The Mesoproterozoic Hallandian event
- a region-scale orogenic event
in the Fennoscandian Shield

Linus Brander

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ABSTRACT

The Sveconorwegian Province occupies the southwestern part of the Fennoscandian Shield. The easternmost tectonic unit of the Province is the 1710-1660 Ma parautochthonous Eastern Segment, which bears the imprint of at least two metamorphic events; the 1460-1380 Ma Hallandian and the 1150-970 Ma Sveconorwegian. However, the nature and extent of the Hallandian event have been difficult to access due to the Sveconorwegian, effectively masking earlier metamorphic assemblages, structures and relations between rock units.

This thesis aims to characterize the Hallandian event by investigating pre-Sveconorwegian deformation and metamorphism in an area of the Eastern Segment that largely escaped later Sveconorwegian reworking. These results are then considered in a regional perspective and related to ~1.45 Ga magmatism and metamorphism observed elsewhere in Fennoscandia. Considering the compiled data from this time period, it now appears that the Hallandian event indeed was a true orogenic event that affected a large portion of the Fennoscandian Shield.
In the study area, located within the Protogine Zone in the eastern part of the Eastern Segment near Jönköping, Sveconorwegian reworking is restricted to discrete, N-S trending shear-zones. Between these shear-zones, structures, mineral assemblages and geochronological information from pre-Sveconorwegian events are preserved. The first paper provides field, mineral and chemical characteristics, as well as a baddeleyite U-Pb crystallization age of 1455±6 Ma for the Jönköping Anorthositic Suite which is abundant across the study area as small intrusive bodies. In these plagioclase-porphyritic and equigranular anorthositic rocks, deformation is restricted to thin, E-W-trending shear-zones. In the second paper we investigate the deformed country-rocks and date metamorphism and the development of the E-W to SE-NW trending gneissic fabric at 1450-1400 Ma, using U-Pb secondary ion mass spectrometric (ion probe) analysis of complex zircons. The folding event is bracketed between 1440 and 1380 Ma, corresponding to the ages of leucosome formation and the emplacement of a cross-cutting aplitic dyke. In the third paper, the gabbroic Moslätt dolerites are dated at 1269±12 Ma using the U-Pb system in baddeleyite. These have well-preserved magmatic parageneses in contrast to nearby metamorphosed mafic dykes of the 1450-1420 Ma Axamo Dyke Swarm. This precludes the Sveconorwegian event from having caused amphibolite facies metamorphism in the area. In the fourth paper, the first estimate of Hallandian pressure and temperature conditions is obtained from mineral assemblages in one of the E-W-trending shear-zones. Pressure-temperature estimates and hornblende microtextures collectively suggest deformation under conditions of 7-8 kbar and 500-550°C. In the fifth paper we constrain the age of the gneissic fabric in the granitoid country-rock at around 1422 Ma by dating a member of the syn-kinematic felsic Axamo dykes, using the U-Pb ion probe technique. It is suggested that the mafic and plagioclase-porphyritic members of the Axamo Dyke Swarm were emplaced coeval with the Jönköping Anorthositic Suite.

This thesis is the first contribution which recognizes the Hallandian as a regional scale orogenic event, acknowledging all the major features of that age in the Fennoscandian Shield. These features include ~1460 Ma rifting, deposition of clastic sediments and extrusion of continental basalts in central Fennoscandia, 1460-1440 Ma emplacement of I- to A-type granitoids in southern Fennoscandia, 1450-1420 Ma deformation and metamorphism in southern Sweden and on Bornholm, and 1410-1380 Ma post-kinematic pegmatite dykes and intrusions of granite, monzonite and charnockite in the Eastern Segment.

The spatial and temporal trends of these features suggest a tectonic model in which the rifting and mafic magmatism to the north are the far-field effects of north-eastward subduction of an oceanic plate, with the subduction zone located to the southwest of present-day Fennoscandia. Collision with an unknown (micro-) continent led to crustal shortening as Fennoscandia overrode this unknown continent. Post-collisional collapse triggered decompressional melting of heated continental crust, resulting in the emplacement of post-kinematic dykes and plutons

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COMPONENT PAPERS

Paper I
Brander, L. & Söderlund, U. (2009): Mesoproterozoic (1.47-1.44 Ga) orogenic magmatism in Fennoscandia; Baddeleyite U-Pb dating of a suite of massif-type anorthosite in S. Sweden. *International Journal of Earth Sciences (Geologische Rundschau) 98, 499-516 (2009).* © Springer-Verlag 2007. Reprinted with kind permission from Springer Science+Business Media.
Brander did the planning, field work, sampling, mineral and whole-rock chemical analysis, interpretations, tables, most of the figures and most of the writing. The U-Pb baddeleyite geochronology and discussion were done in collaboration with Söderlund, who also contributed with Fig. 7 and writing.

Paper II
Brander, L., Appelquist, K., Cornell, D. & Andersson, U.B. (2011): Igneous and metamorphic geochronologic evolution of granitoids in the central Eastern Segment, southern Sweden. *International Geology Review*. First published on: 13 January 2011 (iFirst). © Taylor & Francis 2011. Reprinted with kind permission from Taylor & Francis.
Brander did the planning, field work, sampling, sample preparation, ion probe work and discussions in collaboration with Appelquist. Brander did most of the writing, all tables and all figures except Fig. 1. Cornell contributed with Nissastigen and Vråna data, discussion and writing. Andersson contributed with discussion and writing.

Paper III
Brander, L., Söderlund, U. & Bingen, B. (2011): Tracing the 1271-1246 Ma Central Scandinavian Dolerite Group mafic magmatism in Fennoscania: U-Pb baddeleyite and Hf isotope data on the Moslätt and Børgefjell dolerites. *Geological Magazine*, available on CJO *2011*. © Cambridge University Press 2011. Reprinted with kind permission from Cambridge University Press.
Brander did the planning, sampling, mineral and whole-rock chemical analyses, and most of the figures, tables and writing. Baddeleyite U-Pb geochronology, Hf-isotope work, interpretations and discussion were made in collaboration with Söderlund. Söderlund and Bingen contributed with figures (Figs. 1 and 6) and writing.

Paper IV
Brander, L., Svahnberg, H. & Piazolo, S. Brittle-plastic deformation in initially dry rocks at fluid present conditions: Transient behaviour of feldspar at mid crustal levels. Resubmitted to *Contributions to Mineralogy and Petrology* after major revisions.
Brander performed mineral analyses and thermodynamic calculations and wrote the geological backgrounds and methods, except the EBSD method. Svahnberg led the EBSD analyses. The rest of the paper (planning, writing and interpretations) is a result of cooperation between Brander and Svahnberg under very good and appreciated supervision by Piazolo.

Paper V
Brander, L., Söderlund, U., Lundqvist, L. & Appelquist, K.: Time-constraints for the 1.47-1.40 Ga Hallandian orogeny in Fennoscandia. Manuscript.
Brander did the sample preparation, ion-probe work, SEM work, tables, writing and figures. Planning, interpretations and discussion were made in collaboration with Söderlund and Lundqvist. The Sm-Nd work was performed in collaboration with Appelquist.

"Hem är trakt, och trakt slutar i skog. Västergötland är slätt och silur; nu önska alrik och erik var sina härader, då blir trakt också härad där skog tager vid. Västergötland glesnar i Viken, i västra Dal, i Värmland, i Tiveden, på Hökensås samt vid den mäktiga bergskedja som från Göta älvs os sträcker sig mitt över den skandinaviska halvön till Östersjöns stränder. Hemman är bo, hem är rike och trakt, härad är trettiotvå och bo är åtta. I mörkret äro vi västgötar alle."

ur Den larmande hopens dal, *av* Erik Andersson

Introduction

Orogeny is an inevitable consequence of plate tectonics. Where plate movements converge, mountain chains rise due to the processes of orogenesis. These processes are governed by subduction zones and arc magmatism, when at least one of the plates is oceanic (noncollisional orogeny) and continental-scale thrusting and deformation, when both plates are continental (collisional orogeny). Collisional orogenies generally contribute very small volumes of new crust compared with noncollisional (e.g. Stern and Scholl 2010); rather they rework the existing continental margins within or near the collision zone. Two of the most well-known orogenies occurring today are those of Himalaya (collisional) and the Andes (non-collisional), but the geological record bears witnesses to recurrent orogeny throughout Earth history.

Cratons, like the Fennoscandian (or Baltic) Shield, are characterized by great thickness of lithosphere (150-300 km) and are dominantly composed of Precambrian crystalline rocks (Fig. 1). Cratons have typically experienced several cycles of rifting, collision and accretion, but have been tectonically stable for at least 1000 Ma. The construction of the Fennoscandian shield started over 3500 Ma ago, but it is debated whether "normal" plate tectonic processes operated during planet Earth's oldest history; possibly other processes controlled the formation of Fennoscandia's oldest crust. Subsequent growth, from ca. 2700 Ma and onwards was related to orogeny, such as island-arc magmatism and accretionary tectonics (e.g. the Svecofennian orogeny), continental-arc magmatism (e.g. the Transscandinavian Igneous Belt magmatism) and continent-continent collision (e.g. the Sveconorwegian orogeny).

The part of the Fennoscandian Shield that was affected by the 1150-970 Ma Sveconorwegian orogeny is called the Sveconorwegian Province and consists of the paratochtonous Eastern Segment and several terranes, differing in nature and ages of protoliths and timing and style of Sveconorwegian reworking. The Eastern Segment constitutes reworked crust of the Transscandinavian Igneous Belt, whereas magmatism and accretion of island-arcs in the terranes west of the Eastern Segment probably occurred during the 1550 Ma Gothian orogeny. The 500 Ma long period between the Gothian and Sveconorwegian orogenies has traditionally been considered a period of tectonic quiescence. However, an increasing amount of geochronological evidence emerging during the last decade has called for a re-evaluation for the 1460-1380 Ma period in the Fennoscandian Shield (e.g. Čečys and Benn 2007; Möller et al. 2007; Bogdanova et al. 2008; Zariņš and Johansson 2009; Papers I, II, V). Evidence comes from investigations on Bornholm, eastern Skåne and in Blekinge (Fig. 1), where granitoid plutons were emplaced directly before or simultaneously with N-S to NE-SW-directed compression at 1450-1430 Ma (Čečys and Benn 2007; Zariņš and Johansson 2009; Fig. 1). Further north, in the Eastern Segment, a large number of metamorphic assemblages and migmatization are dated at ca. 1430 Ma. These new results have called for further attention, since this is the only part of the Fennoscandian crust showing reworking including anatexis in this time period (e.g. Söderlund et al. 2002; Austin Hegardt et al. 2005; Möller et al. 2007). Workers commonly use the terms "Hallandian event" or "Danopolonian orogeny" when referring to magmatic and metamorphic activity during this time period (approximately 1450 Ma, see below). However, the pre-Sveconorwegian history within the Eastern Segment is largely masked by Sveconorwegian overprinting, which affected this part of the shield some 400 Ma after the Hallandian orogeny. The
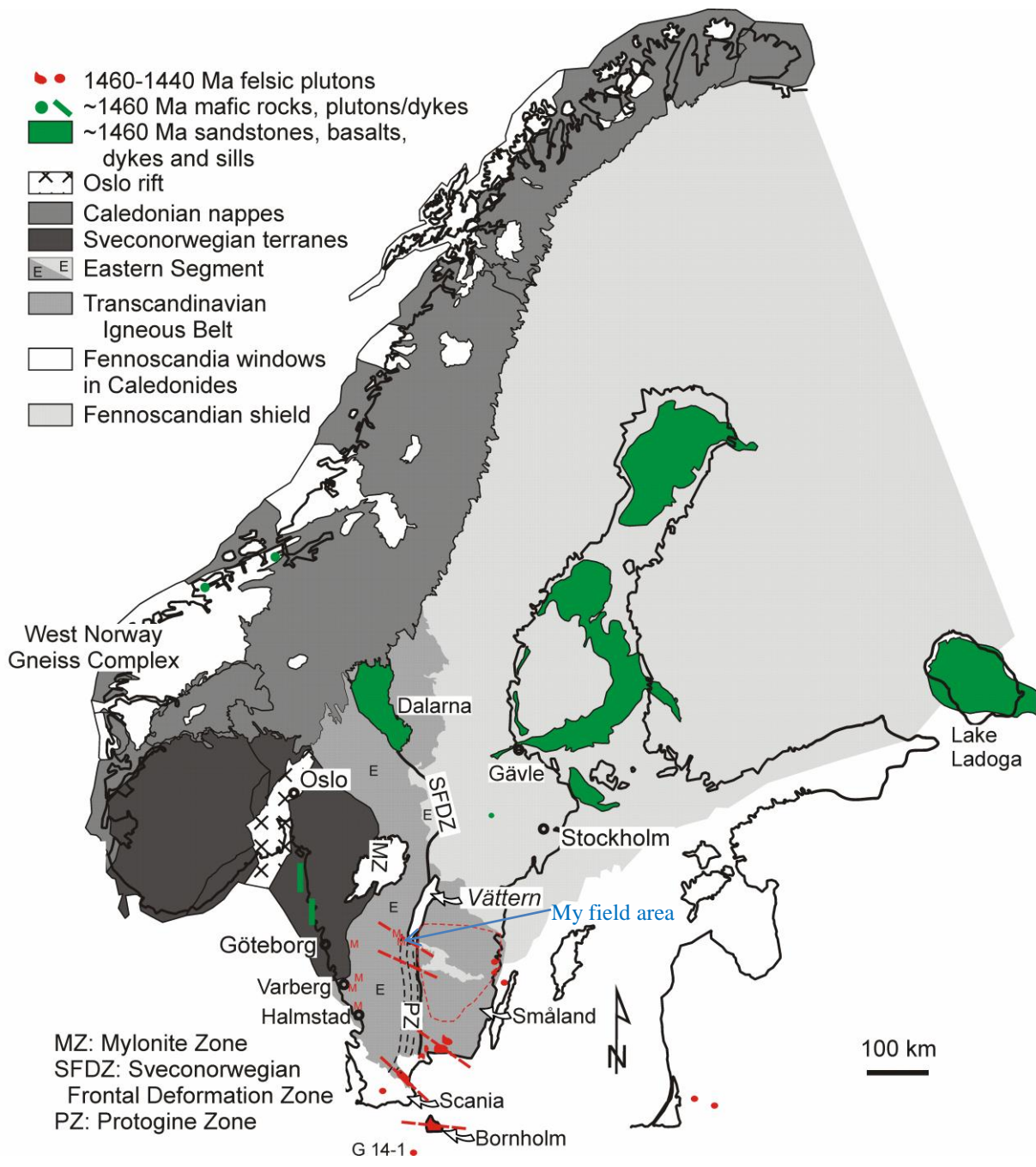
Fig. 1. Map showing the Fennoscandian Shield. The Eastern Segment is delimited by the Mylonite Zone and the Sveconorwegian Frontal Deformation Zone, south of Vättern corresponding to the easternmost Protogine Zone (bold line), according to Berthelsen (1980) and Wahlgren et al. (1994). Stippled red loop marks area of 1500-1400 Ma biotite K-Ar ages in Småland (after Åberg 1978). Red "M" denotes locality of Hallandian migmatization. Stippled red lines show (exaggerated) the general trend of 1450-1420 Ma gneissosity reported by studies discussed in the text. The map is modified from a template kindly provided by Bernard Bingen.

Sveconorwegian event involved migmatization and deformation under high-pressure amphibolite to granulite facies conditions and reset geochronometers with low to moderate closure temperatures.

One way to study the pre-Sveconorwegian history is to survey areas in the Eastern Segment that escaped Sveconorwegian overprinting. My research work has been performed in such an area (figure 4 in Paper V), constricted by discrete N-S trending shear-zones of

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the Protogine Zone, in the easternmost part of the Eastern Segment. The results of previous investigations (e.g. Lundqvist 1996) indicated that this area largely escaped Sveconorwegian reworking, making it possible to study the imprint of the older, pre-Sveconorwegian geological history. The methodology used was mainly U-Pb zircon ion probe (SIMS) and U-Pb baddeleyite thermal ionization mass spectrometer (TIMS) dating of intrusive rock-suites, showing clear relationships with surrounding structures (Papers I-III, V), but also included detailed analysis of microtextures, deformation mechanisms and pressure-temperature conditions in a shear-zone attributed to the Hallandian orogeny (Paper IV).

This thesis summarizes the findings of studies performed in this area, in which many characteristics of the Hallandian event are preserved. The discussion is expanded to include the present knowledge about the Hallandian event, from the Eastern Segment as well as coeval activity in the interior of the Shield. By combining old and new findings, the aim is to show that this was most likely a dynamic (orogenic) event, affecting the southern Fennoscandian Shield on a regional scale.

Nomenclature of the Hallandian Orogeny

Two different terms, partly overlapping, have been used to denote metamorphism, deformation and magmatic activity within the 1470-1380 Ma time period in the Fennoscandian Shield. The term *Hallandian* was introduced over 30 years ago (Hubbard 1975) for a cycle of events in the Varberg region of Halland (Fig. 1), including deposition of supracrustal rocks, folding, amphibolite- to granulite-facies metamorphism and the emplacement of a suite of charnockitic to granitic bodies. Hubbard (1975) also discussed a possible connection to the ca. 1.45 Ga granites in Blekinge. The 'supracrustal' rocks were

later shown to be reworked orthogneisses typical of the Idefjorden Terrane (cf. Lundqvist 1994; Andersson et al. 2002) and the granulite facies metamorphism is now considered by many workers to be the result of Sveconorwegian reworking (cf. Johansson et al., 1991; Möller et al. 2007). Later, the Hallandian has been used for thermo-magmatic events responsible for pre-Sveconorwegian anatexis, emplacement of igneous rock suites, migmatisation and charnockitization of older gneisses in the Varberg-Halmstad region, but not necessarily associated with dynamic reworking (e.g. Åhäll et al. 1997; Christoffel et al. 1999; Söderlund et al. 2002).

The term *Danopolonian* was introduced and defined by Bogdanova (Bogdanova 2001; Bogdanova et al. 2001) for 1550-1450 Ma orogenic activity associated with emplacement of the Anorthosite-Mangerite-Charnockite-Granite (AMCG) suites of eastern Fennoscandia, based on data from deformed granitoids on Bornholm and in Blekinge, and $^{40}Ar/^{39}Ar$ ages from drill cores from northern Poland, Lithuania and Belarus. Later, Bogdanova et al. (2008) revised the time frame of the Danopolonian to 1500-1400 Ma, and included pre-Sveconorwegian ductile structures in the Eastern Segment, but considered the 1400-1380 Ma magmatism in the Varberg-Halmstad region to be post-collisional and representing Hubbard's Hallandian event. Möller et al. (2007), on the other hand, suggested retaining the traditional term Hallandian for the ~1430 Ma metamorphism, migmatization and deformation in the Eastern Segment, as well as younger 1400-1380 Ma intrusions.

In this summary, the 'Hallandian orogeny' is used as a broad term to define 1470-1380 Ma magmatic and metamorphic events in the Fennoscandian Shield, but the terminology may be redefined in the future when these events and how they connect from one region to another, are better understood. The use of Hallandian here is

contradicting our use of Danopolonian in Paper I. When we wrote that paper we chose the Danopolonian thinking that the original meaning of Hallandian should be restricted to localized events in a small part of the Eastern Segment and should not be used outside the Eastern Segment. However, after rereading Hubbard´s paper and his discussion about a possible Hallandian extension across the Protogine Zone, we realize that he actually did not intend to keep this term for the Eastern Segment alone.

Summary of the Component Papers

Paper I

The Jönköping Anorthositic Suite occurs as km-sized bodies across an area in the western Protogine Zone, stretching at least 30 km northwest ward from directly southwest of the southern tip of Vättern (Fig 1; figure 2 in Paper II). In the first paper, the petrography, mineralogy and chemistry for four anorthositic intrusions of the Jönköping Anorthositic Suite are presented. The magmatic emplacement age of the suite is determined by U-Pb baddeleyite TIMS at 1455±6 Ma, which predates the age of the gneissic fabric of the granitoid country-rocks (see Paper II). It is argued that the petrographical, mineralogical and chemical characteristics these rocks exhibit most closely resemble those of *massif-type anorthosites*, as defined by Ashwall (1993). Their small extent does not preclude them from belonging to this class.

Magmatic emplacement ages in the Fennoscandian Shield between 1500 and 1400 Ma compiled in the paper, reveal spatial as well as temporal trends. Mafic magmatism is restricted to the time period 1465-1455 Ma and to central Fennoscandia, in contrast with the 1460-1440 Ma felsic magmatism that occupies the southern part (figures 7 and 8 in Paper I). Anatexis and metamorphism at 1470-1370 Ma in the Eastern Segment peak at 1425 Ma (figure 8 in Paper I). These trends

are suggested to reflect intra-continental rifting as far-field effects from Hallandian (Danopolonian) convergent-margin processes to the south or southwest of the Fennoscandian Shield.

Paper II

The aim of Paper II was to identify crust-forming and metamorphic events in the Protogine Zone area of the Eastern Segment, west of Jönköping (figure 2 in Paper II); the rocks there constitute the country rocks to the Jönköping Anorthositic Suite (Paper I). The rocks in the eastern part of this area are deformed but still discernable granites (referred to as weak gneisses) of the 1810-1650 Ma Transscandinavian Igneous Belt (TIB), in contrast with the thoroughly reworked orthogneisses further to the west (figure 3 in Paper II). Numerous outcrops along a ~30 km long traverse across this border zone were investigated and U-Pb geochronology was carried out on complex zircons from a total of 20 samples using the ion probe at the NORDSIM laboratory in Stockholm.

We found that the protolith age of all studied rocks falls in the range 1710-1660 Ma, without any significant age trend across the traverse. The similar ages and the occurrence of 1690 Ma leucocratic granites across the traverse support the hypothesis that the strongly reworked Eastern Segment constitutes a tectonized and metamorphosed continuation of TIB-2 (1710-1650 Ma) intrusions. Inherited 1800 Ma zircons in one of the 1690 Ma easternmost samples suggest the presence of TIB-1 aged (1810-1760 Ma) rocks at depth.

Secondary zircon rims and replacement domains, exclusively of Hallandian age ($^{207}Pb/^{206}Pb$ ages 1450-1380 Ma; calculated ages 1440-1430 Ma), are found in more than half the samples, in the weak gneisses as well as in the orthogneisses to the west. It is shown that secondary growth of zircon is restricted to samples with E-W to SE-NW-trending

structures whereas secondary zircon is not found in samples with N-S-trending fabrics. This observation, in combination with the complete lack of zircon rims of Sveconorwegian age, makes it logical to conclude that the E-W to NW-SE trending structures in the area are Hallandian in age.

Leucosome formation dated at 1440 Ma at both Vråna and Nissastigen (figure 2 in Paper II) further supports this interpretation. The presence of an 1380 Ma aplitic dyke, cross-cutting the folded leucosome at the Vråna locality, further allow us to constrain the tectonic evolution in the area. The age of the dyke brackets the event of NW-SE folding between 1440 and 1380 Ma in this part of the Eastern Segment. A 1370 Ma titanite U-Pb age obtained from the Nissastigen injection migmatite is similar to previous U-Pb titanite ages obtained in this area (figure 4 in Paper V; Lundqvist 1996).

Paper III

In this paper we present U-Pb and Hf isotope data on baddeleyite from a member of the well-preserved Moslätt dolerite dykes located within the Protogine Zone west of Jönköping (figure 3 in Paper III) and a member of the Børgefjell metadolerites in the Lower Allochthon of the Caledonian Province. Additionally, baddeleyite Hf data from a member of the Satakunta complex of the Central Scandinavian Dolerite Group and the two dated members of the Jönköping Anorthositic Suite (Paper I) are included.

The conclusions of this study emphasize the southward and westward expansion of the region of known Central Scandinavian Dolerite Group magmatism, provided by the two dated samples. The possible link between bimodal magmatism in the Telemarkia Terrane of the Sveconorwegian orogen and the Central Scandinavian Dolerite Group is discussed, as is the probable source for dolerite magmas. The highly positive values of ε_{Hf} indicate a dominant Depleted Mantle component in the source. The large spread

down to lower, but still positive, values of ε_{Hf} is probably due to various degree of crustal contamination. Because Telemarkia and Fennoscandia contain rocks of similar age, this has bearings for the debate about whether or not Telemarkia is a Sveconorwegian exotic terrane.

One of the more important results is the 1269±12 Ma age of the almost pristine Moslätt dolerite, located amongst amphibolite facies mafic members of the 1450-1420 Ma Axamo Dyke Swarm (Fig. 2). This constrains the metamorphism between 1450 and 1270 Ma, hence in agreement with Hallandian rather than Sveconorwegian metamorphism in this area.

Paper IV

E-W trending shear-zones typically 5-10 cm wide, are abundant in most rock-types in the area shown in Fig. 2. The E-W orientation of these shear-zones coincides with the orientation of the regional fabric and they are particularly well developed in the 1455 Ma Jönköping Anorthositic Suite rocks (Paper I). Thus, the shear-zones in these competent rocks record the regional 1450-1410 Ma fabric-forming event (Paper II).

In Paper IV, we investigate a protomylonitic shear-zone in a porphyritic member at the Skinnarebo locality of the Jönköping Anorthositic Suite. This was done on the micro-scale by petrographic microscope and scanning electron microscope with backscattered electron images and electron backscattered diffraction (EBSD) in order to reveal the mechanisms, conditions and history of deformation. Protomylonites are characterized by fractured and elongated plagioclase porphyroclasts with preserved igneous composition, separated by matrix bands characterized by grain-size reduction and the growth of new phases. The localization of strain in initially fresh, dry and isotropic anorthosite, into thin shear-zones, probably starts by fracturing and grain-size reduction of the 1-10 cm large
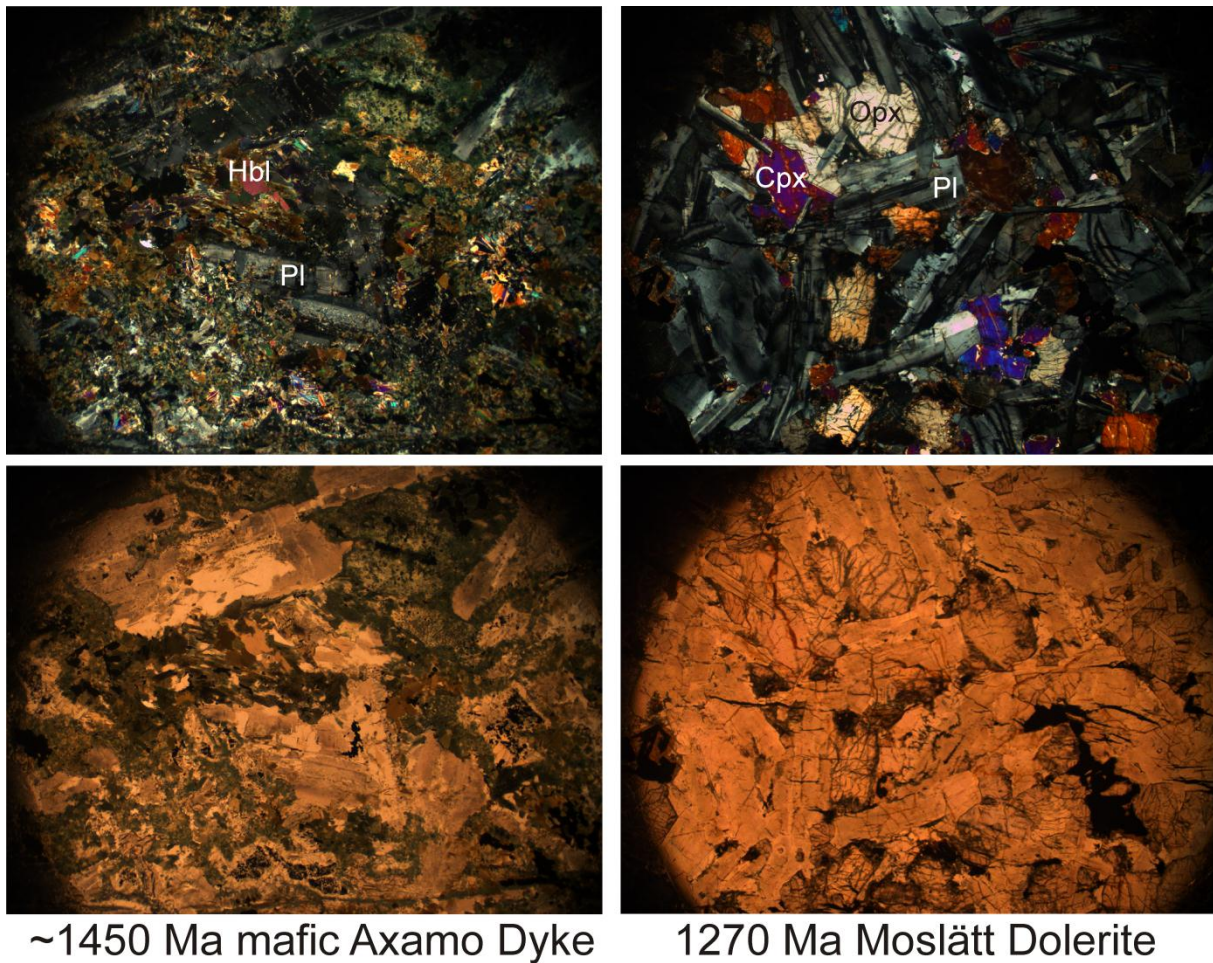
~1450 Ma mafic Axamo Dyke   1270 Ma Moslätt Dolerite

Fig. 4. Thin-sections from a metamorphosed mafic member of the 1450 Ma Axamo Dyke Swarm and a pristine gabbronoritic member of the 1270 Moslätt Dolerites. Upper photos are with crossed polarizers, lower are in plane light. Pl = plagioclase, Hbl = hornblende, Opx = orthopyroxene and Cpx = clinopyroxene. Shown areas are ~12 x 8 mm large.

plagioclase phenocrysts. This provides pathways for fluids, which in turn promotes further plastic deformation.

By the construction of a phase diagram using thermodynamic data, the calculation of average pressure and temperature from mineral compositions, and the analysis of microtextures in hornblende, deformation conditions are estimated at about 7-8 kbar and 500-550°C. The microtextures of hornblende include grain-size reduction, low-angle misorientations between some of the small and large grains and slip on the (100)<001> system, producing a crystallographic preferred orientation. The deformation mechanisms suggested by these textures are dislocation creep and subgrain rotation recrystallisation,

consistent with our inferred deformation conditions. This represents the first estimate of metamorphic conditions related to the Hallandian orogeny.

Paper V
The main idea with this paper is to investigate the relationship between a composite dyke of the Axamo Dyke Swarm and the regional gneissic fabric. We also want to verify the previously determined ages of the Jönköping Anorthositic Suite and the felsic members of the Axamo Dyke Swarm, since the geochronological mismatch between these two suites revealed in Paper II is in conflict with other characteristics, such as field-appearance, rock types and chemistry, which suggest that they are coeval.

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Two important conclusions are drawn from the new U-Pb zircon SIMS age of 1422 ±7 Ma for a felsic member of the Axamo Dyke Swarm. First, it verifies the earlier TIMS age of 1410±10 Ma (Lundqvist 1996). Second, it provides a maximum age for gneiss formation of the TIB country rocks, since the foliation is seen continuous into another felsic member of the Axamo Dyke Swarm. Due to the lack of chilled margins and the presence of xenoliths of gneissic TIB country-rocks in some of the felsic dykes, the felsic members are interpreted to be syn- to latekinematic, suggesting that the main deformation took place at 1420 Ma or slightly before. The U-Pb zircon SIMS age of 1453±7 Ma for a granodioritic rock which shows mingling with a porphyritic member of the Jönköping Anorthositic Suite is in agreement with the U-Pb baddeleyite TIMS age of 1455±6 Ma reported in Paper I, obtained from an equigranular member at the same locality.

The possibility of mafic non-porphyritic and plagioclase-porphyritic members of the Axamo Dyke Swarm being coeval and comagmatic with the Jönköping Anorthositic Suite is also discussed, leading to the suggestion of a 30 Ma hiatus between mafic and felsic members of the swarm, the felsic members being significantly younger at 1420 Ma. This hypothesis relies on the similarities in field appearance and rock types reported by Lundqvist (1996), together with the similarities in geochemistry and Nd-isotopes reported in Paper V. Emplacement of mafic dykes at 1420 Ma is also in conflict with the compressional regime at that time, testified by the ~1420 Ma gneissosity. It is therefore suggested that the Jönköping Anorthositic Suite and the mafic dykes of the Axamo Dyke Swarm intrude at ~1450 Ma in an area of local extension, followed by compression, crustal melting and emplacement of felsic dykes at ~1420 Ma.

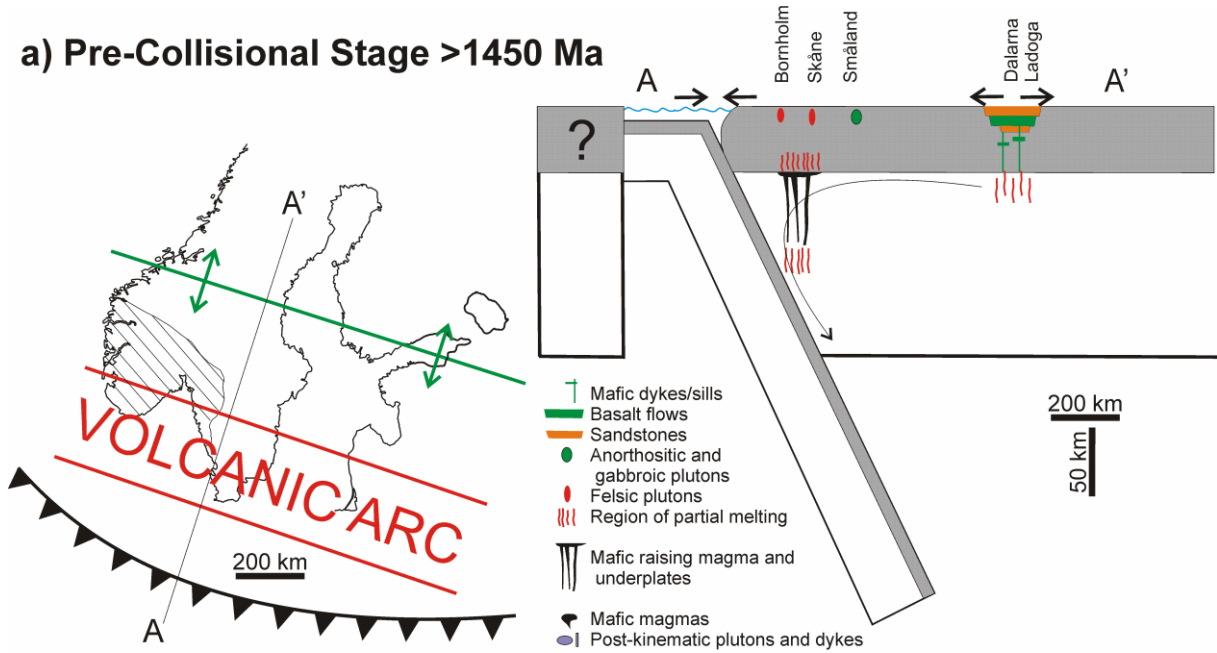**Synthesis: The Hallandian orogeny**
The recognition of the Hallandian as a dynamic event relies on establishing the timing of deformation and the extent of tectonic activity. In this section, a model of the Hallandian orogenic evolution is presented in chronological order. The model is shown in Fig. 3.
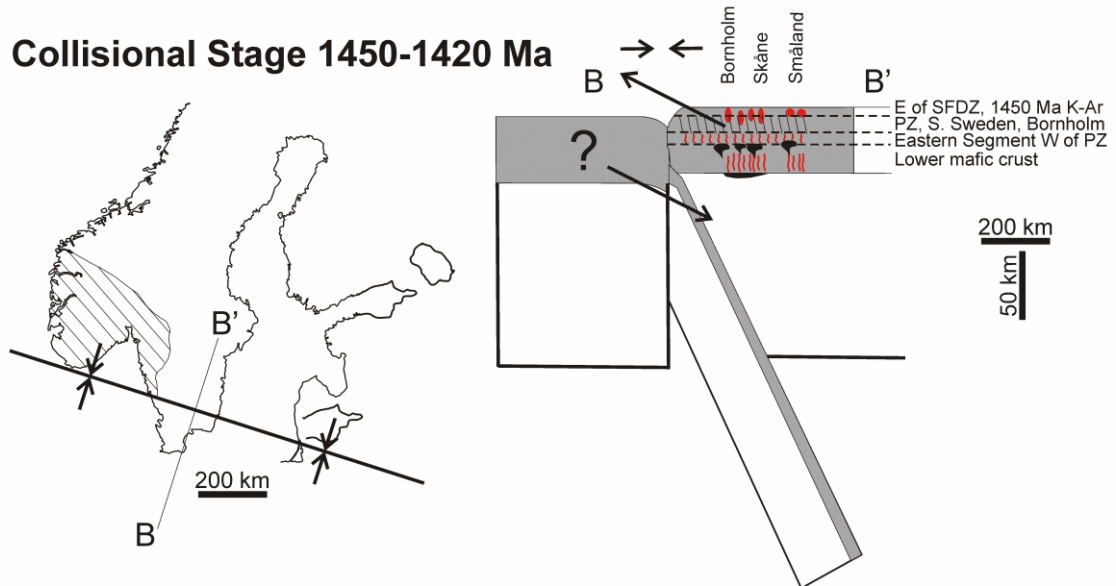
Pre-collisional stage (>1450 Ma)
Following a long period of dispersed emplacement of large AMCG-suites between 1650 and 1500 Ma (references in Paper I), an active margin was established along the south-western border of the Fennoscandian Shield (cf. Paper I). Northeastward subduction of oceanic lithosphere and associated mantle drag in this active margin caused back-arc extension in the interior of the shield several hundreds of km behind the volcanic arc (Fig. 3a), reflecting distances typically observed in modern arc systems (Moores and Twiss 1995, p. 158; Faccenna et al. 2001; Lebedev et al. 2006). Evidence of extension in the central Scandinavian area comes from the emplacement of 1465-1452 Ma mafic dykes and sills and gabbroic to anorthositic intrusions as well as extrusion of continental flood basalts in an extensive region from Lake Ladoga in the east to the Norwegian coast in the west (Fig. 1; see compilation in table 4, Paper I). This voluminous continental basalt magmatism was associated with the deposition of clastic sediments into grabens, with long axes generally trending NW - SE, documenting rifting parallel with the inferred subduction zone to the SW (Fig. 3a). Preserved 1-2 km-thick packages of conglomerate, arkose, sandstone and intercalated sheets of basalt occur over a large area in the central part of the Fennoscandian Shield (Fig. 1).

The basalt eruptions and sedimentation are often referred to as *Jotnian*, which denotes a period of broadly Mesoproterozoic age. However, unconformable contacts to 1590-1540 and 1500 Ma Rapakivi granites in the Lake

a) Pre-Collisional Stage >1450 Ma

Bornholm
Skåne
Småland

Dalarna
Ladoga

A A'

?

Legend:
- Mafic dykes/sills
- Basalt flows
- Sandstones
- Anorthositic and gabbroic plutons
- Felsic plutons
- Region of partial melting
- Mafic raising magma and underplates
- Mafic magmas
- Post-kinematic plutons and dykes

VOLCANIC ARC

200 km

200 km

50 km

b) Collisional Stage 1450-1420 Ma

Bornholm
Skåne
Småland

B B'

?

E of SFDZ, 1450 Ma K-Ar
PZ, S. Sweden, Bornholm
Eastern Segment W of PZ
Lower mafic crust

200 km

200 km

50 km

c) Post-Collisional Stage 1420-1380 Ma

Bornholm
Skåne
Småland

C C'

?

E of SFDZ, 1450 Ma K-Ar
PZ, S. Sweden, Bornholm
Eastern Segment W of PZ
Lower mafic crust

200 km

200 km

50 km

Fig. 3. (previous page) Maps and sections illustrating the three discussed stages in a model for the Hallandian orogeny. The vertical scale in sections is exaggerated four times relative the horizontal (see scale bars). Some geologic units, like intercalated basalt and sandstone, are further exaggerated in order to be visible in the figure. In sections, grey is crust whereas white delimited by black lines is mantle lithosphere.

Ladoga and Gävle areas, respectively, suggest that Jotnian rocks are younger than 1500 Ma (Suominen 1991; Amantov et al. 1996; Andersson 1997). In the Lake Ladoga area, two intercalated sheets of basalt lava (each ~100 m thick) are associated with the 150 m thick 1457±3 Ma Valaam sill (Rämö 2003) and a set of 1452±12 Ma dolerite dykes (Lubnina et al. 2010), hence yielding direct age constraints for Jotnian magmatism. In Dalarna, the Öje basalt accounts for about 100 m of the 900 m Jotnian sandstone-basalt stratigraphy, separating the Dala sandstone into a lower and upper sequence. Only the lower sequence is cut by the 1462±1 Ma Bunkris dyke (Söderlund et al. 2005), indicating deposition both before and after 1460 Ma. This dyke was most likely a feeder-dyke for the Öje Basalt, because of the overall similarities in chemistry and the appearance of the dyke and the basalt (Nyström 2004). Like the basalts in Lake Ladoga, the Öje basalt actually consists of a number of individual lava flows, separated by thin sandstone layers. Thus rifting, sedimentation and basalt eruption in the region most likely occurred close to and around 1460 Ma.

The effect of subduction farther south, closer to the inferred trench, was somewhat different (Fig. 3a). Here, no mafic rocks have been identified; rather the southern border of the Fennoscandian Shield was the scene of emplacement of granite, granodiorite, tonalite, quartz monzodiorite and quartz monzonite plutons between 1460 and 1440 Ma (e.g. Åhäll 2001; Obst et al. 2004; Zariņš and Johansson 2009; Čečys and Benn 2007; Motuza et al. 2006), here interpreted to represent a fossil volcanic arc (Fig. 7). Although collectively often referred to as being of A-type and characterized as so called anorogenic rocks, only the Götemar and Jungfrun are

true A-type granites (Åberg et al. 1984). Some of the others have affinity to A-type in some aspect, like high contents of high field-strength element and high Ga/Al ratios, but dominantly they are meta- to weakly peraluminous I-type granitoids and syenitoids, classified as K-rich to amphibole-rich alkali-calcic to calc-alkaline rocks (e.g. Čečys et al. 2002; Obst et al. 2004; Motuza et al. 2006; Čečys and Benn 2007; Zariņš and Johansson 2009.

Subduction-related mafic rocks of this age are not preserved in the accessible crust of southern Fennoscandia, with the exception of the Jönköping Anorthositic Suite occurring at the southern tip of Vättern (Papers I and V) and in west central Norway (the Selsnes and Haram gabbros, see Paper I for references). The chemistry of equigranular members of the Jönköping Anorthositic Suite supports a subduction zone setting at this time (Papers I and V), in line with Ashwal (2008), who proposed an andean type of setting capable of producing massif-type anorthosites. Also in the Kongsberg, Bamble and Telemarkia Terranes in the western part of the Sveconorwegian Province, calc-alkaline plutons as young as 1460 Ma are abundant (Fig. 1). In the latter terrane, the 1520-1480 Ma old crust was probably created in an active margin setting in what is referred to as the Telemarkian event (Bingen et al. 2005, 2008; Åhäll and Connelly 2008). An analogous crustal block may have existed farther south along the Fennoscandian margin, representing subduction before the Hallandian orogeny (Fig. 3a).

It is inferred that the I-type felsic plutons of Småland, Blekinge, Bornholm and Lithuania do represent volcanic arc magmatism. The synkinematic nature of some of these plutons and the lack of mafic magmatism suggest a subduction zone in

which compression was dominant, perhaps due to continent ward migration of the trench (i.e. a destructive boundary). Continent ward migration of the subduction zone is also supported by the age pattern of the 1460-1440 Ma felsic plutons shown in Fig. 1., where the 1460-1450 Ma more calc-alkaline magmatism occurs closer to the trench (e.g. Bornholm, Lithuania, Skåne and G 14-1 borehole outside Rügen; see table 4 in Paper I for ages), whereas the A-type granites in Småland, farther from the trench, are 1450-1440 Ma old (Åhäll 2001; Fig. 3a and 3b).

Collisional stage (1450-1420 Ma)

Following consumption of the oceanic plate, a continental block of unknown origin collided with the Fennoscandian Shield from the southwest, simultaneously with emplacement with some of the ~1450 Ma felsic plutons (Fig. 3b). The south-western margin of the Fennoscandian Shield was thickened by compressional tectonics, and overrode the southern continent. Regional scale, E-W to NW-SE trending, gneissic fabrics (Fig. 1) have been constrained at 1460-1430 Ma on the island of Bornholm (Holm et al. 2005; Zariņš and Johansson 2009), 1460-1445 Ma in Blekinge and Scania (Čečys et al. 2002; Čečys and Benn 2007), 1450-1420 Ma in a metabasite along the Protogine Zone 30 km south of Vättern (Söderlund et al. 2004), and 1440-1420 Ma in my field-area (Paper II and V). Pressure and temperature estimates from the latter suggest depths of 20-25 km and heating to 500-550°C during metamorphism (Paper IV), even though temperatures were obviously higher in deeper crustal sections, further to the west. Accordingly, in the Eastern Segment south of the lake Vänern, high-temperature metamorphism and local melting with leucosome formation and dyking occurred between 1470 and 1410 Ma, with the peak at 1430-1425 Ma (figure 8 in Paper I). Söderlund et al. (2002), Austin Hegardt et al. (2005) and Möller et al. (2007) reported Hallandian migmatization between 1450 and 1415 Ma in the Halmstad-Varberg-Borås area (Fig. 1). North of Halmstad (Fig. 1), Christoffel et al. (1999) discovered that pre-Sveconorwegian gneiss fabric formed before 1426 $^{+9}/_{-4}$ Ma. Folding around a NW-SE-trending axial plane at Vråna is constrained between 1440 and 1380 Ma, the ages of the folded leucosome and a cross-cutting aplitic dyke, respectively (Paper II).

In contrast with the Eastern Segment, no dynamic metamorphism has been reported from the 1810-1660 Ma volcanic and intrusive rocks in the Transscandinavian Igneous Belt to the east. U-Pb zircon ages from Hallandian metamorphism have not been found, however, 1480-1400 Ma K-Ar biotite ages from the area between the Protogine Zone and the Swedish east coast (Fig. 1) were presented by Åberg (1978), suggesting larger volumes of 1450 Ma intrusives at depth, or a region-scale thermal disturbance.

The differences in style of deformation and metamorphism between these different areas probably reflect exposure of different crustal levels, with crustal depths increasing westward. At 1450 Ma, eastern Sweden (i.e. Småland) represents shallow crustal levels, the Protogine Zone area, Bornholm and Skåne represent intermediate depths and the Eastern Segment west of the Protogine Zone correspond to deep levels.

Post-collisional stage (1420-1370 Ma)

The end of compressional tectonics may have been triggered by break-off of the oceanic slab, leading to orogenic collapse (Fig. 3c). Melting of heated rocks at depth led to the emplacement of late- to post-kinematic granites, pegmatites and aplitic dykes at 1410-1380 Ma. The Varberg granite intruded at 1399+12/-10 Ma (Christoffel et al. 1999) whereas the megacrystic Torpa granite was emplaced at 1380±6 Ma (Fig. 6; Åhäll et al. 1997). In the same area, the coarse-grained Tjärnesjö

granite to quartz monzonite massif intruded at 1370 Ma (Andersson et al. 1999). The plutonic rocks were largely restricted to the Varberg-Ullared area, whereas pegmatitic, granitic and aplitic dykes were more widely emplaced in the Eastern Segment during this period (e.g. Söderlund et al. 1996; Christoffel et al. 1999; Paper II; V). The time frames are reasonable comparing to other orogenies (e.g. Dörr and Zulauf 2010).

High-temperature conditions prevailed in the Eastern Segment for a considerable time period. In my field-area in the easternmost part of the Eastern Segment, where the Sveconorwegian orogeny did not succeed in resetting the U-Pb isotopic system of titanite, temperatures dropped below ~600°C at 1400-1370 Ma (Lundqvist 1996; Paper I), probably reflecting the termination of the Hallandian orogeny. Only ten kilometres to the west, at Vråna (figure 4 in Paper V), resetting of the titanite U-Pb system occurred during the Sveconorwegian orogeny, as seen in most of the Eastern Segment (Connelly et al. 1996).

The Samba connection
Johansson (2009) suggested a common history between Baltica (Fennoscandian Shield) and Amazonia, in which Amazonia occupied and inhibited subduction along the southern margin of Baltica between 1800 and 800 Ma. The model was based on the spatial and temporal fit of geological units and events between the two continents. This configuration allows easterly subduction and the formation of TIB-2 plutonic rocks (e.g. Åhäll and Connelly 2008) as well as E-W convergence during the subsequent Sveconorwegian orogeny (e.g. Bingen et al. 2008), but is in conflict with models proposing N-S directed plate convergence at the southern margin of Fennoscandia at 1800-1780 Ma (Andersson et al. 2004; Rutanen and Andersson 2009), 1500-1400 Ma (Paper II; Bogdanova et al. 2008) and 1000 Ma (Möller et al. 2007). It is also in conflict with a new palaeomagnetic model for 1100 Ma, in which Amazonia is placed in the polar regions of the northern hemisphere whereas Fennoscandia (Baltica) is placed immediately south of the equator (Evans 2009).

The Sveconorwegian Terranes
Mafic magmatism at 1460-1450 Ma did not only occur in the Eastern Segment and the interior of the Fennoscandian Shield, but also in the Idefjorden Terrane, there represented by the Kattsund-Koster and Orust dykes. They deviate from the trends of dolerites in Dalarna by being N-S-trending rather than NW-SE-trending, but large-scale movements and reorientation of crustal units may have occurred during the Sveconorwegian orogeny. Alternatively, since the Idefjorden Terrane does not show other signs of dynamic Hallandian reworking (such as metamorphism or anatexis), the Idefjorden Terrane was perhaps not even part of Fennoscandia at the time, or was positioned farther to the north along the Fennoscandian margin before the Sveconorwegian orogeny (cf. Bingen et al. 2008).

Conclusions
This thesis provides new finding from an area within the Protogine Zone of the Eastern Segment, an area that preserves i) structures; ii) zircon, baddeleyite and titanite U-Pb isotope information; and iii) mineral assemblages, from pre-Sveconorwegian events. Furthermore it suggests a model for the Hallandian event in the Fennoscandian Shield.

In **Paper I**, field, mineral and chemical characteristics of the Jönköping Anorthositic Suite were presented and it was interpreted to represent massif-type anorthosite. The crystallization age was determined at 1455±6, using U-Pb baddeleyite TIMS technique.

In **Paper II**, we identified Hallandian metamorphism, anatexis, folding and gneiss formation in U-Pb zircon SIMS data. This is the most northerly and

easterly example of Hallandian dynamic reworking discovered so far. The age of folding was constrained between 1440 and 1380 Ma.

Paper III provided the emplacement age at 1269±12 Ma for gabbronoritic dolerites in the area, with well-preserved magmatic parageneses in contrast to nearby metamorphosed mafic dykes of the 1450-1420 Ma Axamo Dyke Swarm. Thereby we excluded the Sveconorwegian orogeny as responsible for amphibolite facies metamorphism.

In **Paper IV**, the first estimate of Hallandian pressure and temperature conditions was presented from a shear-zone assemblage. PT calculations and hornblende microtextures suggested conditions in the range 500-600°C and 7-8 kbar.

With **Paper V**, we constrained the age of the gneissic fabric in the granitoid country-rock at about 1422 Ma by dating a member of an apparently synkinematic felsic members of the Axamo Dyke Swarm using the U-Pb SIMS technique.

A **model** is suggested, in which subduction of an oceanic plate along the southern to southwestern margin of the Fennoscandian Shield causes ~1460 Ma rifting, deposition of (arkosic) sandstones and eruption of continental basalts, along a line parallel with the trench axis but several 100s of km inland from it. At the same time, continental arc magmatism occurs in a compressional arc setting much closer to the inferred trench. Between 1450 and 1420 Ma the Fennoscandian Shield collides with an unknown continent or microcontinent, leading to amphibolite facies metamorphism, gneiss formation, migmatization and folding, or simply resetting of the biotite K-Ar system, depending on crustal level. Break-off of the oceanic plate destabilizes the colliding masses and the orogeny collapses soon after 1420 Ma. Post-kinematic plutons and dykes are emplaced at 1410-1370 Ma. This study also supports an Andean-type of setting for the emplacement of massif-type anorthosites, which traditionally have been assigned to so called anorogenic regimes.

References

Åberg, G. (1978) Precambrian geo-chronology of south-eastern Sweden. *GFF* **100**, 125-153.

Åberg, G., Löfvendahl, R. and Levi, B. (1984) The Götemar granite – isotopic and geochemical evidence for a complex history of an anorogenic granite. *GFF* **106**, 327-333.

Åhäll, K.I. (2001) Åldersbestämning av svårdaterade bergarter i sydöstra Sverige. SKB R-01-60, 5-28.

Åhäll, K.I. and Connelly, J.N. (2008) Long-term convergence along SW Fennoscandia: 330 m.y. of Proterozoic crustal growth. *Precambrian Research* **161**, 452-472.

Åhäll, K.I., Connelly, J.N. and Brewer, T.S. (2000) Episodic rapakivi magmatism due to distal orogenesis? Correlation of 1.69-1.50 Ga orogenic and inboard, "anorogenic" events in the Baltic shield. *Geology* **28**, 823-826.

Åhäll, K.-I. And Gower, C.F. (1997) The Gothian and Labradorian orogens: variations in accretionary tectonism along a late Paleoproterozoic Laurentia-Baltica margin. *GFF* **119**, 181-191.

Amantov, A., Laitakari, I. and Poroshin Y (1996) Jotnian and Postjotnian: sandstones and diabases in the surroundings of the Gulf of Finland. Geological Survey of Finland Special Paper 21, 99-113.

Andersen, T., Andersson, U.B., Graham, S., Åberg, G. and Simonsen, S.L. (2009) Granitic magmatism by melting of juvenile continental crust: new constraints on the source of Palaeoproterozoic granitoids in Fennoscandia from Hf isotopes in zircon. *Journal of Geological Society, London* **166**, 233-247.

Andersen, T., Griffin, W.L. and Sylvester, A.G. (2007) Sveconorwegian crustal underplating in southwestern Fennoscandia: LAM-ICPMS U-Pb and Lu-Hf isotope evidence from granites and gneisses in Telemark, southern Norway. *Lithos* **93**, 273-287.

Andersson, J., Möller, C. and Johansson, L. (2002) Zircon geochronology of migmatite gneisses along the Mylonite Zone (S Sweden): a major

Sveconorwegian terrane boundary in the Baltic Shield. *Precambrian Research* **114**, 121-147.

Andersson, J., Söderlund, U., Cornell, D., Johansson, L. and Möller, C. (1999) Sveconorwegian (-Grenvillian) deformation, metamorphism and leucosome formation in SW Sweden, SW Baltic Shield: constraints from a Mesoproterozoic granite intrusion. *Precambrian Research* **98**, 151-171.

Andersson, U.B. (1997) The sub-Jotnian Strömsbro granite complex at Gävle, Sweden. *GFF* **119**, 159-167.

Andersson, U.B., Sjöström, H., Högdahl, K. and Eklund, O. (2004) The Transscandinavian Igneous Belt, evolutionary models. *In* K. Högdahl, U.B. Andersson and O. Eklund (eds.): *The Transscandinavian Igneous Belt in Sweden: a review of its character and evolution*. Geological Survey of Finland Special Paper 37, 123 pp.

Ashwal, L.D. (1993) Anorthosites. Springer-Verlag, Berlin, pp 422.

Ashwal, L.D. (2008) Proterozoic magma -tism: How can we constrain tectonic setting? Joint Annual Meeting GAC – MAC – SEG – SGA in Quebec 2008.

Austin Hegardt, E. (2010) Pressure, temperature and time constraints on tectonic models for southwestern Sweden. *Ph.D. thesis for Doctoral Degree, University of Gothenburg, Gothenburg, Sweden. 26 pp and five papers*.

Austin Hegardt, E., Cornell D., Claesson, L., Simakov, S. and Hannah, J. (2005) Eclogites in the central part of the Sveconorwegian Eastern Segment of the Baltic Shield: Support for an extensive eclogite terrane. *GFF* **127**, 221-232.

Berthelsen, A. (1980) Towards a palinspastic tectonic analysis of the Baltic Shield. *In* J. Cogné and M. Slansky, (eds.): *Geology of Europe from Precambrian to Post-Hercynian Sedimentary Basins*, 5-21. International Geological Congress Colloq C6, Paris.

Bingen, B., Nordgulen, Ø. and Viola, G. (2008) A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. *Norwegian Journal of Geology* **88**, 43-72.

Bingen, B., Skår, Ø., Marker, M., Sigmond, E.M.O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R.D. and Liégeois, J.-P. (2005) Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology* **85**, 87-116.

Bogdanova, S.V. (2001) Tectonic settings of 1.65-1.4 Ga AMCG magmatism in the western East European Craton (western Baltica). *Journal of Conference Abstracts* **6**, 769.

Bogdanova, S.V., Bingen, B., Gorbatschev, R., Kheraskova, T., Kozlov, V., Puchkov, V. and Volozh, Y. (2008) The East European Craton (Baltica) before and during the assembly of Rodinia. *Precambrian Research* **160**, 23-45.

Bogdanova, S.V., Page, L.M., Skridlaite, G. and Taran, L.N., (2001) Proterozoic tectonothermal history in the western part of the East European Craton: 40Ar/39Ar geochronological constraints. *Tectonopysics* **339**, 39-66.

Brueckner, H.K. (2009) Subduction of continental crust, the origin of post-orogenic granitoids(and anorthosites?) and the evolution of Fennoscandia. *In* Eclogite-facies rocks; a window into geodynamics and lithospheric evolution. *Journal of the Geological Society of London* **166(4)**,753-762.

Čečys, A. and Benn, K. (2007) Emplacement and deformation of the ca. 1.45 Ga Karlshamn granitoid pluton, southeastern Sweden, during ENE-WSW Danopolonian shortening. *International Journal of Earth Sciences (Geologische Rundschau)* **96**, 397-414.

Čečys, A., Bogdanova, S., Janson, C., Bibikova, E. and Kornfält K.-A. (2002) The Stenshuvud and Tåghusa granitoids: new representatives of

Mesoproterozoic magmatism in southern Sweden. *GFF* **124**, 149-162.

Christoffel, C., Connelly, J.N. and Åhäll K.-I. (1999) Timing and characterization of recurrent pre-Sveconorwegian metamorphism and deformation in the Varberg-Halmstad region of SW Sweden. *Precambrian Research* **98**, 173-195.

Connelly, J.N., Berglund, J. and Larson S.Å. (1996) Thermotectonic evolution of the Eastern Segment of SW Sweden; tectonic constraints from U-Pb geochronology. In TS Brewer (ed): Precambrian Crustal Evolution in the North Atlantic Regions. *Geological Society of London Special Publications* **112**, 297-313.

Dörr, W. and Zulauf, G. (2010) Elevator tectonics and orogenic collapse of a Tibetan-style plateau in the European Variscides: the role of the Bohemian shear zone. *International Journal of Earth Sciences (Geologische Rundschau)* **99**, 299-325.

Evans, D.A.D. (2009) The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. *Geological Society, London, Special Publications* **327**, 371-404.

Faccenna, C., Funiciello, F., Giardini, D. and Lucente, P. (2001) Episodic back-arc extension during restricted mantle convection in the Central Mediterranean. *Earth and Planetary Science Letters* **187**, 105-116.

Holm , P.M., Heaman, L.M. and Pedersen, L.E. (2005) First direct age determination for the Kelseaa Dolerite dyke, Bornholm, Denmark. *Bulletin of the Geological Society of Denmark* **52**, 1-6.

Hubbard, F.H. (1975) The Precambrian crystalline basement of southwestern Sweden. The geology and petrogenitic development of the Varberg region. *Geologiska Föreningen i Stockholm Förhandlingar* **97**, 223-236.

Johansson, Å. (2009) Baltica, Amazonia and the SAMBA connection − 1000 million years of neighbourhood during the Proterozoic? *Precambrian Research* 175, 221-234.

Johansson, L., Lindh, A. and Möller, C. (1991) Late Sveconorwegian (Grenville) high-pressure granulite facies metamorphism in southwest Sweden. *Journal of Metamorphic Geology* **9**, 283-292.

Larson, S.Å. and Berglund, J. (1995) Map of the solid rocks, 7D Ulricehamn SE. Geological Survey of Sweden Af 178.

Lebedev, S., Meier, T. and van der Hilst, R.D. (2006) Asthenospheric flow and origin of volcanism in the Baikal Rift area. *Earth and Planetary Science Letters* **249**, 415-424.

Lubnina, N.V., Mertanen, S., Söderlund, U., Bogdanova, S., Vasilieva, T.I. and Frank-Kamenetsky, D. (2010) A new key pole for the East European Craton at 1452 Ma: Palaeomagnetic and geochronological constraints from mafic rocks in the Lake Ladoga region (Russian Karelia). *Precambrian Research* **183**, 442-462.

Lundqvist, I. (1994) Map of the solid rocks, 6B Kungsbacka SO. Geological Survey of Sweden Af 187.

Lundqvist, L. (1996) 1.4 Ga mafic-felsic magmatism in the southern Sweden; a study of the Axamo Dyke Swarm and a related Anorthosite-Gabbr*o*. Ph.D. thesis for Licentiate Degree, University of Gothenburg, Gothenburg, Sweden. 93 pp.

Möller, C., Andersson, J. and Claeson, D. (2005) Ion probe dating of complex zircon in high-grade gneisses, southeast Sveconorwegian Province: constraints for metamorphism and deformation. *Geological Survey of Sweden report* 2005:35, pp 59.

Möller, C., Andersson, J., Lundqvist, I. and Hellström, F. (2007) Linking deformation, migmatite formation and zircon U-Pb geochronology in

polymetamorphic orthogneisses, Sveconorwegian Province, Sweden. *Journal of Metamorphic Geology* **25**, 727-750.

Moores, E.M. and Twiss, R.J. (1995) Tectonics. Freeman and Company, pp. 415.

Motuza, G., Čečys, A., Kotov, A.B. and Salnikova, E.B. (2006) The Žemaičių Naumiestis granitoids: new evidences for Mesoproterozoic magmatism in western Lithuania. *GFF* **128**, 243-254.

Nyström, J.O. (2004) Geochemistry, origin and tectonic setting of the Jotnian basalts in central Sweden. Final report, Project 03-1116/2001. Geological Survey of Sweden, pp 34.

Obst, K., Hammer, J., Katzung, G. and Korich, D. (2004) The Mesoproterozoic basement in the southern Baltic Sea: insights from the G 14-1 off-shore borehole. *International Journal of Earth Sciences (Geologische Rundschau)* **93**, 1-12.

Pedersen, S., Andersen, T., Konnerup-Madsen, J. and Griffin, W.L. (2009) Recurrent Mesoproterozoic continental magmatism in South-Central Norway. *International Journal of Earth Sciences* **98**, 1151-1171.

Rämö, O.T., Mänttäri, I., Kohonen, J., Upton, B.G.J., Luttinen, A.V., Lindqvist, V., Lobaev, V., Cuney, M. and Sviridenko, L.P. (2005) Mesoproterozoic CFB magmatism in the Lake Ladoga basin, Russian Karelia. *Fifth International Dyke Conference, Rovaniemi, Finland*, 41-42.

Rutanen, H. and Andersson, U.B. (2009) Mafic plutonic rocks in a continental-arc setting: geochemistry of 1.87-1.78 Ga rocks from south-central Sweden and models of their palaeotectonic setting. *Geological Journal* **44**, 241-279.

Söderlund, P., Söderlund, U., Möller, C., Gorbatschev, R. and Rodhe, A. (2004) Petrology and ion microprobe U-Pb chronology applied to a metabasic intrusion in southern Sweden: A study on zircon formation during metamorphism and deformation. *Tectonics* **23**, 1-16.

Söderlund, U., Isachsen, C., Bylund, G., Heaman, L., Patchett, P.J., Vervoort, J.D. and Andersson, U.B. (2005) U-Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga. *Contributions to Mineralogy and Petrology* **150**, 174-194.

Söderlund, U., Möller, C., Andersson, J., Johansson, L. and Whitehouse, M. (2002) Zircon geochronology in polymetamorphic gneisses in the Sveconorwegian orogen, SW Sweden: ion microprobe evidence for 1.46-1.42 and 0.98-0.96 Ga reworking. *Precambrian Research* **113**, 193-225.

Stern, R.J. and Scholl, D.W. (2010) Yin and yang of continental crust creation and destruction by plate tectonic processes. *International Geology Review* **52**, 1-31.

Suominen, V. (1991) The chronostratigraphy of southwestern Finland with special reference to Postjotnian and Subjotnian diabases. *Geological Survey of Finland Bulletin* **356**, pp 106.

Wahlgren, C.-H., Cruden, A.R. and 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.

Zariņš, K. and Johansson, Å. (2009) U-Pb geochronology of gneisses and granitoids from the Danish island of Bornholm: new evidences for 1.47-1.45 Ga magmatism at the southwestern margin of the East European Craton. *International Journal of Earth Sciences (Geologische Rundschau)* **98**, 1561-1580.