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Abstract

In this work, a number of key localities have been investigated in detail in order to provide precise constraints on models for the tectonic evolution of southern Sweden. The new data presented in this thesis show that there are large differences in terms of pre-Sveconorwegian tectonic evolution between the Eastern and Median-Western Segments situated on either side of the Mylonite Zone, a major shear zone as well as a structural and lithological boundary. This has a direct influence on the possible tectonic scenarios that can be suggested when reconstructing the formation of the south-western part of the Fennoscandian Shield.

At Viared in the central Eastern Segment, Sveconorwegian eclogite facies metamorphism is dated at 0.97 Ga using mainly U-Pb on zircon. This is similar to other localities showing high-pressure granulite or eclogite facies metamorphism in the Eastern Segment and suggests that this high grade event was a regional feature east of the Mylonite Zone.

On the well exposed Nordön Island in the Western Segment, both pre-Sveconorwegian and Sveconorwegian metamorphism and deformation was dated using several isotope methods, including U-Pb SIMS zircon and Sm-Nd garnet dating. In the Median Segment, veining was dated using U-Pb SIMS zircon methods. In addition to age determinations, thermobarometry was done on several samples and the results compared with published data. The results show that Sveconorwegian peak metamorphism reached amphibolite to granulite facies west of the Mylonite Zone at 1.02-1.04 Ga. This is 50-70 Ma before the orogenic activity started in the Eastern Segment.

In the central Eastern Segment, Pre-Sveconorwegian veining is dated at 1.42 Ga, thus belonging to the 1.42-1.46 Ga Hallandian veining found elsewhere in the Eastern Segment. Pre-Sveconorwegian veining and isoclinal folding in the Western Segment is dated at 1.55 Ga. Neither the 1.55 Ga nor the 1.02-1.04 Ga events have been found in the Eastern Segment. Further, the 1.42-1.46 Ga veining event documented in the Eastern Segment has not been found in the Western or Median Segments. Only a few 0.97 Ga zircon U-Pb ages have been found in the Western and Median Segments west of the Mylonite Zone. In the Western Segment, Ar-Ar dating of muscovite related to late Sveconorwegian uplift gives 981±4 Ma, interpreted to reflect the crystallization of muscovite below 400 °C. This indicates that the Western Segment already was exhumed at the time when the Eastern Segment experienced its Sveconorwegian high-pressure peak metamorphism.

Additionally this work shows that there is an age difference between the 1.34 Ga Askim, the 1.30 Ga Göta and 1.31 Ga Kärra granites west of the Mylonite Zone and the 1.38-1.40 Ga granites and monzonites east of the Mylonite Zone, thus disproving the previous concept of “stitching granites” that was used as an argument for a pre-Sveconorwegian correlation between the Eastern and Western Segments. The differences in pre-Sveconorwegian history between the segments east and west of the Mylonite zone suggest that the zone originally formed as a Sveconorwegian first order crustal suture. However, no ophiolites have been found along the zone and no calk-alkaline magmatism related to subduction of oceanic crust slightly before 0.97 Ma has yet been documented. If such features were found it would strengthen the idea that the Mylonite Zone is a crustal suture, however their lack does not preclude it.

Geothermobarometry on retrograde eclogite facies rocks exposed at Viared indicates that those rocks experienced metamorphic conditions of 15.0–16.7 kbar at temperatures of 719 to 811°C. The equivalent burial depth of ~50 km is compatible with metamorphism in a subduction setting. The partial preservation of a high pressure paragenesis indicates rapid exhumation after burial. A two-dimensional model involving continental subduction of the Eastern Segment is proposed to explain the cycle of eclogite and high-pressure granulite facies that took place during the ~0.97 Ga Falkenberg phase of the Sveconorwegian Orogeny.

Keywords: Sveconorwegian, Gothian, Hallandian, U-Pb zircon ion probe dating, Sm-Nd garnet dating, thermobarometry, continental subduction, Eastern Segment, Median Segment, Western Segment

Preface

Included in this thesis are five papers (four as first author, one as co-author) of which three are published in GFF, one has been submitted and one is not yet submitted. The papers are:

Eclogites in the central part of the Sveconorwegian Eastern Segment of the Baltic Shield: Support for an extensive eclogite terrane. *By* Austin Hegardt, E., Cornell, D., Claesson, L. Simakov, S., Stein, H. & Hannah, J., 2005: GFF, Vol. 127, pp. 221–232. Reprinted with permission from GFF

Emplacement ages of the mid-Proterozoic Kungsbacka Bimodal Suite, SW Sweden. *By* Austin Hegardt, E., Cornell, D., Hellström, F.A. & Lundqvist, I., 2007: GFF, Vol. 129, pp. 227–234. Reprinted with permission from GFF

Nature and stratigraphic position of the 1614 Ma Delsjön augen granite-gneiss in the Median Segment of south-west Sweden. *By* Ahlin, S., Austin Hegardt, E. & Cornell, D., 2005: GFF, Vol. 128, pp. 21–32. Reprinted with permission from GFF

Relative and Absolute Temporal Relationships between Folding, Foliation and Metamorphism of the Stora Le-Marstrand Formation in the Sveconorwegian Province, Baltic Shield. *By* Austin Hegardt, E., Stigh, J., Cornell, D., Sjöström, H., Anczkiewicz, R., Page, L., Finger, F. Submitted to Mineralogy and Petrology.

An exhumation model for the eclogite-bearing Eastern Segment in the Sveconorwegian Province of the Baltic Shield. *By* Austin Hegardt, E., Cornell, D. Manuscript.

Authors are indicated in order of their contributions with the first author as the main writer. I have contributed to both field work and analytical work including isotope work (ion-probe U-Pb zircon and titanite dating, wet chemical methods for Sm-Nd and Lu-Hf garnet dating and sample preparation for Ar-Ar hornblende and muscovite dating). My contributions also include petrography, geochemistry, SEM-EDS work, interpretations, writing and the preparation and submission of the manuscripts. My estimated contributions to the specific papers are: Paper I, 60 %, paper II, 70%, paper III and IV 50% and paper V, 80%.

The Re-Os analyses in paper I were done by co-authors H. Stein and J. Hannah and garnet-clinopyroxene pressure calculations were done by co-author S. Simakov. The Ar-Ar analyses in paper III were done by co-author L. Page and the U-Pb electron-probe U-Pb isochron dating on xenotime was done by co-author F. Finger.

Contents

Introduction

The 1.15-0.9 Ga Sveconorwegian Province occupies the polymetamorphic region of southwestern Sweden and southern Norway (Fig. 1). The region is, with only minor differences, also commonly referred to as the Southwest Scandinavian Domain (SSD). The complex history of this area during and before the Sveconorwegian orogeny has been a matter of debate for more than 100 years. In 1936, Wahl introduced the name Gothian for the orogenic cycle that caused folding in southwestern Sweden and southwest Norway, at that time considered to be Archean in age. When radiometric dating became available, rocks in the region gave ages younger than 1130 Ma, which led Magnusson (1960) to introduce the name Sveconorwegian, then described as “a period of regeneration”. The Sveconorwegian regeneration period was later described as an orogeny, roughly coeval with the well-known Grenvillian orogeny of North America and many other structural provinces on other continents, commonly referred to as Grenvillian.

This doctoral thesis presents and discusses new and published data that are relevant when constructing tectonic models for the Swedish part of the Sveconorwegian orogeny. Localities investigated are shown in Figure 2, together with some of the most important geological features in this region, such as shear zones and documented observations of Sveconorwegian high-pressure mineral assemblages. Based on the data, I suggest a plausible tectonic scenario that can explain many (but not all) of the observed geological features. Such a model is a way to visualise a tectonic sequence of events, linking cause and effects (Paper V).

Traditional models describing the formation of the Fennoscandian Shield envisage successive growth from an Achean nucleus located in the present northeastern part of the shield (Gaal & Gorbachev, 1987). In this model, the Southwest Scandinavian Domain has been part of the Fennoscandian shield since the end of the Gothian cycle which was completed at about 1.5 Ga (Åhäll & Connelly, 2008).

Understanding the pre-Sveconorwegian history is of utmost importance as it provides possible starting points for any Sveconorwegian tectonic model. For this reason, the doctoral research has not been limited to the Sveconorwegian orogeny. For example, the magmatic and metamorphic ~1.4 Ga event affecting the Eastern Segment of the Southwest Scandinavian Domain was described by Hubbard (1975) as the Hallandian orogen. Although Hubbard´s (1975) original description of Hallandian veining was actually Sveconorwegian in age, the widespread migmatites in the region now dated at 1.46-1.41 are referred to as the Hallandian orogeny (Möller et al., 2007).

Table 1 summarises some key features of each Proterozoic orogeny thought to have affected the Southwest Scandinavian Domain. A few other features not ascribed to the main orogenic events are also given.

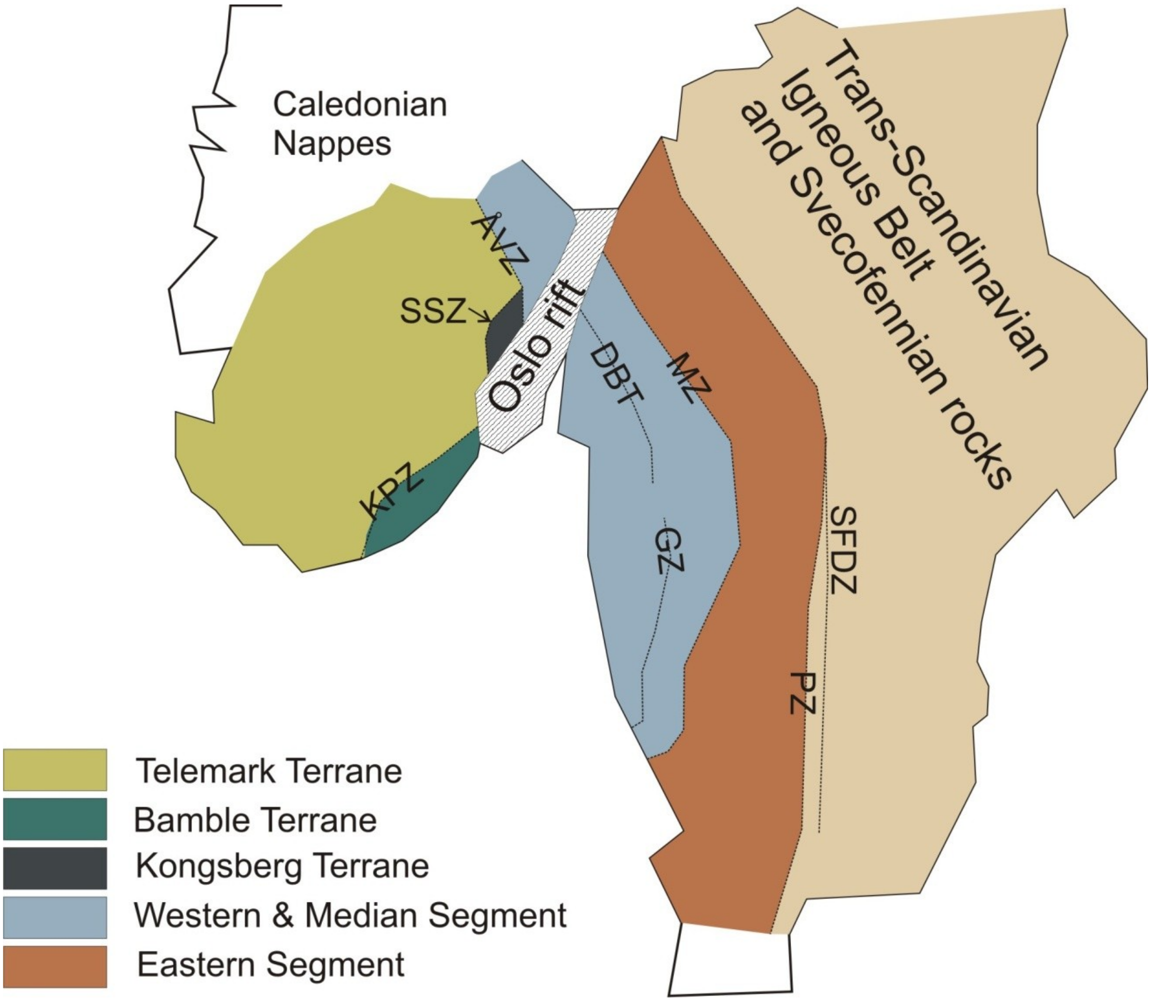


Figure 1. Outline of the Sveconorwegian orogeny showing the shear zones and main tectonic units.KPZ=Kristiansand-Porsgrunn Shear Zone, SSZ=Saggrenda-Sokna Shear Zone, ÅVT= Åmot-Vardefjell Shear Zone, GZ= Göta Älv Shear Zone, DBT=Dalsland Boundary Thrust, MZ=The Mylonite Zone, PZ=The Protogine Zone, SFDZ=Sveconorwegian Front Deformation Zone. Redrawn from Bingen et al. (2008)

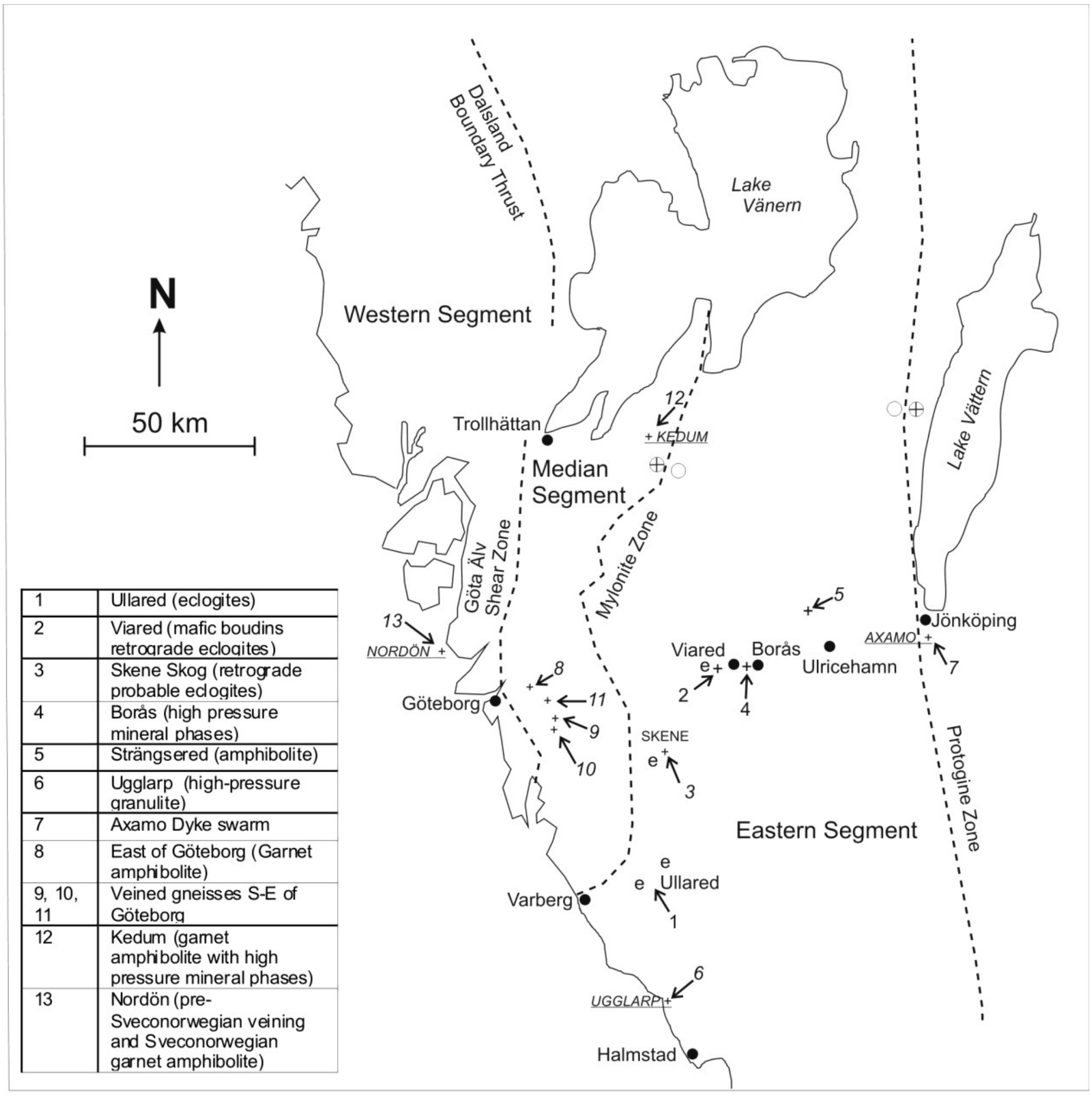


Figure 2. Map showing localities with documented high-pressure rocks and sample sites investigated in this work. Numbers in the map refer to the sites listed in the inset table.

Table 1. Summary of orogenies and events that affected the Swedish part of the Sveconorwegian Province.

Orogeny/ Event	Age	Location	Metamorphism	Metamorphic grade	Selected reference
Gothian Orogeny	1.75–1.55 Ga	Western, Median and Eastern Segments	Folding and Veining	Amphibolite facies	Gorbatschev 1980; Åhäll & Gower 1997; Åhäll & Conelly 2008
Hallandian aged granite-monzonit intrusions	1.40-1.38 Ga	Eastern Segment	Granulite-Charnockites	High temperature	Christoffel et al. 1999; Söderlund et al. 2002
Hallandian Orogeny	1.46-1.41 Ga	Eastern Segment	Veining and syn-deformation migmatite formation	High temperature	Christoffel et al. 1999; Söderlund et al. 2002, Paper I, Möller et al 2007
1.47-1.44 Ga Dykes and 1.55-1.45 Ga AMCG magmatism related to the Danopolonian Orogeny	1.47-1.44 Ga	Eastern Segment and western East European Craton (and possibly the Western Segment).	-	-	Bogdanova et al. 2001, 2006; Brander & Söderlund 2009
Kungsbacka Bimodal Suite	1.34-1.31 Ga	Western and Median Segments	-	-	Welin & Samuelsson 1987; Paper II
Central Scandinavian Dolorites and equivalents	1.28-1.25 Ga	Western Fennoscandia	-	-	Söderlund et al. 2006
Sveconorwegian Orogeny		The Telemark, Bamble and Kongsberg terranes and the Western, Median and Eastern Segments	Regional folding, foliation and veining	greenshist - high-P granulite-eclogite	Berthelsen 1980; Bingen et al. 2008

Summary of the papers

Paper I

Austin Hegardt, E., Cornell, D., Claesson, L. Simakov, S., Stein, H. & Hannah, J., 2005: Eclogites in the central part of the Sveconorwegian Eastern Segment of the Baltic Shield: Support for an extensive eclogite terrane. GFF, Vol. 127, pp. 221–232. Stockholm. ISSN 1103-5897.

This paper presents new pressure-temperature and time data from a locality situated near Viared in the central Eastern Segment, well north of the high pressure granulite region in the southern Eastern Segment. Work was done on mafic boudins found along a road cutting, close to Viared in the central Sveconorwegian Eastern Segment. The locality was originally investigated by Claesson (2002) who showed that the mafic boudins display both mineralogical and textural features demonstrating that these rocks were once eclogites.

The paper presents the extended work, including additional petrographic and pressure-temperature calculations and a range of age determinations using several isotopic methods.

The mafic boudins at Viared comprise largely hornblende-plagioclase amphibolite, but their clinopyroxene and garnet-bearing interiors indicate that they retrogressed from eclogite. Clinopyroxene grains contain exsolved plagioclase. From electron microscope images and EDS analyses it was possible to calculate the original clinopyroxene composition which indicates original omphacite. Plagioclase coronas surrounding garnets (with a kyanite inclusion) also indicate retrogression from high-pressure conditions.

Geothermobarometry indicates that the rock experienced metamorphic conditions of 15.0–16.7 kbar at temperatures of 719 to 811°C. Calculations using the existing retrograde assemblage of clinopyroxene-garnet-plagioclase-quartz give values of 10.5–12.5 kbar and 700–770°C, reflecting conditions during rapid exhumation. The textural and mineralogical features, together with the calculated P–T conditions, show that the mafic boudins at Viared were subjected to eclogite facies conditions at ~50 km depth, evidence for a subduction process. The Ullared eclogites found by Möller (1998) are thus not a unique occurrence in the Eastern Segment and high pressure metamorphism is shown to be widespread in this tectonic unit.

To date the boudin formation, molybdenite in quartz-plagioclase veins that formed after boudin formation were sampled and dated using the Re-Os method. The results give 974±3 Ma. The age thus represents a minimum age for boudin formation. The results are also supported by U-Pb dating of titanite from an inter-boudin pegmatitic granite melt that gave a 961±26 Ma age. Two related molybdenite samples gave ages at 957±4 and 949±4 Ma respectively, representing either protracted amphibolite facies conditions or a low grade 230–320°C alteration event.

The host rock surrounding the boudins comprises a veined orthogneiss. The veining event was dated at 1426±18 and 1415±15 Ma from two separate samples using ion-probe zircon dating. The age indicates that Hallandian veining is a widespread feature in the Eastern Segment. The intrusive age of the country rock was dated at 1701±10 Ma from the zircon cores.

Paper II

Austin Hegardt, E., Cornell, D.H., Hellström, F.A. & Lundqvist, I., 2007: Emplacement ages of the mid-Proterozoic Kungsbacka Bimodal Suite, SW Sweden. GFF, Vol. 129 (Pt. 3, September), pp. 227–234. Stockholm. ISSN 1103-5897.

This paper originated from the re-dating of the Mesoproterozoic Askim Granite in the Western Segment at 1336±10 Ma, presented in Austin Hegardt (2000). The dating was done to test the age correlation with similar aged granites east of the Mylonite Zone. The previous Askim Granite age of 1362±9 Ma had been an important argument for a pre-Sveconorwegian assembly of the Eastern and Median-Western Segments, now shown to be invalid. The paper includes dates from the 1311±8 Ma Kärra Granite and the ≥1304±6 Ma Göta Granite. In addition, oscillatory zoned magmatic zircon grains in a pegmatite dyke in the Kärra Granite were dated at 1325±8 Ma, within analytical uncertainty of the age of the host granite and not related to a different metamorphic event as had been thought.

The dated granites are part of a 1.34–1.30 Ga bimodal magmatic suite for which the name Kungsbacka Bimodal Suite is proposed. The suite forms a N–S trending linear belt from Kungsbacka in the south to Trollhättan in the north. Other possible members are the 1.32 Ga Ursand Granite and 1.33 Ga Hästefjorden Granite (Piontek et al. 1998), the 1.31 Ga Veddige augen gneiss and 1.33 Ga Stråvalla augen gneiss (Andersson 2001) and the 1.33 Ga Chalmers Mafic Intrusion (Kiel et al. 2003).

The suite probably formed in a continental rift environment. This study demonstrated that the Kungsbacka Bimodal Suite, which seems restricted to the Western and Median Segments, is significantly younger than the 1.38 Ga Tjärnesjö and Torpa granites east of the Mylonite Zone (Åhäll et al. 1997; Andersson et al. 1999) in the Eastern Segment of the Sveconorwegian Province. This age difference disproof the concept of pre-Sveconorwegian stitching granites and allows the Mylonite Zone to be interpreted as a first order Sveconorwegian tectonic boundary, separating crustal segments with distinct pre-Sveconorwegian histories.

The paper also presents new age-data on Sveconorwegian migmatite formation in the Western Segment. Metamorphic overgrowths on zircons from the Kärra pegmatite are dated at 1043±11 Ma and confirm the age of Sveconorwegian metamorphism at 1.04 Ga in the Western Segment. This indicates that the peak of Sveconorwegian metamorphic evolution in the Western Segment differs by about 70 Ma from the ~970 Ma metamorphic peak in the Eastern Segment.

This study also documents the occurrence of penetrative deformation and high-grade metamorphism including partial melting in the Western and Median Segments, after 1.3 Ga, which was previously thought to be of >1.5 Ga Gothian age. It also proves that in some areas it is impossible to distinguish post-Gothian from older units, based only on their degree of deformation.

Paper III

Ahlin, S., Austin Hegardt, E. & Cornell, D., 2005: Nature and stratigraphic position of the 1614 Ma Delsjön augen granite-gneiss in the Median Segment of south-west Sweden. GFF, Vol. 128 (Pt. 1, March), pp. 21–32. Stockholm. ISSN
1103-5897.

The paper reports on the age and tectonic setting of the Delsjön augen granite-gneiss, a rock which is unique to the Median Segment. It occurs as elongated, up to 50 km long bands which in some cases are associated with the Härsjön supracrustal gneiss. The rock generally contains 25–30% megacrysts of recrystallized microcline aggregates in a matrix of quartz, plagioclase, microcline and biotite.

The Delsjön augen granite-gneiss is part of the mainly ~1.6 Ga plutonic calc-alkaline granodioritic to granitic rocks and dacitic volcanic belonging to the Göteborg Suite (e.g. Åhäll & Connelly 2008). Note, in Paper III, the alternative name Kallebäck Suite (Mell 2005) is used for the granitic-to granodioritic rocks of the suite.

Even though the Delsjön augen granite-gneiss is interpreted to belong to the Göteborg Suite rocks, field relationships indicate that the Delsjön augen granite-gneiss is probably older than most of the non-megacrystic members of the suite, the granitoid gneisses which dominate the region.

The work included geochemical comparisons between the Delsjön augen granite-gneiss and the non-megacrystic Kallebäck Suite granitoids. The comparison shows that the rocks have overlapping chemical characteristics, although the non-megacrystic members show a much larger compositional spread than the uniform Delsjön augen granite-gneiss. The Delsjön augen granite-gneiss and the non-megacrystic granitoids also have remarkably similar trace element characteristics and both plot as volcanic arc granites. Comparing only samples with >65% silica, both groups may be explained as water-unsaturated eutectic melts derived by partial melting of subduction-related mafic source rocks. The K-feldspar megacrysts might be accounted for by a moderate increase in water content before crystallization during magma ascent, which moved the cotectic lines so that mainly orthoclase crystallized from the melt. The non-megacrystic samples probably did not experience this hydration process.

Ion probe U–Pb zircon dating of the Delsjön augen granite-gneiss gives a 1614±5 Ma date. This age is interpreted to date the intrusion of the suite as bodies and dykes along a zone of magma chambers.

Sveconorwegian metamorphic zircon rims from a migmatised Delsjön augen granite-gneiss were dated at 974±22 Ma, indicating movement in a major shear zone between the Western and Median Segments at the same time as high grade metamorphism occurred in the Eastern Segment. Noteworthy is that no sign of Pre-Sveconorwegian (Gothian or Hallandian) veining events are found in this part of the Median Segment.

Paper IV

Austin Hegardt, E., Stigh, J., Cornell, D. H., Sjöström, H., Anczkiewicz, R., Page, L., Finger, F.: Relative and Absolute Temporal Relationships between Folding, Foliation and Metamorphism of the Stora Le-Marstrand Formation in the Sveconorwegian Province, Baltic Shield. Submitted to Mineralogy and Petrology.

Paper IV originated from the detailed structural and geologic investigation of the Nordön Island which was led by Jimmy Stigh in the late 1970s. The several generations of amphibolite and pegmatite intrusions that occur on the island provide good structural markers and made it ideal for further studies of the polymetamorphic evolution that affected this region. The island is small, only 1 x 1 km but the rocks are very well exposed. The work included dating of several metamorphic events and pressure-temperature calculations from mineral analyses.

Meta-greywackes belonging to the Stora Le-Marstrand formation are the most common rock type on the island but a major folded amphibolite dyke, the Nordön Amphibolite Dyke, is also a dominant feature.

Four major phases of deformation (D1-D4) were previously recognised and three of them (D2-D4) could be dated. In addition, U-Pb SIMS analyses on detrital zircons constrain deposition of the Stora Le-Marstrand Formation to before 1575±21 Ma and a maximum age at 1596 Ma.

Sedimentation was followed by D1/S1 foliation resulting from sediment compaction. U-Pb ion probe zircon analyses dates partial melting conditions and isoclinal folding M2/F2 at 1545±13 Ma, followed by intrusion of the Nordön Amphibolite Dyke at 1548±11 Ma.

Sm-Nd garnet analyses date Sveconorwegian D3 peak metamorphic conditions and F3 folding at 1029±6 Ma, within error of the 1043±11 Ma metamorphism documented in the Kärra granite (Paper III).

Thermobarometry calculated on D3 metamorphic paragenesis indicates conditions at ~11.5 kbar and ~750ºC. A post-D3 pegmatite, probably formed by heating of the post- orogenic overthickened crust gives an Ar-Ar muscovite age at 994±4 Ma which is interpreted as the intrusion age. Sub-horizontal F4 folding reflecting late Sveconorwegian uplift was accompanied by recrystallisation of muscovite, dated at 981±4Ma by Ar-Ar.

Paper V

Austin Hegardt, E. & Cornell, D.: An exhumation model for the eclogite-bearing Eastern Segment in the Sveconorwegian Province of the Baltic Shield.

This paper originated from the tectonic model and ideas presented in my Master´s thesis (Austin Hegardt, 2000). In this study, new pressure-temperature and time data were combined with published data to investigate the distribution and origin of high-pressure rocks in south-western Sweden. Metabasic rocks with partially preserved eclogite facies paragenesis have now been found at several localities in the Sveconorwegian Province. This profoundly influences models for tectonic evolution in the Eastern Segment of the Sveconorwegian Province. In particular, the paper addresses the question whether the occurrence of retrograde eclogites is an indicator of the former presence of a subduction zone, now seen as a crustal suture along the Mylonite Zone. The metamorphic discontinuities across the two major terrane boundaries, the Mylonite and Protogine Zones were also evaluated. The results indicate that a significant part of the Eastern Segment has been through a high-pressure eclogite facies event, followed by retrogression at ~10 kbar and 700-800ºC to amphibolite or high-pressure granulite facies.

The eclogite facies and retrograde metamorphism took place within a short period close to 970 Ma. This sequence of events is not seen in the neighbouring Western and Median Segments to the west, nor in the Trans-Scandinavian Igneous Belt to the east.

Migmatite formation in the Median Segment is dated at 1017±7 Ma, comparable to published dates of 1.03-1.04 Ga for the main metamorphic event in the Western and Median Segments. This shows that the Western and Median Segments experienced a very different Sveconorwegian tectonometamorphic history compared to the Eastern Segment, with a >50 Ma difference in the timing of the peak metamorphic conditions. A crustal subduction and exhumation model, based on the physical experiments by Chemenda et al. (1996), is applied to the region and presented as a possible explanation for the 970 Ma event that affected the Eastern Segment.

Summary of the Sveconorwegian Orogeny

The ~1.14-0.90 Ga Sveconorwegian province (Fig. 1) forms a ~500 km wide belt, bounded to the west and north by sea or Caledonian nappes (Bingen et al. 2008). It forms the Scandinavian counterpart of the Grenville orogeny and resulted from a continent-continent collision between Baltica and another large continent, possibly Amazonia. Figure 3 shows a simplified lithology map of the Sveconorwegian Province.

To the east, the Sveconorwegian province is delimited by a metamorphic break at the Protogine Zone (PZ), followed by the Sveconorwegian Front Deformation Zone (SFDZ) in which the Sveconorwegian deformation is seen in shear zones which die out eastwards (Wahlgren et al. 1994). East of the Protogine Zone are the only slightly deformed granitoids and porphyries of the 1.85-1.66 Ga Trans-Scandinavian Igneous Belt (TIB).

Sveconorwegian tectonic units

The Sveconorwegian province is made up of large 1.68 to 1.59 Ga lithotectonic units or terranes, separated by roughly N-S trending zones of ductile deformation (Berthelsen, 1980; Wahlgren et al., 1994, Andersen 2005; Bingen et al. 2008). The Sveconorwegian tectonic units have been referred to as Segments, Sectors, Terranes or Blocks. The nomenclature used in this work is based on the work by Berthelsen (1980), Starmer (1996) and Bingen et al. (2001; 2008). From west to east, the names used for tectonic units which lie west of the late Palaeozoic Oslo rift are the Telemarkia, Kongsberg and Bamble Terranes following Bingen et al. (2008). Units east of the Oslo rift are from west to east referred to as the Western, Median and Eastern Segments in accordance with Berthelsen (1980). The Begna sector is interpreted as the Western and Median Segment's continuation west of the Oslo rift following Bingen et al. (2001). Alternative nomenclatures were reviewed by Andersen (2005).

The Eastern Segment

The Eastern Segment and Sveconorwegian province (Fig. 1 and 3) is delimited to the east by a metamorphic break at the Protogine Zone and structurally by the Sveconorwegian Frontal Deformation Zone (Wahlgren et al. 1994). The Mylonite zone (Magnusson 1937) is a major west-dipping shear zone which forms the western boundary of the Eastern Segment (Fig. 1). Eastern Segment mainly comprises orthogneisses, with several generations of minor mafic rocks (Fig. 2). In the northern The Eastern Segment, 1.67 Ga granitoid rocks can be traced across the Sveconorwegian Frontal Deformation Zone into the Trans-Scandinavian Igneous Belt (TIB). In the southern Eastern Segment, orthogneisses with emplacement ages between 1.73-1.66 Ga show similar chemical characteristics to coeval

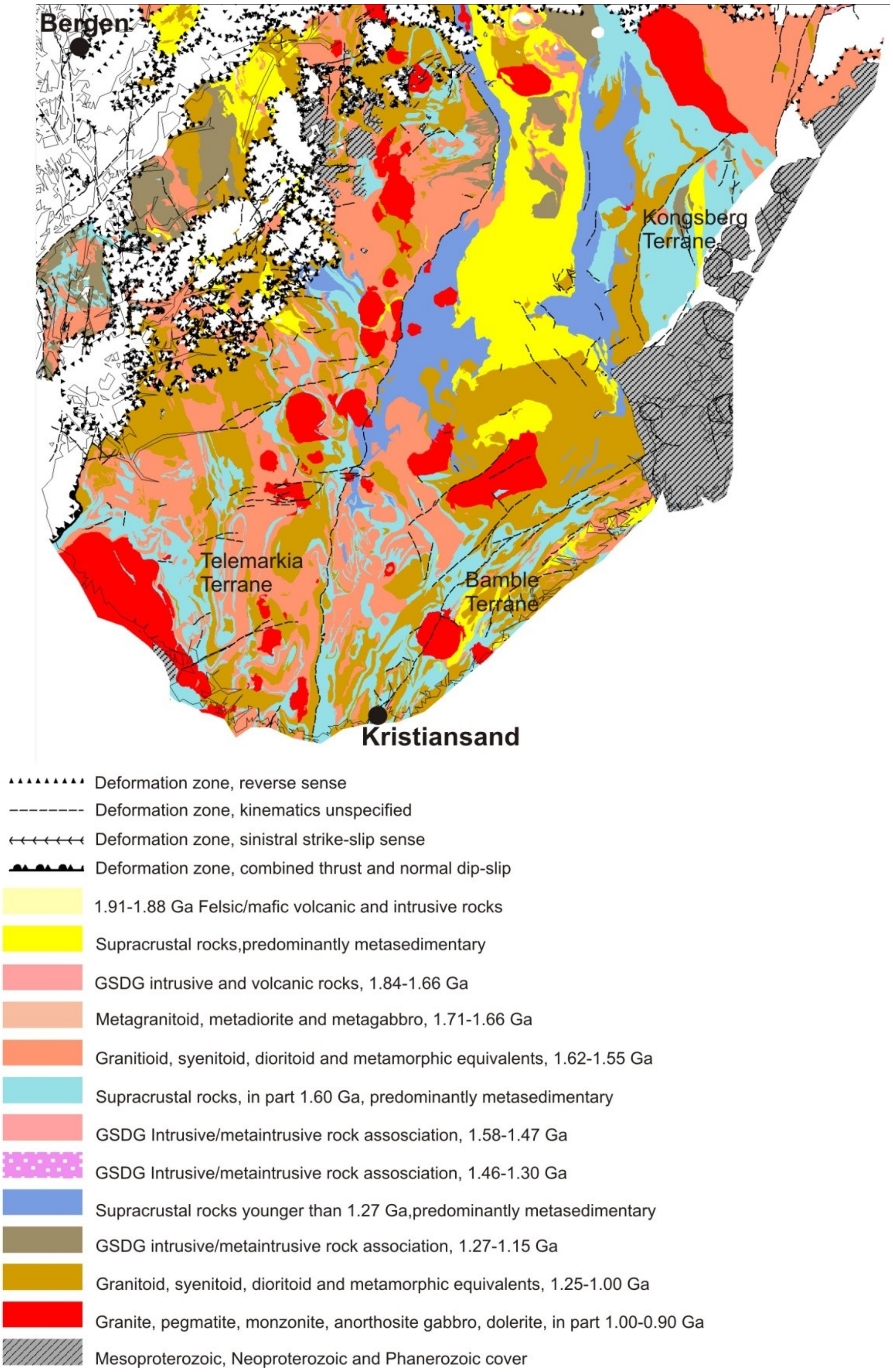
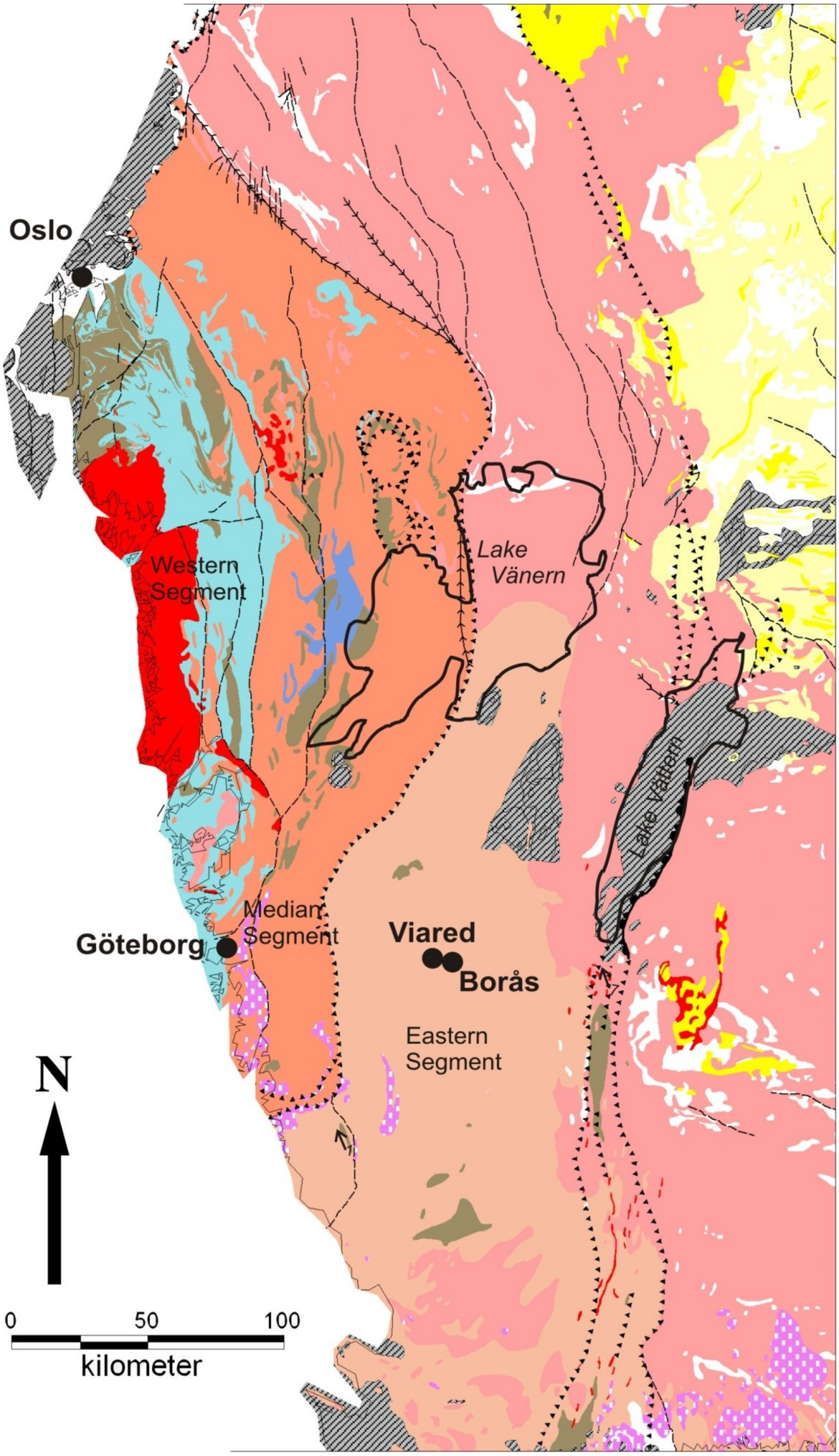


Figure 3. Geologic map of the Sveconorwegian Province (modified from Koistinen et al. (2001). This page shows SW Norway, opposite page shows SW Sweden using the same scale.


Oslo
Western Segment
Lake Vänern
Lake Vättern
Median Segment
Göteborg
Viared
Borås
Eastern Segment
N
0
50
100
kilometer

undeformed TIB rocks (Connelly et al. 1996; Andersson 2001; Söderlund et al. 2002; Möller et al. 2007). This implies that the bulk gneisses of the Eastern Segment comprise reworked TIB rocks.

Pre-sveconorwegian Hallandian migmatite formation is dated at 1.46-1.42 Ga and occurs on a regional scale in the Eastern Segment (Christoffel et al. 1999, Söderlund et al. 2002, Möller et al. 2007, Paper I). It is probable that deformation was connected with migmatisation during convergent tectonism (Bogdanova et al. 2006; Möller et al. 2007). This was followed by granite and monzonite magmatism at 1.40-1.38 Ga (Hubbard 1975; Åhäll et al. 1997; Andersson et al. 1999; Rimsa et al. 2007)

Granites, syenites and dolerites intruded the Protogine Zone at ~1.2 Ga and dolerites also intruded along the easternmost Sveconorwegian border at 0.98-0.97 and at 0.95 (Söderlund et al. 2005 and references therein).

Sveconorwegian metamorphic grade increases from north to south. It generally reached upper amphibolite to high-pressure granulite facies in the southern Eastern Segment around 970 Ma (Johansson et al., 1991; Johansson & Kullerud, 1993; Wang & Lindh, 1996; Söderlund, 1999; Möller 1998, 1999; Paper I). Pressure and temperature estimates range between 8-12 kbar and 680-800 °C for the amphibolite to granulite facies rocks.
Evidence of Sveconorwegian high-pressure metamorphism has been documented at several localities (Paper I, V). Eclogites formed at >15 kbar in mafic rocks were documented at Ullared (Fig. 2), showing garnets with preserved prograde zonation (Möller 1999). This indicates rapid burial and exhumation from depths of at least 45 km. Zircon inclusions inside garnets are dated at 972 ±14 Ma interpreted to reflect eclogite formation (Johansson et al. 2001). Hornblende 40Ar-39Ar dates around 0.93 Ga are interpreted to reflect cooling through 500-550 ºC (Page et al. 1996a, 1996b).

In the Eastern Segment, the gentle folding with roughly east-west oriented fold axes (Larson & Stigh 1987) is visible on the detailed aeromagnetic map published by the Swedish Geological Survey (Fig. 4). The pattern results from the tectonic banding of alternating gneisses, migmatites and metabasic rocks.

Western and Median Segments

The Median and Western Segments (Fig. 1 and 3) are separated by the Dalsland Boundary Thrust in the north and bounded to the east by the Mylonite zone and to the west by the Åmot-Vardefjell Shear Zone (Berthelsen 1980; Bingen et al. 2001). The boundary between the Median and Western Segments south of the Dalsland Boundary Thrust is less clear. In this thesis, the Göta Älv Shear Zone is used as it roughly separates the Stora Le-Marstrand Formation and 1522-1588 Ma Hisingen Suite granitoids (named Frölunda Suite by Mell 2005) from the 1634–1594 Ma Göteborg Suite (named Kallebäck Suite by Mell 2005) of calc alkaline granites to granodiorites and its volcanic equivalents (Åhäll et al. 1995, 1998; Åhäll & Connelly 2008; Mell 2005; Paper III). The southern part of the Göta Älv Shear Zone also constitutes the eastern border for ~1.5 Ga Gothian veining as well as being a Sveconorwegian metamorphic break, separating greenschist facies granites west of the zone from veined amphibolite facies rocks east of the zone.

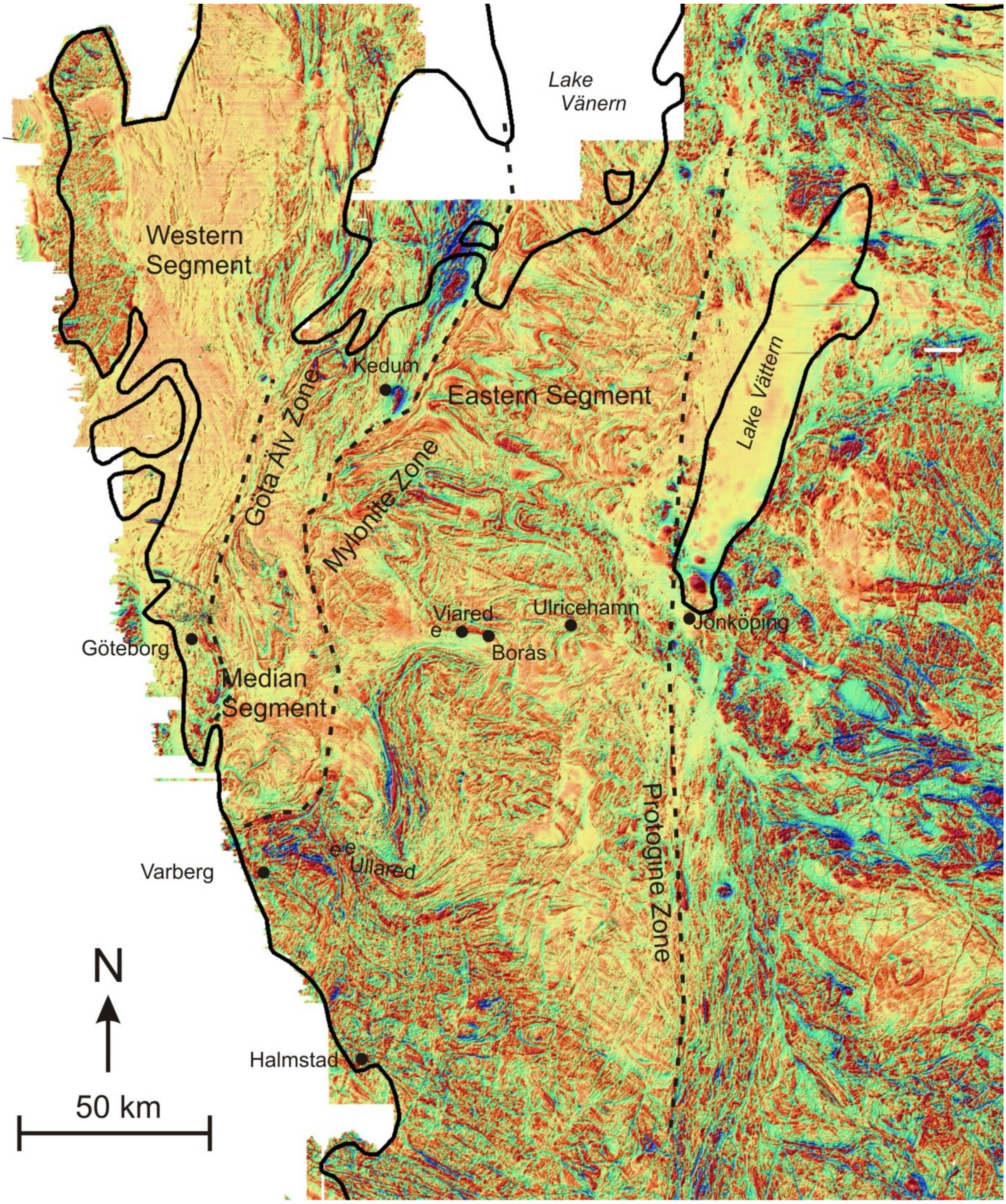


Figure 4. Map of the total magnetic field showing the different structural aspects in the segments. Map from the Geological Survey of Sweden)

The Western Segment is dominated by ~1.59 Ga Stora Le-Marstrand Formation comprising metamorphosed lithic wackes with minor metabasic rocks (Åhäll et al. 1998). These sediments were intruded by granites at 1.59-1.52. An andesitic dyke on Orust, coeval with the mafic Orust dykes, is dated at 1.46 Ga (Åhäll & Connelly 1998). Emplacement of the Kungsbacka Bimodal Suite occurred along the Göta Älv Shear Zone at ~1.3 Ga (Paper II). Along the north coast of the Western Segment lies the 0.92 Ga late Sveconorwegian Bohus Granite (Eliasson & Schöberg 1991). Gothian veining and deformation is dated at ~1.55 Ga (Åhäll & Connelly, 2008; Paper IV) and Sveconorwegian metamorphism reached amphibolite facies at ~1.04-1.03 Ga in the Western Segment east of the Oslo rift (Johansson 1993; Romer & Smeds 1996; Åhäll et al. 1998; Paper II, IV). West of the Oslo rift in the Begna Sector, high grade metamorphism is dated at 1.09 Ga, at 1.05-1.04 and at 1.03-1.02 (Bingen et al. 2008). Veining near the Göta Älv Shear Zone dated at 0.97 Ga (Paper III) indicates that this zone was active after the general 1.05-1.02 event.

The Median Segment comprises mainly ~1.6 Ga plutonic calc-alkaline granodioritic to granitic rocks and dacitic volcanic rocks (Åhäll et al. 1995, 1998; Paper III and V). No pre-Sveconorwegian veining has so far been documented in the Median Segment. Sveconorvegian metamorphism is dated at ~0.92 Ga to ~1.04 Ga (Jarl 1992; Larson et al. 1999; Scherstén et al. 2004; Paper III and V). Migmatites developed near the Mylonite Zone at ~0.97 Ga (Larson et al. 1999). High-pressure granulite facies metamorphism, dated at 1.05-1.03 Ga, was documented near Trollhättan by Söderlund et al. (2008).

Structures in the Western and Median Segments are generally north-south trending and thus show a clear contrast in the observed total magnetic field compared to the east-west trends in the Eastern Segment (Fig. 4).

The Kongsberg and Bamble Terranes

The Kongsberg and Bamble Terranes (Fig. 1 & 3) mainly comprise 1570-1460 Ma metapelites, metagraywackes, quartzites and orthogneisses with a strong N-S to NE-SW deformation pattern, forming two tectonic wedges overlying the Telemarkia Terrane. Mafic magmatism in the Kongsberg Terrane is dated at 1.2 Ga. In the Bamble Terrane, the gabbro-tonalite Tromøy complex is dated at 1.20-1.18 Ga and Granite-charnockite plutons at 1.17-1.15 Ga. (Bingen et al. 2008 and references therein).

Two Sveconorwegian metamorphic events are documented. Upper amphibolite to granulite facies metamorphism is dated at 1.14-1.13 Ga in the Bamble Terrane and amphibolite facies conditions are dated at 1.11-1.08 Ga in the Bamble and Kongsberg Terranes (Bingen et al. 2008, and references therein). Neither of these events have a direct age correlation to those documented in the Swedish Western, Median and Eastern Segments.

The Telemarkia Terrane

The Telemarkia Terrane is limited to the east by the Kristiansand-Porsgrunn Shear Zone and to the west by sea or Caledonian nappes (Fig. 1 & 3). It is mainly made up of a >10 km thick supracrustal sequence, metamorposed at greenschist to amphibolite facies conditions and 1.52-1.48 Ga orthogneisses. Several generations of Sveconorwegian granitoids intruded the Telemarkia Terrane between 1.05 and 0.92 Ga (Bingen et al. 2005; 2008 and references therein).

The Sveconorwegian metamorphism starts at 1035 Ma in most of the Telemarkia

Terrane but the metamorphic grade varies between different areas. Upper amphibolite facies dates are more or less continuous from 1035 Ma to c. 950 Ma in southern Telemarkia.

Sveconorwegian Shear Zones in SW Sweden

The Sveconorwegian tectonic units are divided by major shear zones that cut the main 1.7–1.2 Ga gneisses. The main two zones that separate the Swedish tectonic units are the Protogine Zone (including the Sveconorwegian Frontal Deformation Zone) and the Mylonite Zone.

The Protogine Zone and Sveconorwegian Frontal Deformation Zone

The Protogine Zone is a tectonostratigraphic boundary between the Trans-Scandinavian Igneous Belt and the Sveconorwegian Province (Fig. 1). South of Lake Vättern it is steeply dipping and 25-30 km wide. It exhibits a fan-like structure between Karlstad and Karlskoga, with a foliation dip changing from steep westerly in the east, to easterly in the west. Top-to-the-east shear sense is seen in Värmland north of Lake Vättern (Wahlgren et al. 1994). The sense of movement is more complex to the south but the overall displacement is oblique dextral (Berglund et al. 1992). The Protogine Zone is also a Sveconorwegian metamorphic discontinuity, separating high-grade rocks to the west from low-grade rocks to the east (Johansson 1992), implying a large vertical movement.

Wahlgren et al. (1994) described the Sveconorwegian Frontal Deformation Zone, in which Sveconorwegian shear zones are recognised east of the Protogine Zone. It is structurally younger than the Protogine Zone, with steep westerly or vertical dip and the dominant shear sense is top-to-the-east, showing that the Eastern Segment moved up and over the Trans-Scandinavian Igneous Belt.

The Mylonite zone

The Mylonite zone is a 400 km long major lithological and tectonostratigraphic boundary. The southern part of the zone divides less-veined gneisses and supracrustal rocks, of the Western and Median Segments, from more intensely migmatised gneisses in the Eastern Segment. Stephens et al. (1996) describes it as a west-dipping left-lateral transpressive ductile shear zone. It has a steep dip of 70-90° in the northern parts that becomes gentler to the south. Approximately 60 km south of Lake Vänern the zone becomes narrower and near Varberg it splits into several branches before disappearing into the sea (Fig. 1).

Berglund (1997) describes the Mylonite Zone movements as compressional with top-to-the-east shear sense in the Vänern area and extensional, top-to-the-west, in the southern part. He also suggested that extension followed compression. This contradicts a recent investigation by Viola & Henderson (2010), who explain the zone as a simple Sveconorwegian thrust. In this recent investigation it is noteworthy that strike-slip components only exist in the northern and southern part of the zone, thus the geological differences across the zone cannot be explained by a several 100 km strike slip movement.

In the southern part of the Mylonite Zone, a metamorphic break is seen between the amphibolite-facies hanging-wall (Median Segment) and high-pressure granulites of the adjacent Eastern Segment (Stephens et al. 1996).

The Mylonite Zone is not only a lithological boundary, but also marks a significant change of structural and geophysical fabric. The Western and Median Segments have dominantly north-south trending structures while the Eastern Segment is dominated by east-west trending structures (Fig. 3).

Constraints on tectonic models for the Sveconorwegian Orogeny

The results obtained in this research project have implications for the tectonic evolution during the Sveconorwegian orogeny. Important aspects are discussed below and a possible tectonic model to explain the high-pressure metamorphism in the Eastern Segment at 970 Ma is suggested.

Terrane analysis

Reconstructing the tectonic history of a Precambrian structural province such as the Sveconorwegian is complicated by the fact that it is too old for any ocean floor spreading record to be preserved, because the oceanic crust has disappeared down a subduction zone. Remnants of oceanic crust can only be preserved as rare occurrences of ophiolites. Interpreting tectonic units as exotic terranes and establishing the location of possible suture zones that represent the closure of ancient oceans can however be done, using a terrane analysis in which the differences and similarities between the units are compared. More recent or ongoing orogenic belts involving a continent-continent collision, where the ocean floor spreading record is preserved and with remaining mountain chains, reveal that the tectonic sequence of events during an orogeny is complicated. An example is the Himalayan orogeny, which involved the late Cretaceous collision between Tibet and the Kohistan-Ladakh island arc before the main collision involving India (O'Brian 2001). Models for the Cordilleran orogeny along the North American west coast involve closure of four basins with changes in subduction direction (Moors & Twiss, 1995). According to the principle of uniformitarianism, there is no reason to believe that continent-continent collisions were less complicated in the late Mesoproterozoic.

Is the Mylonite Zone a Sveconorwegian crustal suture?

Do the tectonic units west of the Mylonite Zone share a pre-Sveconorwegian history with the Fennoscandian Shield? Below is a compilation of geologic criteria which characterise an exotic terrane:

Presence of ophiolites

Ophiolites are the undisputed geological features that prove an ancient suture zone and closure of an ocean basin. Ophiolites are common in modern orogenic belts, but rare in Precambrian ones. For example in the 1.2-1.0 Ga Namaqua-Natal orogeny of southern Africa, only one possible ophiolite is found in the boundaries between nine established terranes with different pre-Grenvillian histories and well-established collisions (Cornell et al., 2006). Many Phanerozoic ophiolites are now interpreted as having formed in back-arc basins rather than in major ocean basins. This is because the obduction of ophiolites onto the crust is more likely if the oceanic crust is relatively young and warm. The mafic rocks near the Mylonite Zone at Kedum, which show evidence of a high-pressure metamorphic history, could be the remains of an (Gothian?) ophiolite, but this is highly speculative. The lack of well-preserved ophiolites along the Mylonite Zone is an argument against the interpretation of the Mylonite Zone as a crustal suture, but does in no way disprove it.

Differences in rock ages

A sharp boundary separating domains with distinct differences in crustal ages is suggestive of an ancient crustal suture. The Mylonite Zone effectively separates the 1.73-1.66 Ga Eastern Segment from the 1.63-1.55 Ga Median and Western Segments. No pre-Sveconorwegian metamorphism has been dated in the Mylonite Zone. The present crustal architecture is mainly a Sveconorwegian feature, although the protolith ages do not exclude the units east and west of the Mylonite Zone having come together during the Gothian orogeny, as proposed for example by Åhäll & Connelly (2008).

The 1.46 Ga Orust and Koster-Kattsund dykes in the Western Segment (Åhäll & Connelly 2008; Åhäll et al. 2004) might be correlated with mafic dykes which occur east of the Mylonite Zone. These are the 1.46 Ga Valaam dykes (Rämö et al. 2001), the 1.47–1.46 Gustafs- and Tuna dykes (Lundström et al. 2002), the 1.46 Ga Bunkris dyke (Söderlund et al. 2004, 2005) and the 1.46 Ga Jönköping Anorthositic Suite (Brander & Söderlund 2009; see table 1). In the Western Segment the Orust dykes and the Koster-Kattsund dykes have been dated at 1.46 Ga and 1.42 Ga respectively, although only Rb-Sr dating was used for the Koster-Kattsund dykes. The rare occurrence of 1.46 Ga dykes in the Eastern Segment immediately west of the Mylonite Zone questions the significance of this age-correlation.

Differences in metamorphic history

In the Eastern Segment, Hallandian 1.46-1.42 Ga migmatitic veining is widespread and this event cannot be correlated across the Mylonite Zone. No pre-Sveconorwegian veining has so far been dated in the Median Segment. In the Western Segment, 1.55 Ga veining and folding is dated in the Stora Le-Marstrand Formation and this veining has no correlation east of the Mylonite Zone. A similar interpretation was made by Larson et al. (1998) in a study further north, in the Värmland county. There are no signs of ~1040-1020 Ma metamorphism and veining in the Eastern Segment east of the Mylonite Zone despite these being predominant in the Western and Median Segments. Thus the timing of peak metamorphic events differs by 50-70 Ma across the Mylonite zone.

Regarding the 970 Ma Sveconorwegian metamorphism found in the Eastern Segment, subordinate ~970 Ma metamorphism and veining is recorded in a few localities west of the Mylonite Zone which can be correlated with the peak metamorphism in the Eastern Segment. This leads to the suggestion that the Eastern Segment collided with the units west of the Mylonite Zone after 1020 Ma and close to 970 Ma.

Closure of an ocean, subduction and related magmatism.

Subduction-related magmatism is expected in the overriding plate of a subduction zone, with a volcanic front 100-300 km from the trench axis depending on the subduction angle of the down-going slab. If subduction-related magmatism did occur, it would have been in a region now covered by the Skagerrak Sea or (further north) in southern Norway. Any volcanic rocks would most likely have been eroded away, but one would expect to find mafic dykes or calc-alkaline plutonic rocks. No Sveconorwegian calc-alkaline magmatism has been documented close in time to 970 Ma in any of the Sveconorwegian terranes but numerous granites, regarded as post tectonic were emplaced in southern Norway from ~1000 Ma. The lack of typical subduction-related magmatism above subduction zones was explained for the western Mediterranean part of the Alpine orogeny by the young oceanic crust being too warm to subduct to the ~100km depths required for magma generation (Moores & Twiss, 2005). If closure of Sveconorwegian ocean basins took place in a similar setting, then this has implications on tectonic models involving subduction of continental crust, e.g. the Chemenda model in paper V. A young and relatively buoyant sub-oceanic mantle lithosphere would not as easily pull down the continental crust as an older and heavier sub-oceanic mantle lithosphere.

Structural aspects

The aeromagnetic map of southern Sweden in Fig. 4 shows that the main structures are north-south directed in the Western and Median Segment and east-west directed in the Eastern Segment. The Mylonite Zone is seen as a sharp boundary between these two units. The east-west structures have been explained as the result from an east-west extension related to Sveconorwegian exhumation of the Eastern Segment (e.g. Berglund, 1997). Ideas involving N-S compression and crustal shortening at ~970 Ma have also been mentioned to explain the east-west structures (Möller et al. 2007).

Does the Mylonite Zone need to be a Sveconorwegian suture?

The eclogites and high pressure granulites in the Eastern Segment formed at least 50 Ma after the main Sveconorwegian event in the Western and Median Segments. By this time the Eastern and Western-Median Segments must have been exhumed to near their present level. That is probably why the 970 Ma event is not well represented west of the Mylonite Zone. The work by Möller (1998) indicates a rapid burial and exhumation of the relict eclogites. The recognition of relict eclogites at four localities in the Eastern Segment (Ullared, Skene, Viared and Borås, Fig. 2) means that much of the segment had been at >30 km depth. Thus models interpreting the Mylonite Zone as a purely intra-cratonic shear zone need to explain the driving mechanism for massive crustal thickening. Furthermore, recent work near Borås in the central Eastern Segment indicates 22-25 kbar at 600 °C, corresponding to a minimum depth of 75 km during initial garnet growth at 956 ±9 Ma (Cornell et al. 2008; Danielsson 2008; Mohammad et al. submitted). Such great depths at such a low temperature are typical in a subduction zone setting. Figure 5 shows the Viared eclogites in a P-T diagram with typical geothermal gradients for a modern subduction zone and an intra-continental setting. Typical metamorphic facies fields are included for comparison. The Viared eclogites plot at the high temperature side of the 20 °C/km line, just inside the field of an inter-continental geothermal gradient. However, the Proterozoic age and the granitic composition of the Eastern Segment results in a comparatively high heat production which disallows a direct comparison with modern oceanic subduction zones.

Bingen et al (2008) suggested that the Bamble and Kongsberg Terranes could represent the remnants of a Sveconorwegian basin followed by an early 1140-1080 Ma collision between the Telemark Terrane and the Western-Median Segment. Looking at modern orogenic belts, it is likely that such a long-lived orogeny as the Sveconorwegian involved the closure of more than one ocean basin. An early 1140-1080 Ma collision west of the Western Segment is likely, although it does not satisfactory explain deep burial of the Eastern Segment close to 970 Ma. A collision close to 970 Ma in the proximity of the Eastern Segment seems needed to explain the observed high pressure metamorphism in the Eastern Segment. A model

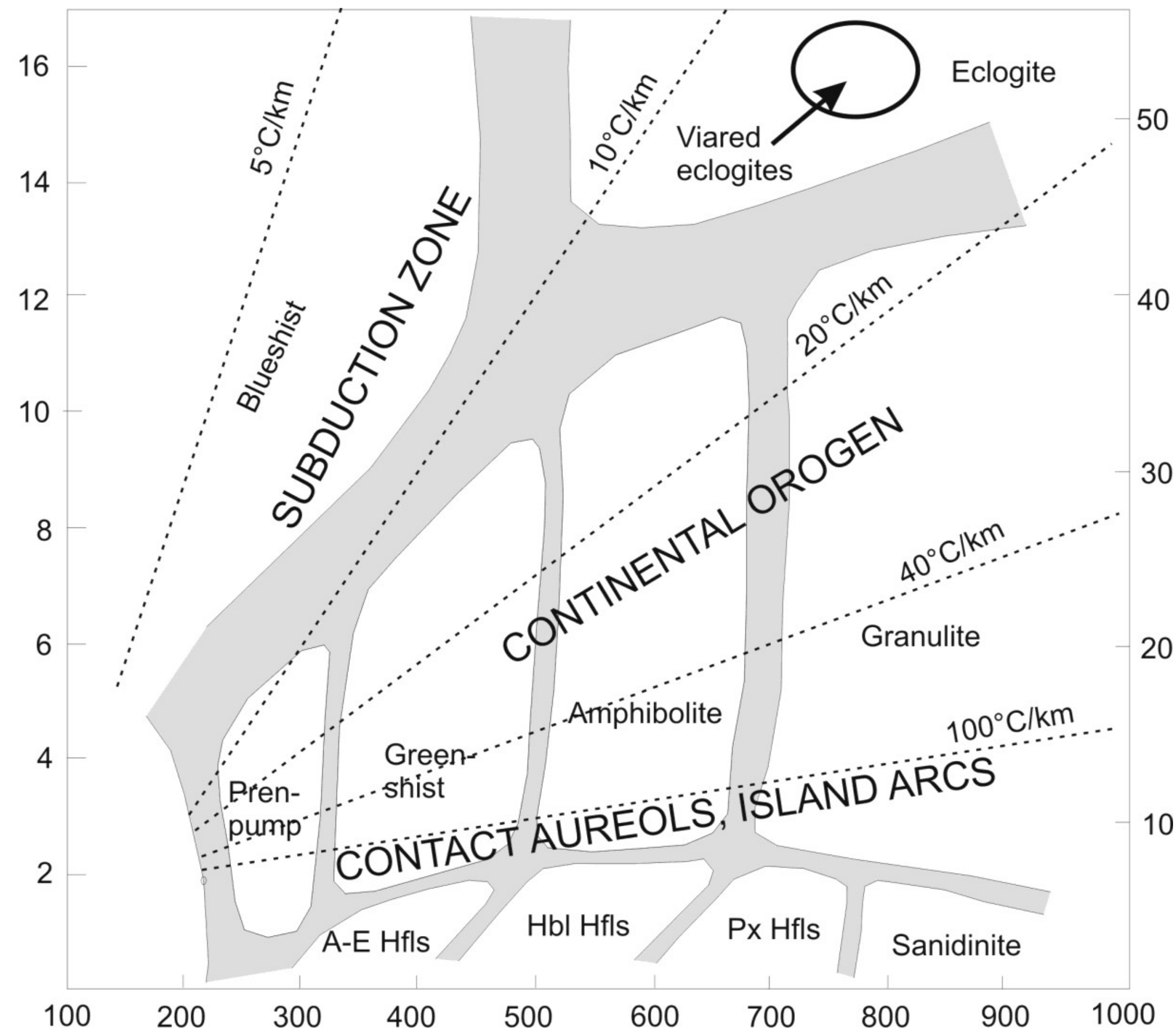


Figure 5. The estimated pressure-temperature conditions for the Viared rocks in relation to typical geothermal gradients for common tectonic settings. Pressure and temperature fields for metamorphic facies shown as reference. Figure modified from Spear (1993) and Turner (1968).

envisaging east-west compression from an indentor off the present west coast of southern Norway seems unlikely, because high-grade metamorphism is lacking in the tectonic units west of the Mylonite Zone during the time when stacking of crustal slices in the Eastern Segment was required.

The rock protolith ages, the metamorphic history of the rocks and the structural pattern support the idea that the Mylonite Zone is a late Sveconorwegian suture zone. Two lines of evidence against this interpretation are that documented subduction-related magmatism in Norway or the Kattegat at 970 Ma is lacking and that well-preserved Sveconorwegian ophiolites are not found along the Mylonite Zone. However these are not seen as compelling. Alternative interpretations need to explain the occurrence of several localities in the Eastern Segment which show high-pressure metamorphism, such that a subduction-exhumation tectonic cycle seems difficult to exclude.

Tectonic models for the Sveconorwegian orogeny

Austin Hegardt (2000) suggested a possible model to explain the Sveconorwegian high-pressure metamorphism in the Eastern Segment. The model was based on the physical experiments by Chemenda et al. (2006) and involved subduction of continental crust along the Mylonite Zone. The same Chemenda-based model is included in paper V in this thesis.

Bingen et al. (2008) presents a four stage model for the whole of the Sveconorwegian orogeny describing the relative position and timing and metamorphic conditions of the involved tectonic units. A scenario having an exotic Telemark Terrane is discussed as an alternative to an indigenous Telemark Terrane but the Mylonite Zone is regarded as an intra-cratonic shear zone in both cases. Regardless of an exotic or indigenous origin of the Telemark Terrane, the model by Bingen et al. (2008) involves four stages:

1. *Arendal phase, 1140-1080 Ma*

The Arendal phase is interpreted as an early collision at 1140 Ma between the Telemark Terrane and Western-Median Segments forming the Kongsberg and Bamble Terranes.

2. *Agder phase, 1050-980 Ma*

This is interpreted as the main Sveconorwegian orogenic event following collision between Fennoscandia and another large continent, causing the 1.05-1.02 Ga amphibolite-granulite facies metamorphism in the Western and Median Segments. In the Telemark Terrane, crustal thickening is documented from 1035 Ma.

3. *Falkenberg phase, 980-970 Ma*

Crustal thickening propagates towards the east giving rise to granulite and eclogite facies metamorphism in the Eastern Segment.

4. *Dalane phase, 970-900*

Relaxation and post collisional gravitational collapse exhuming the Eastern Segment and the Telemark Terrane.

For the 980-970 Ma Falkenberg phase, Möller et al. (2007) suggested that the initial extrusion of the eclogites at Ullared in the southern Eastern Segment was contemporaneous with formation of the E-W folding seen on the aeromagnetic map (Fig. 2). Möller et al. (2007) also suggested that the E-W structures could have formed during a N-S directed compression but points out that a substantial strike-slip component along the Protogine Zone is needed if this scenario is correct, as no crustal shortening is observed in the Trans-Scandinavian Igneous Belt. If true, as shown in this work, a similar strike-slip component must be taken up by the Mylonite Zone as the Sveconorwegian metamorphism in the Western and Median Segments pre-dates the 970 Ma extrusion of eclogites by >50 Ma. So far, no E-W directed 970 Ma structures have been dated in the neighboring segments west of the Mylonite Zone.

The Chemenda based model that is proposed by Austin Hegardt (2000) and in Paper V suggests a tectonic driving mechanism for the burial of the Eastern Segment during the Falkenberg phase. The Chemenda model does not contradict the model by Bingen et al. (2008), although Bingen implies that the Mylonite Zone is not a crustal suture.

The work presented in this thesis establishes that the Western and Median Segments with 1.05-1.02 Ga Sveconorwegian metamorphism have more in common with the Bamble, Kongsberg and Telemark Terranes than with the Eastern Segment and that the Eastern Segment did not participate in the main Sveconorwegian event (the 1050-980 Ma Agder phase of Bingen et al. 2008).

The uniqueness of the Eastern Segment supports the essential principles behind the Chemenda model presented in paper V, and the interpretation of the Mylonite Zone as a Sveconorwegian crustal suture. However the model does not address north-south variations in the metamorphic gradient in the Eastern Segment. The 1.04-1.02 Ga metamorphism documented in the Western and Median Segments is also not covered by the model. Crustal thickening could have resulted from a collision with the Telemark Terrane as suggested by Bingen et al (2008), although it seems problematic with an increasing metamorphic grade from west to east in the Western and Median Segments. Also, the high grade granulites east of Trollhättan (Söderlund et al. 2008) and the possibly retrograded eclogites at Kedum occur in the vicinity of the present Mylonite Zone, an area interpreted as the eastern border of an exotic terrane at that time.

Alternative models having the Eastern and Western-Median Segments together since pre-Sveconorwegian times must however explain the paradox of the complete lack of 1.04-1.02 Ga ages east of the Mylonite Zone, still considering the position of the high grade rocks in the Median Segment and the dip and age of the Mylonite Zone.

Conclusions

1.

Eclogite facies metamorphism at 970 Ma is documented at several localities in the central Eastern Segment, suggesting that Sveconorwegian high grade metamorphic conditions are a regional feature in much of the Eastern Segment. Retrograde eclogite facies rocks exposed at Viared were buried to depths of ~50 km before being rapidly exhumed. The rapid burial-exhumation cycle is compatible with metamorphism in a continental subduction setting.

2.

Pre-Sveconorwegian high grade metamorphism including veining is dated at 1.42 Ga in the central Eastern Segment. The results extend the region where veining related to the Hallandian Orogeny is documented. In the Median Segment west of the Mylonite Zone, Sveconorwegian veining is dated at 1.02 Ga, thus significantly older than the 0.97 Ga Falkenberg phase in the Eastern Segment. However, 0.97 Ga metamorphism is dated in the Göta Älv Shear Zone between the Western and Median Segments suggesting some tectonic movements west of the Mylonite Zone during the Falkenberg phase. The veined gneisses west of the Mylonite Zone show no sign of a 1.46-1.41 Ga Hallandian event.

3.

Re-dating of 1.36-1.31 Ga granites in the Western Segment disproves the previous age correlation with 1.40-1.38 Ga granites and monzonites in the Eastern Segment, suggesting that the segments on either side of the Mylonite Zone had different pre-Sveconorwegian histories.

4.
In the Western Segment, peak Sveconorwegian metamorphism is dated at 1.04-1.03 Ga, thus similar in age to crustal thickening in the Median Segment and in the Telemark Terrane.

5.
Pre-Sveconorwegian syn-deformational Gothian veining is dated at 1.55 Ga in the Western Segment. No veins with a similar age have so far been found in the Eastern Segment, thus establishing that the Mylonite Zone is the eastern limit of Gothian veining.

6.
A 2-dimensional tectonic model involving continental subduction along the Mylonite Zone can explain the metamorphic evolution including eclogite facies conditions documented in the Eastern Segment. Variations in metamorphic grade within the Eastern and Western-Median Segments, with metamorphic grade increasing northwards in the Western-Median Segments but decreasing northwards in the Eastern Segment, will require a more complex scenario to explain the 3-dimensional configuration.

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