki, Report S-41, 101–106.
- Kousa, J. & Lundqvist, Th. 2000.** Svecofennian Domain. In: Description to the Bedrock Map of Central Fennoscandia (Mid-Norden). Geological Survey of Finland, Special Paper 28, 47–75.
- Kresten, P. 1986.** The granites of the Västervik area, southeastern Sweden. Sveriges Geologiska Undersökning C 814. 35 p.
- Kresten, P. 1988.** Granitization – fact or fiction? Geologiska Föreningens i Stockholm Förhandlingar 110, 335–340.
- Kresten, P. & Aaro, S. 1987.** Berggrundskartan 13F Falun NO. Sveriges Geologiska Undersökning Ai 16.
- Kresten, P., Aaro, S., & Karis, L. 1991.** Pre-Quaternary geological maps in the scale 1:50 000. Map sheets 14E NO and SO; 14F NV, NO, SV and SO, Sveriges Geologiska Undersökning Ai 46–51.
- Kumpulainen, R.A., Mansfeld, J., Sundblad, K. Neymark, L.A. & Bergman T. 1996.** Stratigraphy, age, and Sm-Nd isotope systematics of the country rocks to Zn-Pb sulfide deposits, Åmmeberg district, Sweden. Economic Geology 91, 1009–1021.
- Lagerblad, B. 1988.** Evolution and tectonic history of the Bergslagen vulcano-plutonic complex, central Sweden. Geologie en Mijnbouw 67, 165–176.
- Lahtinen, R. 1994.** Crustal evolution of the Svecofennian and Karelian domains during 2.1–1.79 Ga, with special emphasis on the geochemistry and origin of 1.93–1.91 Ga gneissic tonalites and associated supracrustal rocks in the Rautalampi area, central Finland. Geological Survey of Finland, Bulletin 378. 128 p.
- Lahtinen, R. & Huhma, H. 1997.** Isotopic and geochemical constraints on the evolution of the 1.93–1.79 Ga Svecofennian crust and mantle in Finland. Precambrian Research 82, 13–34.
- Lahtinen, R., Huhma, H. & Kousa, J. 2002.** Contrasting source components of the Paleoproterozoic Svecofennian metasediments: detrital zircon U-Pb, Sm-Nd and geochemical data. Precambrian Research 116, 81–109.
- Larson, S.Å. & Berglund, J. 1992.** A chronological subdivision of the Transscandinavian Igneous Belt – three magmatic episodes? Geologiska Föreningens i Stockholm Förhandlingar 114, 459–461.
- Larson, S.Å. & Hellström, F. 2003.** Studies of Proterozoic layered mafic intrusions in central Sweden – with special emphasis on internal structures, magmatic differentiation and mineralisations. SGU-rapport 2003: 4, 27–29.
- Larsson, W. 1935.** Der Nygård pluton. Bulletin of the Geological Institute of the University of Upsala 25, 13–134.
- LeBreton, N. & Thompson, A.B. 1988.** Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis. Contributions to Mineralogy and Petrology 99, 226–237.
- Lee, J.K.W., Onstott, T.C. & Henne, R. 1988.** ⁴⁰Ar/³⁹Ar laser microprobe and U-Pb geochronology of Siljan Ring samples. Geological Society of America Abstracts and programs, p. A 24.
- Lee, T.-Y. & Lawver, L.A. 1995.** Cenozoic plate reconstruction of southeast Asia. Tectonophysics 251, 85–138.
- Lindh, A. & Gorbatschev, R. 1984.** Chemical variation in a Proterozoic suite of granitoids extending across a mobile belt craton boundary. Geologische Rundschau 73, 881–893.
- Lindh, A. & Johansson, I. 1995.** Country rock contamination of granites: an example from southeast Sweden. Neues Jahrbuch für Mineralogie, Abhandlungen 170, 1–19.
- Lindh, A. & Persson, P.-O. 1990.** Proterozoic granitoid rocks of the Baltic shield – trends of development. In: Gower, C.F., Rivers, T. & Ryan, A.B. (eds.) Mid-Proterozoic Laurentia-Baltica. Geological Association of Canada, Special Paper 38, 23–40.
- Lindh, A., Krauss, M. & Franz, K.-M. 2001a.** Interpreting the Småland-Blekinge deformation zone from chemical and structural data. GFF 123, 181–191.
- Lindh, A., Andersson, U.B., Lundqvist, Th. & Claesson S. 2001b.** Evidence of crustal contamination of mafic rocks associated with rapakivi rocks: an example from the Nordingrå complex, central Sweden. Geological Magazine 138, 371–386.
- Lindroos, A., Romer, R.L., Ehlers, C. & Alviola, R. 1996.** Late-orogenic Svecofennian deformation in SW Finland constrained by pegmatite emplacement ages. Terra Nova 8, 567–574.
- Lindström, M., Lundqvist, J. & Lundqvist, Th. 2000.** Sveriges geologi från urtid till nutid. Studentlitteratur. 491 p.
- Ludwig, K.R. 1999.** Isoplot/Ex version 2.00. A geochronological toolkit for Microsoft Excel. Berkeley Geochronological Center, Special Publication 2. 46 p.
- Lund, C.E., Gorbatschev, R. & Smirnov, A. 2001.** A seismic model of the Precambrian crust along the coast of southeastern Sweden: the Cost Profile wide-angle airgun experiment and the southern part of FENNOLOGIA revisited. Tectonophysics 339, 93–111.
- Lundegårdh, P.H. 1967.** Berggrunden i Gävleborgs län. Sveriges Geologiska Undersökning Ba 22. 303 p.
- Lundegårdh, P.H. 1987.** Beskrivning till berggrundskartan Filipstad SV. Sveriges Geologiska Undersökning Af 157. 77 p.
- Lundegårdh, P.H. 1995.** Beskrivning till berggrundskarta över Värmlands län. Östra och mellersta Värmlands berggrund. Sveriges Geologiska Undersökning Ba 45:1. 180 p.
- Lundegårdh, P.H. 1997.** Södra Härjedalens berggrund. Sveriges Geologiska Undersökning Ca 53:1, 175–202.
- Lundegårdh, P.H., Gorbatschev, R., Kornfält, K.-A., Strömberg, A.G., Karis, L., Zachrisson, E., Sjöstrand, T. & Skoglund, R. 1984.** Karta över berggrunden i Jämtlands län. Bedrock geology of Jämtland county: Sveriges Geologiska Undersökning Ca 53.
- Lundqvist, L. 1996.** Kartbladen 18F Bräcke NV, NO och 19F Häggenås SV, SO. In: Wahlgren, C.-H. (ed.) Regional berggrundsgeologisk undersökning sammanfattning av pågående undersökningar 1995, Sveriges Geologiska Undersökning, Rapporter och meddelanden 84, 62–66.
- Lundqvist, L. & Antal, I. 2000.** Kartbladen 18F Bräcke NV, NO och 19F Häggenås SV, SO. In: Delin, H. (ed.) Regional berggrundsgeologisk undersökning. Sammanfattning av

- pågående undersökningar 1999, Sveriges Geologiska Undersökning, Rapporter och meddelanden 102, 43–50.
- Lundqvist, L. & Korja, A. 1997.** Kartbladen 18F Bräcke NV, NO och Hågenås SV, SO. In: Wahlgren, C.-H. (ed.) Regional berggrundsgeologisk undersökning sammanfattning av pågående undersökningar 1996, Sveriges Geologiska Undersökning, Rapporter och meddelanden 89, 27–34.
- Lundqvist, Th. 1968.** Precambrian geology of the Los-Hamra region, central Sweden. Sveriges Geologiska Undersökning Ba 23. 255 p.
- Lundqvist, Th. 1987.** Early Svecofennian stratigraphy of southern and central Norrland, Sweden, and the possible existence of an Archaean basement west of the Sveco-karelidés. Precambrian Research 35, 343–352.
- Lundqvist, Th. & Persson, P.-O. 1996.** U-Pb ages of porphyries and related rocks in northern Dalarna, south-central Sweden. GFF 118, Jubilee Issue, p. A17–A18.
- Lundqvist, Th. & Persson, P.-O. 1999.** Geochronology of porphyries and related rocks in northern and western Dalarna, south-central Sweden. GFF 121, 307–322.
- Lundqvist, Th., Gee, D.G., Kumpulainen, R., Karis, L. & Kresten, P. 1990.** Beskrivning till karta över berggrunden i Västernorrlands län. Sveriges Geologiska Undersökning Ba 31. 429 p.
- Lundqvist, Th., Bygghammar, B., Stephens, M.B., Beckholmen, M., Norling, E. 1994.** Sveriges berggrund 1 : 250 000. In: Freden, C. (ed.) Berg och jord. Sveriges Nationalatlas. Sveriges Nationalatlas Förlag. 208 p.
- Lundqvist, Th., Vaasjoki, M. & Persson, P.-O. 1998.** U-Pb ages of plutonic and volcanic rocks in the Svecofennian Bothnian Basin, Central Sweden, and their implications for the Palaeoproterozoic evolution of the Basin. GFF 120, 357–363.
- Lundström, I. 1995.** Berggrundskartan 11F Filipstad NO. Sveriges Geologiska Undersökning Af 185.
- Lutro, O., Robinson, P. & Solli, A. 1997.** Proterozoic geology and Scandian high-pressure overprinting in the Western Gneiss Region. NGU Report 97.132. 86 p.
- Magnor, B., Stigh, J. & Larson, S.-Å. 1996.** Mesoproterozoic deformation of the Lower Dala Group and the Jotnian sedimentary rocks. GFF 118, Jubilee Issue, p. A18.
- Magnusson, N.H. 1922.** Berggrunden. In: Magnusson, N.H., Munthe, H. & Rosén, S. (eds.) Beskrivning till kartbladet Mjölby. Sveriges Geologiska Underökning Aa 150, 14–32.
- Magnusson, N.H. 1924.** Berggrunden. In: Magnusson, N.H., Ekström, G. & Lundqvist, G. (eds.) Beskrivning till kartbladet Strålsnäs. Sveriges Geologiska Underökning Aa 154, 10–23.
- Magnusson, N.H. 1925.** Persbergs malmtrakt och berggrunden i den centrala delarna av Filipstads bergslag i Värmlands län. Kungliga kommerskollegium och Sveriges Geologiska Undersökning, Beskrivning över mineralfyndigheter nr. 2. Victor Petterssons bokbinderiaktiebolag. 475 p.
- Magnusson, N.H. 1929.** Nordmarks malmtrakt, geologisk beskrivning. Sveriges Geologiska Undersökning Ca 13. 90 p.
- Magnusson, N.H., Lundqvist, G. & Regnéll, G. 1963.** Sveriges geologi. Norstedts, Stockholm. 698 p.
- Maniar, P.D. & Piccoli, P.M. 1989.** Tectonic discrimination of granitoids. Geological Society of America Bulletin 101, 635–643.
- Mansfeld, J. 1991.** U–Pb age determinations of Småland-Värmland granitoids in Småland, southeastern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 113, 113–119.
- Mansfeld, J. 1996.** Geological, geochemical and geochronological evidence for a new Palaeoproterozoic terrane in southeastern Sweden. Precambrian Research 77, 91–103.
- Mansfeld, J., Sturkell, E. & Broman C. 1998.** Meteorite impact influence on a Proterozoic shear zone mineralization at Gullgruvan, Jämtland, Sweden. In: Wilson, R.J. (ed.) Abstract, 23. Nordiske Geologiske Vintermøde, Århus, Denmark, p. 195.
- Mansfeld, J. & Beunk, F.F. 2004.** The Oskarshamn-Jönköping Belt, a well preserved Palaeoproterozoic volcanic arc. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. GFF 126, 29–30.
- Mattsson, H. & Elming, S.-Å. 2001.** Magnetic fabrics and paleomagnetism of the Storsjön-Edsbyn deformation zone, central Sweden. Precambrian Research 107, 265–281.
- Mehnert, K.R. & Busch, W. 1985.** The formation of K-feldspar megacrysts in granites, migmatites and augen gneisses. Neues Jahrbuch für Mineralogie, Abhandlungen 151, 229–259.
- Mellqvist, C. 1999.** Proterozoic crustal growth along the Archaean continental margin in the Luleå and Jokkmokk areas, northern Sweden. Luleå University of technology 1999:24. 15 p. (dissertation)
- Meschede, M. 1986.** A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. Chemical Geology 56, 207–218.
- Meurer, W.P. & Claeson D.T. 2002.** Evolution of crystallizing interstitial liquid in an arc-related cumulate determined by LA ICP-MS mapping of a large amphibole oikocryst. Journal of Petrology 43, 607–629.
- Middlemost, E.A.K. 1994.** Naming materials in the magma/igneous rock system. Earth-Science Reviews 37, 215–224.
- Miller, C.F. & Barton, M.D. 1990.** Phanerozoic plutonism in the Cordilleran interior, U.S.A. In: Kay, S.M. & Rapela, C.W. (eds.) Plutonism from Antarctica to Alaska. Geological Society of America, Special Paper 241, 213–231.
- Milsom, J. 2001.** Subduction in eastern Indonesia: how many slabs? Tectonophysics 338, 167–178.
- Möller, C. 1998.** Decompressed eclogites in the Sveconorwegian (-Grenvillian) orogen of SW Sweden: petrology and tectonic implications. Journal of Metamorphic Geology 16, 641–656.
- Möller, C. 1999.** Sapphirine in SW Sweden: a record of Sveconorwegian (-Grenvillian) late-orogenic tectonic exhumation. Journal of Metamorphic Geology 17, 127–141.
- Nilsson, M. 1992.** Geochemistry of Middle Proterozoic mafic and composite mafic-felsic dykes in southeastern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 114, 113–130.
- Nilsson, M. & Wikman, H. 1997.** U-Pb zircon ages of two Småland dyke porphyries at Påskallavik and Alserbro, southeastern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results 3. Sveriges Geologiska Undersökning C 830, 31–40.
- Nironen, M., 1997.** The Svecofennian Orogen: a tectonic model. Precambrian Research 86, 21–44.
- Nironen, M., Lahtinen, R., & Korja, A., 2002.** Paleoproterozoic tectonic evolution of the Fennoscandian shield – comparison to modern analogues: Lithosphere 2002: Institute of Seismology, University of Helsinki, Report S-42, p. 95–97.
- Nurmi, P.A. & Haapala, I. 1986.** The Proterozoic granitoids of Finland: granite types, metallogeny and relation to crustal evolution. Bulletin of the Geological Society of Finland 58, 203–233.
- Nyström, J.-O. 1982.** Post-Svecokarelian Andinotype evolu-

- tion in central Sweden. *Geologische Rundschau* 71, 141–157.
- Nyström, J.O. 1983.** Pumpellyite-bearing rocks in central Sweden and extent of host rock alteration as a control of pumpellyite composition. *Contributions to Mineralogy and Petrology* 83, 159–168.
- Nyström, J.-O. 1999.** Origin and tectonic setting of the Dala volcanites. Sveriges Geologiska Undersökning, project 03-889/96, Final report Dec. 1999, 41 p. + tables.
- Öhlander, B. & Romer, R.L. 1996.** Zircon ages of granites occurring along the central Swedish gravity low. *GFF* 118, 217–225.
- Öhlander, B. & Schöberg, H. 1991.** Character and U-Pb zircon age of the Proterozoic Ale granite, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 113, 105–112.
- Öhlander, B. & Skiöld, T. 1994.** Diversity of 1.8 Ga potassic granitoids along the edge of the Archaean craton in northern Scandinavia: a result of melt formation at various depths and from various sources. *Lithos* 33, 265–283.
- Öhlander, B. & Zuber, J. 1988a.** Genesis of the Fellingsbro-type granites: evidence from gravity measurements and geochemistry. *Geologiska Föreningens i Stockholm Förhandlingar* 110, 39–54.
- Öhlander, B. & Zuber, J. 1988b.** Geochemistry of the Fellingsbro type granites, south central Sweden. *Geologie en Mijnbouw* 67, 213–225.
- Öhlander, B., Skiöld, T., Hamilton, P.J. & Claesson L.-Å. 1987.** The western border of the Archean province of the Baltic shield: evidence from northern Sweden. *Contribution to Mineralogy and Petrology* 95, 437–450.
- Öhlander, B., Skiöld, T., BABELworking group, Claesson, S. & Nisca, D.H. 1993.** Delineation and character of the Archaean-Proterozoic boundary in northern Sweden. *Precambrian Research* 64, 67–84.
- Öhlander, B., Mellqvist, C. & Skiöld, T. 1999.** Sm-Nd isotope evidence of a collision event in the Precambrian of northern Sweden. *Precambrian Research* 93, 105–117.
- Page, L.M., Stephens, M.B. & Wahlgren, C.-H. 1996.** ⁴⁰Ar/³⁹Ar geochronological constraints on the tectonothermal evolution of the Eastern Segment of the Sveconorwegian Orogen, south-central Sweden. In: Brewer, T.S. (ed.) *Precambrian Crustal Evolution in the North Atlantic Region*. Geological Society Special Publication 112, 315–330.
- Patchett, P.J. 1978.** Rb/Sr ages of Precambrian dolerites and syenites in southern and central Sweden. *Sveriges Geologiska Undersökning C* 747, 63 p.
- Patchett, P.J. & Arndt, N.T. 1986.** Nd isotopes and tectonics of 1.9–1.7 Ga crustal genesis. *Earth and Planetary Science Letters* 78, 329–338.
- Patchett, P.J. & Kouvo, O. 1986.** Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes and U-Pb zircon ages in the Svecokarelian terrain of south Finland. *Contribution to Mineralogy and Petrology* 92, 1–12.
- Patchett, P.J., Gorbatshev, R. & Todt, W. 1987.** Origin of continental crust of 1.9–1.7 Ga age. Nd isotopes in the Svecofennian orogenic terrains of Sweden. *Precambrian Research* 35, 145–160.
- Patchett, P.J., Lehnert, K., Rehkämper, M. & Sieber, G. 1994.** Mantle and crustal effects on the geochemistry of Proterozoic dikes and sills in Sweden. *Journal of Petrology* 35, 1095–1125.
- Peacock, M.A. 1931.** Classification of igneous rocks. *Journal of Geology* 39, 54–67.
- Pearce, J.A. 1982.** Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe, R.S. (ed.) *Andesites: orogenic andesites and related rocks*. Wiley, 525–548.
- Pearce, J.A. 1983.** Role of the sub-continental lithosphere in magma genesis at active continental margins. In: Hawkesworth, C. & Norry, M.J. (eds.) *Continental basalts and mantle xenoliths*. Shiva, 230–249.
- Pearce, J.A. 1996a.** Sources and settings of granitic rocks. *Episodes* 19, 120–125.
- Pearce, J.A., 1996b.** A Users Guide to Basalt Discrimination Diagrams. In: Wyman, D.A. (ed.) *Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration*. Geological Association of Canada, Short Course Notes 12, 79–113.
- Pearce, J.A. & Peate, D.W. 1995.** Tectonic implications of the composition of volcanic arc magmas. *Annual Reviews of Earth and Planetary Sciences* 23, 251–285.
- Pearce, J.A., Harris, N.B.W. & Tindle, A.G. 1984.** Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* 25, 956–983.
- Persson, A.I. 1997.** The Ragunda rapakivi complex. In: Ahl, M., Andersson, U.B., Lundqvist, Th. & Sundblad, K. (eds.) *Rapakivi granites and related rocks in central Sweden*. Sveriges Geologiska Undersökning Ca 87, 49–58.
- Persson, K.S. 2002.** Deformation zones in models and nature. Uppsala University. 58 p. (dissertation)
- Persson, L. 1974.** Precambrian rocks and tectonic structures of an area in northeastern Småland, southern Sweden. *Sveriges Geologiska Undersökning C* 703, 55 p.
- Persson, L. 1978.** The Revsund-Sörvik granites in the western parts of the province of Ångermanland, central Sweden. *Sveriges Geologiska Undersökning C* 741, 59 p.
- Persson, L. 1985.** Beskrivning till berggrundskartorna Vetlanda NV och NO. (English summary) *Sveriges Geologiska Undersökning Af* 150 & 151, 138 p.
- Persson, L. 1989.** Beskrivning till berggrundskartorna Vetlanda SV och SO. (English summary) *Sveriges Geologiska Undersökning Af* 170 & 171, 130 p.
- Persson, L., Bruun, Å. & Dahlman, B. 1981.** Beskrivning till berggrundskartan Linköping SV. *Sveriges Geologiska Undersökning Af* 132, 150 p.
- Persson, P.-O. & Ripa, M. 1993.** U-Pb zircon dating of a Järna-type granite in western Bergslagen, south-central Sweden. In: Lundqvist, Th. (ed.) *Radiometric dating results*. Sveriges Geologiska Undersökning C 823, 41–45.
- Persson, P.-O. & Wikström, A. 1993.** A U-Pb dating of the Askersund granite and its marginal augen gneiss. *Geologiska Föreningens i Stockholm Förhandlingar* 115, 321–329.
- Priem, H.N.A. & Bakker, J.D. 1973.** A Rb-Sr whole-rock isochron study of the Loftahammar granitic gneiss in the Västervik area, southeastern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 95, 400–403.
- Ramberg, H. 1967.** Gravity, deformation and the Earth's crust. London: Academic Press. 214 p.
- Rämö, O.T. 1990.** Diabase dyke swarms and silicic magmatism – evidence from the Proterozoic of Finland. In: Parker, A.J., Rickwood, P.C. & Tucker, D.H. (eds.) *Mafic dykes and emplacement magmatism*. Rotterdam: Balkema, 185–199.
- Rämö, O.T. 1991.** Petrogenesis of Proterozoic rapakivi granites and related basic rocks of southeastern Fennoscandia: Nd and Pb isotopic and general geochemical constraints. *Bulletin of the Geological Survey of Finland* 355, 161 p.
- Rämö, O.T. & Haapala, I. 1995.** One hundred years of rapakivi granite. *Mineralogy and Petrology* 52, 129–185.
- Rehnström, E. 2003.** Geography and geometry of Pre-Caledonian western Baltica: U-Pb geochronology and palaeomagnetism. LITHOLUND Theses – No.1, Lund

- University, Department of Geology. 29 p. (dissertation)
- Rickard, D. 1988.** Regional metamorphism in the Bergslagen province, south central Sweden. *Geologie en Mijnbouw* 67, 139–155.
- Riddihough, R.P. 1972.** Regional magnetic anomalies and geology in Fennoscandia: A discussion. *Canadian Journal of Earth Sciences* 9, 219–232.
- Rimsa, A. 2002.** Petrological study of the metamafic rocks across the Småland-Blekinge deformation zone. Unpublished masters thesis, Lunds university, Department of Geology 154. 51 p.
- Ripa, M. 1994.** The mineral chemistry of hydrothermally altered and meamorphosed wall-rocks at the Stollberg Fe-Pb-Zn-Mn(-Ag) deposit, Bergslagen, Sweden. *Mineralium Deposita* 29, 180–188.
- Romer, R.L. 1994.** Rb-Sr data structure – a possible cause for differences in Rb-Sr whole-rock and U-Pb zircon ages. *GFF* 116, 93–103.
- Romer, R.L. & Öhlander, B. 1994.** U-Pb age of the Yxsjöberg tungsten-skarn deposit, Sweden. *GFF* 116, 161–166.
- Romer, R.L. & Öhlander, B. 1995.** Tectonic implications of an 1846±1 Ma old migmatitic granite in south-central Sweden. *GFF* 117, 69–74.
- Romer, R.L. & Smeds, S.-A. 1994.** Implications of U-Pb ages of columbite-tantalites from granitic pegmatites for the Palaeoproterozoic accretion of 1.90 – 1.85 Ga magmatic arcs to the Baltic Shield. *Precambrian Research* 67, 141–158.
- Romer, R.L. & Smeds, S.-A. 1997.** U-Pb columbite chronology of post-kinematic Palaeoproterozoic pegmatites in Sweden. *Precambrian Research* 82, 85–99.
- Romer, R.L., Kjösnes, B., Korneliussen, A., Lindahl, I., Skyseth, M. & Sundvoll, B. 1992.** The Archean-Proterozoic boundary beneath the Caledonides of northern Norway and Sweden: U-Pb, Rb-Sr and epsilon Nd isotope data from the Rombak-Tysfjord area. *Norges Geologiske Undersøkelse Rapport 91/225*. 67 p.
- Ruppel, C. & Hodges, K.V. 1994.** Pressure-temperature-time paths from two-dimensional thermal models: prograde, retrograde, and inverted metamorphism. *Tectonics* 13, 17–44.
- Rutanen, H. 2001.** Geochemistry and petrogenesis of the 1.8 Ga old post-collisional intrusions in southern Finland and Russian Karelia. Unpublished licentiate-thesis, Department of Geology and Mineralogy, Åbo Akademi University, Turku. 87 p.
- Rutanen, H., Eklund, O. & Konopelko, D.L. 1997.** Rock and mineral analyses of Svecofennian postorogenic 1.8 Ga intrusions in southern Finland and Russian Karelia. *Geocenter informerar Turku (Geocenter information)* 16.
- Sabatier, H. 1991.** Vaugnerites. Special lamprophyre-derived mafic enclaves in some Hercynian granites from western and central Europe. In: Didier, J. & Barbarin, B. (eds.) *Enclaves and granite petrology. Developments in petrology* 13. Amsterdam: Elsevier, 63–81.
- Schmitz, M., Heinsohn, W.D. & Schilling, F.R. 1997.** Seismic, gravity and petrological evidence for partial melt beneath the thickened Central Andean crust. *Tectonophysics* 270, 313–326.
- Schreiber, U. & Schwab, K. 1991.** Geochemistry of Quaternary shoshonitic lavas related to the Calama-Olacapato-El Toro Lineament, NW Argentina. *Journal of South American Earth Science* 4, 73–85.
- Sederholm, J.J. 1897.** Om indelningen af de prekambiska formationerna i Sverige och Finland och om nomenklaturen för dessa äldre bildningar. *Geologiska Föreningens i Stockholm Förhandlingar* 19, 20–53.
- Sjöberg, B., Pisarevsky, S. & Wikström, A. 1999.** Sveconorwegian (c. 1000 Ma) remagnetisation of the Askersund granite (c. 1850 Ma old), south-central Sweden. *European Union of Geosciences, Strasbourg, France, Journal of Conference Abstract* 4, p. 845.
- Sjöblom, B. 1982.** “Projekt Jämtland’s” berggrundskarta 18 E SO i skala 1 : 50 000. *Sveriges Geologiska Undersökning, Berggrundsbyrå*.
- Sjöström, H. & Bergman, S. 1998.** Svecofennian metamorphic and tectonic evolution of east central Sweden. Unpublished report. *Sveriges Geologiska Undersökning*. 50 p. + figures.
- Sjöström, H., Högdahl, K., Aaro, S. & Bergman, S. 2000.** The Hassela Shear Zone in central Sweden, the western part of a paleo-Proterozoic tectonic domain boundary across the Baltic Shield? Abstract, 24. *Nordiska Geologiske Vintermøte, Trondheim* 6–9.1. 2000. *Geonytt* 1, p. 153.
- Skår, Ö. 2002.** U-Pb geochronology and geochemistry of early Proterozoic rocks of the tectonic basement windows in central Nordland, Caledonides of north-central Norway. *Precambrian Research* 116, 265–283.
- Skjöld, T. 1981.** Radiometric ages of plutonic and hypabyssal rocks from the Vittangi-Karesuando area, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 103, 317–329.
- Skjöld, T. 1988.** Implications of new U-Pb zircon chronology to early Proterozoic crustal accretion in northern Sweden. *Precambrian Research* 38, 147–164.
- Skjöld, T., Öhlander, B., Vock, Jr., R.D. & Hamilton, P.J. 1988.** Chemistry of Proterozoic orogenic processes at a continental margin in northern Sweden. *Chemical Geology* 69, 193–207.
- Skjöld, T., Öhlander, B., Markkula, H., Widenfalk, L. & Claesson, L.-Å. 1993.** Chronology of Proterozoic orogenic processes at the Archaean continental margin in northern Sweden. *Precambrian Research* 64, 225–238.
- Smeds, S.-A. 1994.** Geochemical fractionation and zoning of some granitic rare-element pegmatite fields in Sweden. *Uppsala University*. 19 p. (dissertation)
- Söderhielm, J. & Sundblad, K. 1996.** The Solstad Cu-Co-Au mineralization and its relation to post-Svecofennian regional shear zones in southeastern Sweden. *GFF* 118 Jubilee Issue, p. A47.
- Söderlund, U. 1999.** Geochronology of Tectonothermal Events in the Parautochthonous Eastern Segment of the Sveconorwegian (Grenvillian) Orogen, Southwestern Sweden. *Lund University*. 22 p. (dissertation)
- Söderlund, U. & Rodhe, A. 1998.** Constrains on syn-intrusive ca. 1.8 Ga conglomerate deposits associated the Småland-Värmland Belt, SE Sweden: Pb-Pb zircon evaporation dating of the Malmbäck conglomerate. *GFF* 120, 69–74.
- Söderlund, U., Jarl, L.-G., Persson, P.-O., Stephens, M.B. & Wahlgren, C.-H. 1999.** Protolith ages and timing of deformation in the eastern, marginal part of the Sveconorwegian orogen, southwestern Sweden. *Precambrian Research* 94, 29–48.
- Söderlund, U., Möller, C., Andersson, J., Johansson, L. & Whitehouse, M. 2002.** Zircon geochronology in metamorphic gneisses in the Sveconorwegian orogen, SW Sweden: ion microprobe evidence for 1.46–1.42 and 0.95–0.96 Ga reworking. *Precambrian Research* 113, 193–225.
- Söderlund, U., Patchett, P.J., Isachsen, C., Vervoort, J. & Bylund, G. 2004.** Baddeleyite U-Pb dates and Hf-Nd isotope composition of mafic dyke swarms in Sweden and Finland. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. *GFF* 126, 38.
- Stålhös, G. 1991.** Beskrivning till berggrundskartorna Östhammar NV, NO, SV, SO. *Sveriges Geologiska*

- Undersökning Af 161, 166, 169, 172. 249 p.
- Stephens, M.B. 1998.** Berggrundskartan Karlskoga NO. Sveriges Geologiska Undersökning Af 184.
- Stephens, M.B. & Wahlgren, C.-H. 1995.** Thermal and mechanical responses to bilateral collision in the Svecofennian orogen. In: Kohonen T. & Lindberg B. (eds.) The 22nd Nordic Geological Winter meeting, Åbo, Finland, p. 203.
- Stephens, M.B., Wahlgren, C.-H. & Annertz, L. 1993.** U-Pb zircon dates in two younger suites of Palaeoproterozoic intrusions, Karlskoga area, south-central Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. Sveriges Geologiska Undersökning C 823, 46–59.
- Stephens, M.B., Wahlgren, C.-H. & Weihed, P. 1994.** Geological Map of Sweden. Sveriges Geologiska Undersökning Ba 52.
- Stephens, M.B., Wahlgren, C.-H., Weijermars, R. & Cruden, A.R. 1996.** Left-lateral transpressive deformation and its tectonic implications, Sveconorwegian orogen, Baltic Shield, southwestern Sweden. *Precambrian Research* 79, 261–279.
- Sturkell, E.F.F. 1998.** The marine Lockne impact structure, Jämtland, Sweden: A review. *Geologische Rundschau* 87, 253–267.
- Sukotjo, S. 1995.** Berggrundskartan 15H Hudiksvall NV. Sveriges Geologiska Undersökning Ai 64.
- Sultan, L., Claesson, S., Plink-Björklund, P. & Björklund, L. 2004.** Proterozoic and Archaean zircon ages from the Palaeoproterozoic Västervik Basin, southern Fennoscandian Shield. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. GFF 126, 39.
- Sun, S.S. & McDonough, W.F. 1989.** Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D. & Norry, M.J. (eds.) *Magmatism in the ocean basins*. Geological Society, Special Publications 42, 313–345.
- Sundblad, K. 1994.** Paleoproterozoic ore-bearing Mg-rich greenstone belts at Hackås, central Sweden. Research report, Sveriges Geologiska Undersökning. 33 p.
- Sundblad, K. 1997.** Syngenetic Pb-Zn-Cu sulphide mineralization in 1.8 Ga subareal volcanic rocks, southeastern Sweden. GFF 119, 103–108.
- Sundblad, K. & Ahl, M. 1999.** Contrasting metallogenetic features of Palaeoproterozoic granitoids in the Svecofennian Domain, northern Europe. *Anais da Academia Brasileira de Ciências* 71, 89–98.
- Sundblad, K., Ahl, M. & Schöberg, H. 1993.** Age and geochemistry of granites associated with Mo-mineralizations in western Bergslagen, Sweden. *Precambrian Research* 64, 319–335.
- Sundblad, K., Mansfeld, J. & Särkinen, M. 1997.** Palaeoproterozoic rifting and formation of sulphide deposits along the southwestern margin of the Svecofennian Domain, southern Sweden. *Precambrian Research* 82, 1–12.
- Sundblad, K., Gyllencreutz, R. & Flodén, T. 1998.** The Precambrian crust beneath the Baltic Sea. *Geophysical Journal* 20, 121–124.
- Sundius, N. 1927.** Om ögongnejserna inom sydöstra Östergötlands gnejsområde och deras åldersställning. *Geologiska Föreningens i Stockholm Förhandlingar* 49, 631–644.
- Sundius, N. 1928.** Berggrunden. In: Sandegren, R. & Sundius, N. (eds.) *Beskrivning till kartbladet Valdemarsvik*. Sveriges Geologiska Undersökning Aa 158, 18–32.
- Svedmark, E. 1895.** Orsa Finnmarks geologi. Sveriges Geologiska Undersökning C 147. 37 p.
- Svensson, U. 1970.** Geochemical investigation of the principal Precambrian rocks of Västerbotten county Sweden. Sveriges Geologiska Undersökning C 652. 73 p.
- Taylor, S.R. & McLennan, S.M. 1985.** The continental crust: its composition and evolution. Oxford: Blackwell. 312 p.
- Tikoff, B. & Teyssier, C. 1994.** Strain modelling of displacement-field partitioning in transpressional orogens. *Journal of Structural Geology* 16, 1575–1588.
- Törnebohm, A.E. 1881.** Beskrifning till bland N:o 4 af geologisk öfersigtskarta öfver mellersta Sveriges bergslag på bekostnad av Jernkontoret. Stockholm: K.L. Beckman. 62 p.
- Tucker, R.D., Krogh, T.E. & Råheim, A. 1991.** Proterozoic evolution and age-province boundaries in the central parts of the Western Gneiss Region, Norway: results of U-Pb dating of accessory minerals from Trondheimsfjord to Geiranger. *Geological Association of Canada, Special Paper* 38, 149–173.
- Väisänen, M. 2002.** Tectonic evolution of the Palaeoproterozoic Svecofennian orogen in southwestern Finland. *Annales Universitatis Turkuensis, Sarja – Ser. AII Osa Tom. 154*. 21 p. (dissertation)
- Väisänen, M., Mänttari, I. & Hölttä, P. 2002.** Svecofennian magmatic and metamorphic evolution in southwestern Finland as revealed by U-Pb zircon SIMS geochronology. *Precambrian Research* 116, 111–127.
- Väisänen, M., Andersson, U.B., Huhma, H. & Mouri, H. 2004.** Age of late Svecofennian regional metamorphism in southern Finland and south-central Sweden. 26th Nordic Geological Wintermeeting, Uppsala, 040106-09. GFF 126, 40–41.
- Valbracht, P.J. 1991.** The origin of the continental crust of the Baltic shield, as seen through Nd and Sr isotopic variations in 1.89–1.85 Ga old rocks from the western Bergslagen, Sweden. Amsterdam, GUA papers of geology, Series 1 (29). 222 p. (dissertation)
- Valbracht, P.J., Oen, I.S. & Beunk, F.F. 1994.** Sm-Nd isotope systematics of 1.9–1.8 Ga granites from western Bergslagen, Sweden: inferences on a 2.1–2.0 Ga crustal precursor. *Chemical Geology* 112, 21–37.
- Vernon, R.H. 1990.** K-feldspar augen in felsic gneisses and mylonites – deformed phenocrysts or porphyroblasts? *Geologiska Föreningens i Stockholm Förhandlingar* 112, 157–167.
- Vinnfors, A. 1985.** Post-Svecofennian basic plutonics and bronzite diabases in eastern Värmland, Sweden. University of Gothenburg, Geological Institute Publication A 50. 228 p. (dissertation)
- Vivallo, W. & Claesson, L.-Å. 1987.** Intra-arc rifting and massive sulphide mineralization in an early Proterozoic volcanic arc, Skellefte district, northern Sweden. In: Pharaoh, T.C., Beckinsale, R.D. & Rickard, D. (eds.) *Geochemistry and mineralization of Proterozoic volcanic suites*. Geological Society Special Publication 33, 69–79.
- Vivallo, W. & Willdén, M. 1988.** Geology and geochemistry of an early Proterozoic volcanic arc sequence at Kristineberg, Skellefte district, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 110, 1–12.
- Wahlgren, C.-H. 1992.** Berggrundskartan Karlskoga NV. Sveriges Geologiska Undersökning Af 176.
- Wahlgren, C.-H. 1993.** Berggrundskartan Karlskoga SV. Sveriges Geologiska Undersökning Af 182.
- Wahlgren, C.-H. 1995.** Berggrunden på kartbladet 9E Askersund NV/9D Mariestad NO. Sveriges Geologiska Undersökning, Rapporter och meddelanden 79, 20–27.
- Wahlgren, C.-H. 1996.** Berggrunden på kartbladet 9E Askersund NV/9D Mariestad NO. Sveriges Geologiska Undersökning, Rapporter och meddelanden 84, 22–28.
- Wahlgren, C.-H., Cruden, A.R. & Stephens, M.B. 1994.**

- Kinematics of a major fan-like structure in the eastern part of the Sveconorwegian orogen, Baltic Shield, south-central Sweden. *Precambrian Research* 70, 67–91.
- Wahlgren, C.-H., Bergman, S., Lundström, I. & Stephens, M.B. 1996a.** Orogen terminologi. *Geologiskt forum* 11, 20–21.
- Wahlgren, C.-H., Cruden, A.R. & Stephens, M.B. 1996b.** Kinematics of a major fan-like structure in the eastern part of the Sveconorwegian orogen, Baltic Shield, south-central Sweden – reply. *Precambrian Research* 78, 293–296.
- Wahlgren, C.-H., Heaman, L.M., Kamo, S. & Ingvald, E. 1996c.** U-Pb baddeleyite dating of dolerite dykes in the eastern part of the Sveconorwegian orogen, south-central Sweden. *Precambrian Research* 79, 227–237.
- Wasström, A. 1993.** The Knaften granitoids of Västerbotten County, northern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. *Sveriges Geologiska Undersökning C* 823, 60–64.
- Wasström, A. 1996.** U-Pb zircon dating of a quartz-feldspar porphyritic dyke in the Knaften area, Västerbotten County, northern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. *Sveriges Geologiska Undersökning C* 828, 34–40.
- Weihed, P. & Antal, I. 1998.** Berggrundskartorna 22J Kalvträsk. *Sveriges Geologiska Undersökning Ai* 92–95.
- Weihed, P., Billström, K., Persson, P.-O. & Bergman Weihed, J. 2002.** Relationship between 1.90–1.85 Ga accretionary processes and 1.82–1.80 Ga oblique subduction at the Karelian craton margin, Fennoscandian Shield. *GFF* 124, 163–180.
- Welin, E. 1987.** The Depositional Evolution of the Svecofennian Supracrustal Sequence in Finland and Sweden. *Precambrian Research* 35, 95–113.
- Welin, E. 1994.** Isotopic investigations of Proterozoic igneous rocks in south-western Sweden. *GFF* 116, 75–86.
- Welin, E. & Lundqvist, Th. 1977.** Rb-Sr dating of the Råtan granite, central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 99, 417–420.
- Welin, E., Christiansson, K. & Kähr, A.-M. 1993.** Isotopic investigations of metasedimentary and igneous rocks in the Paleoproterozoic Bothnian Basin, central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 115, 285–296.
- Westra, L., Elbers, F.J. & Sijperda, W.W. 1969.** Investigations in the Västervik area, southeastern Sweden. 1. Structural geology and the genesis of “younger” granites. *Geologie en Mijnbouw* 48, 529–544.
- Whalen, J.B., Currie, K.L. & Chappell, B.W. 1987.** A-type granites: geochemical characteristics, discrimination, and petrogenesis. *Contribution to Mineralogy and Petrology* 95, 407–419.
- Wickman, F.E. 1981.** Displacements and the Siljan ring structure. *Geografiska Annaler* 63A, 313–317.
- Wikman, H. 1993.** U-Pb ages of Småland granites and a Småland volcanite from the Växjö region, southern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. *Sveriges Geologiska Undersökning C* 823, 65–72.
- Wikman, H. 1997.** U-Pb ages of three granitoids from the Växjö region, south central Sweden. *Sveriges Geologiska Undersökning C* 830, 63–72.
- Wikman, H. 1998.** Beskrivning till berggrundskartorna Växjö SV och SO. *Sveriges Geologiska Undersökning Af* 188 and 200. 90 p.
- Wikman, H. 2000a.** Kartbladen 5E Växjö. *Sveriges Geologiska Undersökning, Rapporter och meddelanden* 102, 13–14.
- Wikman, H. 2000b.** Beskrivning till berggrundskartorna 5E Växjö NE och NW. *Sveriges Geologiska Undersökning Af* 201 and 216. 108 p.
- Wikman, H., Bruun, Å. & Dahlman, B. 1980.** Beskrivning till berggrundskartan Linköping NV. *Sveriges Geologiska Undersökning Af* 119. 105 p.
- Wikström, A. 1975.** Beskrivning till berggrundskartan Norrköping NO. *Sveriges Geologiska Undersökning Af* 112. 78 p.
- Wikström, A. 1976.** Beskrivning till berggrundskartan Katrineholm SV. *Sveriges Geologiska Undersökning Af* 116. 88 p.
- Wikström, A. 1979.** Structure of the oldest Svecokarelian plutonics. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 119–124.
- Wikström, A. 1984.** A possible relationship between augen-gneisses and post-orogenic granites in SE Sweden. *Journal of Structural Geology* 6, 409–415.
- Wikström, A. 1987.** Magmatic diapirism of granites in south-eastern Sweden. *Revista Brasil. Geociencias* 17, 456–458.
- Wikström, A. 1988a.** The Loftahammar augen gneiss; a discussion. *Geologiska Föreningens i Stockholm Förhandlingar* 110, 191–194.
- Wikström, A. 1988b.** The Loftahammar augen gneiss, revisited. *Geologiska Föreningens i Stockholm Förhandlingar* 110, 289–291.
- Wikström, A. 1991.** Structural features of some younger granitoids in central Sweden, and implications for the tectonic subdivision of granitoids. *Precambrian Research* 51, 151–159.
- Wikström, A. 1992.** Some composite dikes in Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 114, 385–394.
- Wikström, A. 1993.** U-Pb dating of the Stormanbebo rhyolite in the Västervik area, southeastern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results. *Sveriges Geologiska Undersökning C* 823, 73–76.
- Wikström, A. 1995.** Berggrunden på kartbladet 9E Askersund SO. In: Wahlgren, C.-H. (ed.) Regional berggrundsgelogisk underökning. Sammanfattning av pågående undersökningar 1994. *Sveriges Geologiska Undersökning, Rapporter och meddelanden* 79, 17–20.
- Wikström, A. 1996.** U-Pb zircon dating of a coarse porphyritic quartz monzonite and an even grained, grey tonalitic gneiss from the Tiveden area, south central Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results 2. *Sveriges Geologiska Undersökning C* 828, 41–47.
- Wikström, A. & Aaro, S. 1986.** The Finspång augen-gneiss massif – geology, geophysics and relationships to post-orogenic granites. *Sveriges Geologiska Undersökning C* 813. 39 p.
- Wikström, A. & Karis, L. 1991.** Beskrivning till berggrundskartorna Finspång NO, SO, NV, SV. *Sveriges Geologiska Undersökning Af* 162, 163, 164, 165. 216 p.
- Wikström, A. & Karis, L. 1997.** Beskrivning till berggrundskartan Karlskoga SO. *Sveriges Geologiska Undersökning Af* 183. 112 p.
- Wikström, A. & Karis, L. 1998.** Beskrivning till berggrundskartorna Askersund NO och SO. *Sveriges Geologiska Undersökning Af* 186, 195. 143 p.
- Wikström, A. & Larsson, L. 1993.** Geothermometry of garnet-cordierite rocks in Kilsbergen and northern Tiveden, southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 115, 339–344.
- Wikström, A. & Persson, P.-O. 1997.** Two Haparanda type granodiorites with contrasting ages in the southeastern part of Norrbotten County, northern Sweden. In: Lundqvist, Th. (ed.) Radiometric dating results 3. *Sveriges Geologiska Undersökning C* 830, 73–80.

- Wikström, A. & Persson, P.-O. 2002.** A c. 1845 Ma (“Askersund”) age of the Hälla augen gneiss in south-eastern Östergötland, south-east Sweden. In: Bergman, S. (ed.) Radiometric dating results 5. Sveriges Geologiska Undersökning C 834, 58–61.
- Wikström, A., Aaro, S. & Lagmansson, M. 1980.** The Graversfors and Stavsjö granites and some problems connected with the magmatism in the final stages of the Svecokarelian orogeny. Sveriges Geologiska Undersökning C 773. 48 p.
- Wikström, A., Sjöberg, B. & Kapicka, A. 1997.** A precursory study of magnetic fabrics in the transition zone between magmatic and metamorphic textures in the Askersund granitoid, Sweden. GFF 119, 285–290.
- Wilson, M.R. 1980.** Granite types in Sweden. Geologiska Föreningens i Stockholm Förhandlingar 102, 167–176.
- Wilson, M.R. 1982.** Magma types and the tectonic evolution of the Swedish Proterozoic. Geologische Rundschau 71, 120–128.
- Wilson, M.R. & Åkerblom, G. 1980.** Uranium enriched granites in Sweden. Sveriges Geologiska Undersökning, Rapporter och meddelanden 19. 30 p.
- Wilson, M.R., Hamilton, P.J., Fallick, A.E., Aftalion, M. & Michard, A. 1985.** Granites and early Proterozoic crustal evolution in Sweden: evidence from Sm-Nd, U-Pb and O isotope systematics. Earth and Planetary Science Letters 72, 376–388.
- Wilson, M.R., Fallick, A.E., Hamilton, P.J. & Persson, L. 1986.** Magma sources for some mid-Proterozoic granitoids in SE Sweden: geochemical and isotopic constraints. Geologiska Föreningens i Stockholm Förhandlingar 108, 79–91.
- Wolff, F.C., Nysuen, J.P. & Heim, M. 1995.** Geologisk kart over Norge. Berggrunnskart Orsa, M 1 : 250 000. Norges Geologiske Undersøkelse.
- Wood, D.A. 1980.** The Application of a Th-Hf-Ta diagram to problems of tectomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary Volcanic Province. Earth and Planetary Science Letters 50, 11–30.
- Woodhead, J.D., Eggins, S.M. & Johnson, R.W. 1998.** Magma genesis in the New Britain Island Arc: Further Insights into Melting and Mass Transfer Processes. Journal of Petrology 39, 1641–1668.
- Wyllie, P.J., Cox, K.G. & Biggar, G.M. 1962.** The habit of apatite in synthetic systems and igneous rocks. Journal of Petrology 3, 238–243.
- Zuber, J. & Öhlander, B. 1990.** Geophysical and geochemical evidence of Proterozoic collision in the western marginal zone of the Baltic shield. Geologische Rundschau 79, 1–11.
- Zuber, J. & Öhlander, B. 1991.** Gravimetrical and geochemical studies of 1.8 Ga old granites in the Strängnäs-Enköping area, south central Sweden. Geologiska Föreningens i Stockholm Förhandlingar 113, 309–318.