UiT THE ARCTIC UNIVERSITY OF NORWAY

Faculty of Science and Technology, Department of Geosciences

Geometry and kinematic evolution of ductile shear zones in the Ersfjord Granite (1.79 Ga), West Troms Basement Complex:

A Svecofennian accretionary thrust system

—

Linda Cecilia Haaland

Master's thesis in Geology, GEO-3900, November 2018

Big challenges give big rewards

Acknowledgements

Wow, that was a lot of hard work. But it was also really, really fun. Rocks are awesome. I could never have done this without a whole bunch of people who have provided me with invaluable help and support in writing this thesis. Here is a far-too-short summary of thank-you's:

First of all, to my supervisor, Professor Steffen Bergh – your infinite knowledge never ceases to amaze me. Also, the enthusiasm and passion you have for your research, even after all these years, is a true inspiration. Thank you for all the wisdom you have shared, and for the endless hours you have spent guiding me through the mess that has been writing this thesis. And last but not least, thank you for giving me the unique opportunity to work on a challenging and rewarding pioneering project like this, I am forever grateful for having spent so much time on something that I highly enjoy.

Hanne, you deserve a very special thank you for taking non-existent time out of your schedule to help me out, both physically and mentally. This would have been very difficult without you!

The tedious task of proof-reading page after page of "blah-di-blah" was heroically performed by Thomas, Vebjørn, Maren Hanne, Håvard, Ida, Kristian and Lene. I know how boring that must have been - it is very much appreciated, thank you! Also, to my English-writing-expert-panel, thank you for *expert* guidance.

During my months-long endeavour of recording field data, a number of people spent hours on end helping me out. Thank you so much to Kjetil, Bjarne, Gjermund, Berit, Solveig, Linn and Torunn – you are a patient lot!

Also, to all the students, professors and lab-people who have patiently helped me out with microscopy, data treatment, that paper I can't find, and all kinds of stupid questions. Academia isn't so bad when there are resources like you all around.

And thank you to my friends, for making me take a break, giving me exercise, feeding me, motivating me, supporting me, and dealing with me not being there (literally and figuratively!). I miss you and can't wait to hang out again. Wenche and Kjell-Lauritz, thank you for wonderful motivation in the "innspurten", it really made a difference!

I also have a *world-class* family that must be mentioned. Thomas, Mom, Dad, Farmor, Farfar, Grandma and Grandpa: thank you so much for your help, motivation and support in all of this. And thank you for raising me to be curious. Aaand for showing me that mountains are pretty cool. Oh, and also for helping me when my PC crashed. That was fun.

And finally, thank you Kjetil. For being who you are, and showing me new depths of compassion, patience and care I never thought you were capable of. For this you have earned a well-deserved *Kjetil of the Year*-award! I can't wait to be yours again.

If you need me, I'll be skiing from now on.

Linda

Abstract

The Ersfjord Granite is a 1.79 Ga felsic intrusion in the geological region of West Troms Basement Complex (WTBC). Its intrusion history and evolution relative to surrounding Neoarchean TTG-gneisses has until now been poorly understood, providing the basis for this thesis. The present study focuses on internal deformation structures in the granite, as well as the nearby Gråtind Migmatite, in order to propose a tectono-magmatic model for the granite, and to compare the deformation to existing relevant literature.

The Neoarchean to Svecofennian deformation in the area can be summarized as follows: (i) Crustal shortening during the Neoarchean formed a well-foliated migmatitic fabric in the Gråtind Migmatite, prior to the intrusion of the Ersfjord Granite. (ii) The Ersfjord Granite intruded into the Neoarchean mid-crustal lithosphere in the late stages of the Svecofennian orogeny, creating a weak, distributed magmatic foliation. (iii) During, or shortly after, the intrusion of the Granite, WNW-directed thrusting formed low-angled, migmatitic shear zones in an accretionary orogenic setting involving partial anatexis. (iv) E-W directed crustal shortening folded the shear zones in the Ersfjord Granite and surrounding lithologies into open, upright folds, likely in the late stages of accretion. (v) A final deformation refolded the accretionary thrust systems into steeply plunging folds, in the Ersfjord Granite also leading to axial-planar strike-slip movement.

A tentative correlation is proposed to the evolutionary history of WTBC as outlined by Bergh et al. (2010), suggesting that the Ersfjord Granite intruded into the Neoarchean crust in an accretionary island arc or subduction system, involving partial anatexis and mixing of crustal components. The Ersfjord Granite is proposed to be a part of an oblique, antithetic thrust to the main tectonic transport direction during the Svecofennian accretion in WTBC. It is further suggested that the intrusion and deformation of the Ersfjord Granite, as well as the WTBC, is a part of the late-Svecofennian orogeny in the Fennoscandian shield. This deformation involved continental collision and underplating associated with magmatic activity and island-arc accretionary tectonics.

Table of contents

1 Introduction

The Ersfjord Granite (Landmark, 1973; Andresen, 1980) is a major granitic pluton on Kvaløya in western Troms of northern Norway (fig. 1), within the geological region of West Troms Basement Complex (WTBC; Zwaan & Bergh, 1995; Bergh et al., 2010). A crystallization age of 1.79 Ga is reported for the granite (Corfu et al., 2003), which is truncated through its center from west to east by the long and narrow fjord of Ersfjorden, from where it has its name (fig. 2). A range of spectacular, alpine peaks, all included in the Ersfjord Granite, surround the fjord on the northern and southern sides.

This thesis will investigate ductile deformation within and surrounding the Ersfjord Granite, as a part of an ongoing regional study at the department of bedrock geology at the University in Tromsø. The project is called "Precambrian crustal development, focusing on terrane accretionary shear zones in the West Troms Basement Complex (WTBC): age, formation and reactivation history", which is focused on regional ductile shear zones of Precambrian age. These shear zones are studied in order to find their significance in crustal formation, evolution and accretion of Archean crustal fragments in the WTBC region.

West Troms Basement Complex is an excellent place to study Archean and Paleoproterozoic basement rocks, as the region shows hardly any disturbance by the Caledonian orogenic event, and has good exposure. This is in contrast to the Precambrian bedrock found in southern Norway, where the Caledonian overprint makes much of the Precambrian structures and stratigraphy difficult to distinguish (e.g. Olesen et al., 1997). The Ersfjord Granite is a poorly studied part of the WTBC, despite its easy access. Most places within the Ersfjord Granite are less than an hour's drive from the city center of Tromsø, and can easily be reached by foot from the car. Also, alpine terrain and sparse vegetation make outcrops easy to come by.

1.1 Objectives

The main objective of this study is to describe and analyze ductile shear zones in the Ersfjord Granite of the WTBC, and to propose a tectonic model for the emplacement of the granite and the enclosed ductile shear zones. In order to achieve these goals, internal shear zones and related deformation structures in the granite and surrounding Neoarchean TTG-gneisses have been mapped and analyzed in detail. A second goal is to compare the obtained data with previous results and models for the WTBC as well as the Fennoscandian shield.

This thesis focuses on a set of low-angle, ductile shear zones that truncate the entire granite, and form gently dipping sets of localized, foliated fabrics in otherwise massive granite. The shear zones, which were first mentioned in the literature by Bergh et al. (2010), have not been mapped or described in detail so far. Landmark (1973) thought such structures were linked to

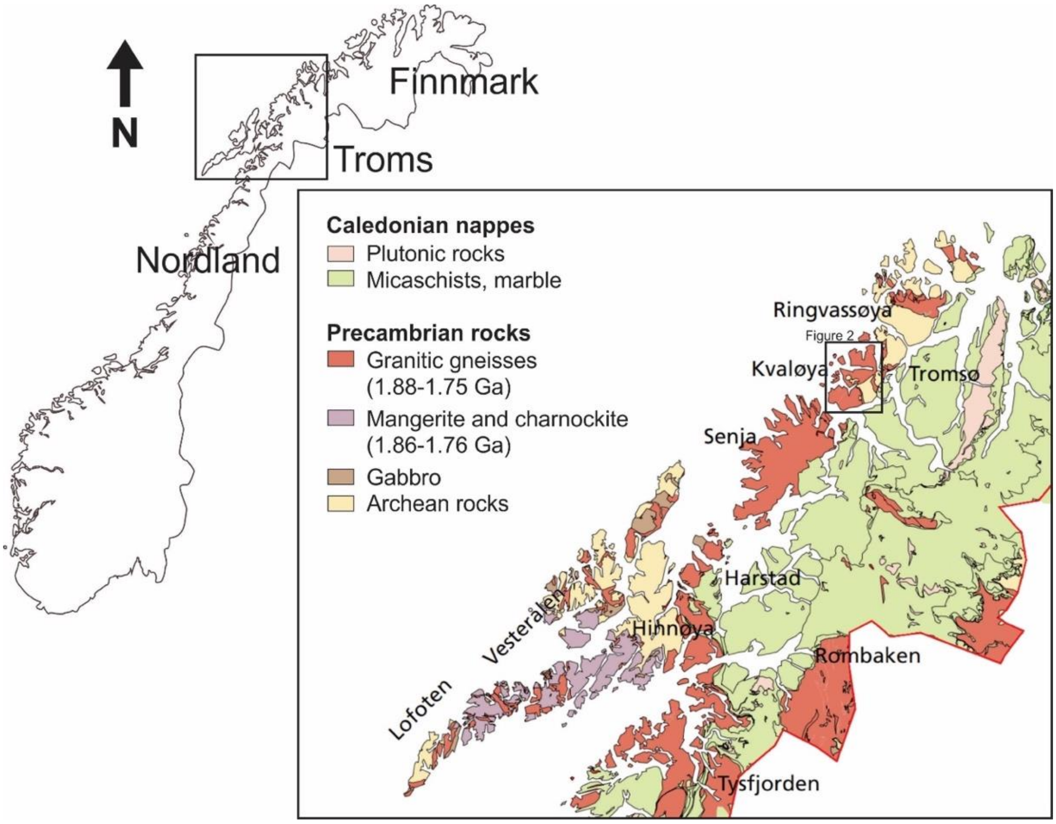

Figure 1. Geological overview map of Troms, showing the location of Kvaløya. Inset is an overview map of Norway, showing location of the geological map. Modified from Ramberg et al. (2013).

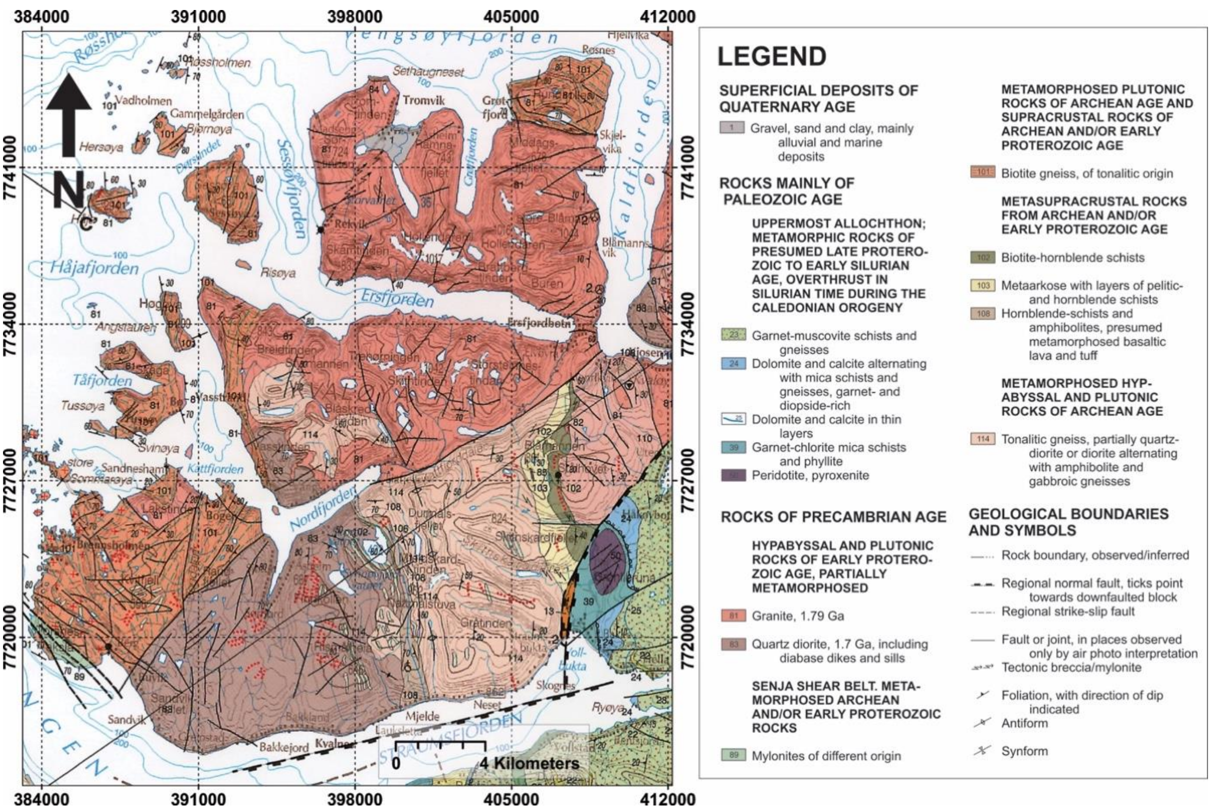

Figure 2. Geological map of the Ersfjorden area on Kvaløya, showing the extent of the Ersfjord Granite as mapped by Zwaan et al. (1998).

shear zones found in the Caledonian nappes of Troms, but their relation to the Ersfjord Granite, however, have not yet been resolved. In this study, these low-angle shear zones have been mapped and analyzed in detail, including internal structures and kinematics, as well as the relationship to other deformational events portrayed in the granite. Other deformation structures have also been studied, and used to compose a structural model. Rocks of the WTBC surrounding the Ersfjord Granite have been studied as well, making it possible to compare the structural and tectonic model for the granite with the surrounding lithologies.

No absolute dating of deformational events, internal lithologies or structures have been attempted in this investigation. Such data could substantially contribute to reinforcing or disproving findings from this study.

1.2 Methods

This chapter presents the methods used for data collection and analysis, as well as software used for data analysis and presentation.

Around 6 weeks were in total spent in the field, from July to October 2017, and comprised mostly mapping of shear zones and internal structures. In order to accurately map the study areas, published maps and aerial photographs from NGU.no and Norgeibilder.no were downloaded and brought into the field. A GPS was used in addition, making it possible to note down precise locations. Strike and dip of individual features were measured using a compass with an inclinometer, and recorded using the right-hand-rule (360/90). Other useful field equipment included binoculars, a hammer, a hand magnifying lens, pencils and paper.

For analyzing and presenting map data, ESRI ArcMAP 10.5 was used, and the topographic map from geonorge.no, projected in the coordinate system WGS 1984 UTM Zone 34W through a WMS-server, functioned as a background map for all map illustrations in this presentation, unless other references are specified. The geological background map is modified from NGU's mapping of Norway in 1:50 000 and 1:250 000. For analyzing orientation data, lower-hemisphere stereonets were made in Orient 3.6.3. Most figures, illustrations and images were modified and corrected with CorelDRAW Graphics X8.

22 samples were collected in the field, and studied in hand specimen and thin section. The thin section work mostly consisted of analyzing mineral growth in combination with deformation (Passchier & Trouw, 2005). This work was done using a petrographic microscope (Leica DMLP), and images of thin sections were taken with a Leica camera (DCF 450). Analyzing software (Leica's LAS v4.12) was used to enhance and stitch images together.

2 Regional geology

2.1 Introduction

The geology of northern Norway consists of Precambrian basement rocks and overlying Caledonian nappes (fig. 3). A description of the Precambrian basement in the Fennoscandian shield will be given in this chapter, with a more detailed description of the West Troms Basement Complex (WTBC) and the study area of the Ersfjord Granite. Finally, a short overview of the Caledonian nappes in Troms will be presented.

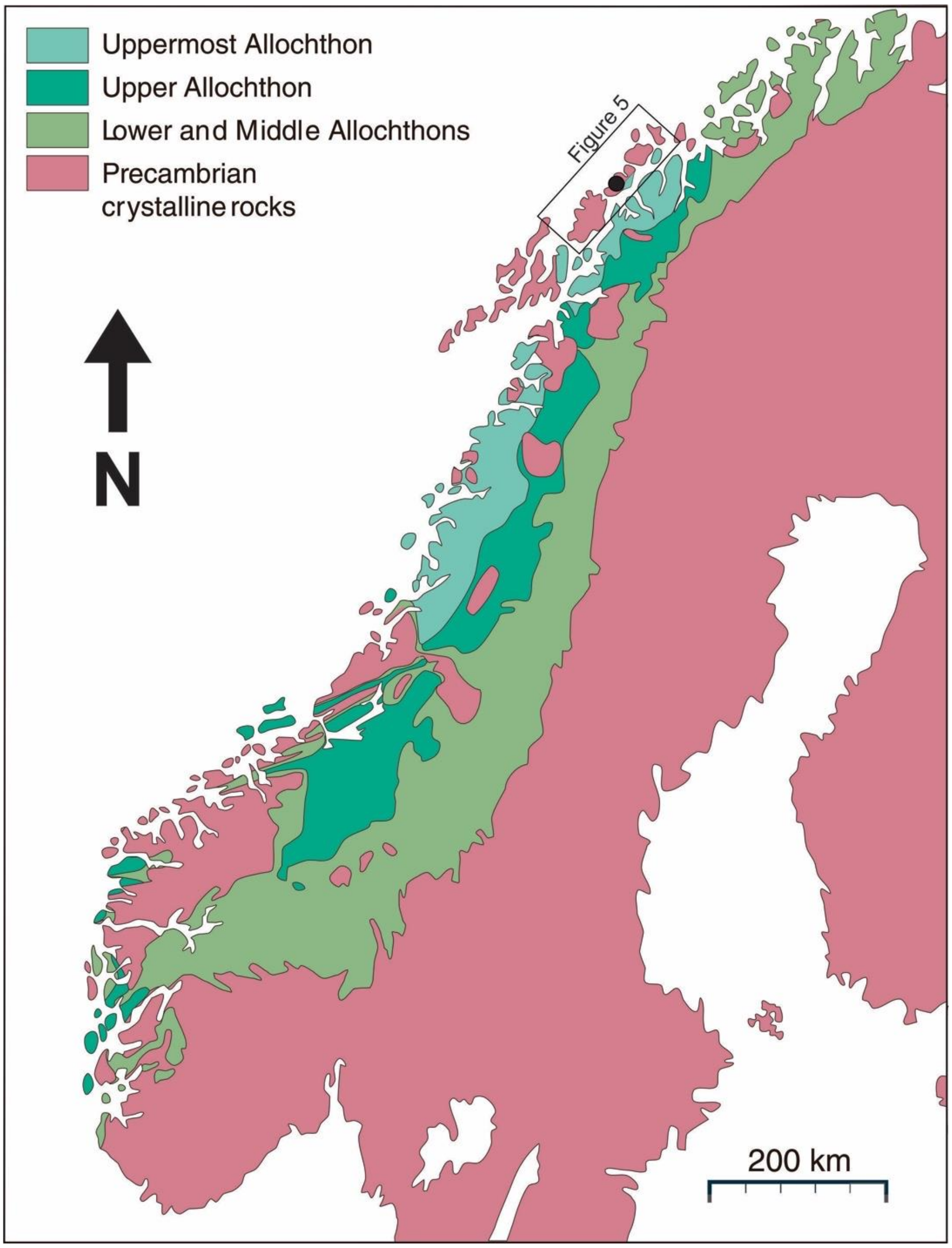

Figure 3. *Geological overview map of Norway, showing the division between the Precambrian basement and the Caledonian nappe pile. The Caledonian nappes are subdivided into four major units, the Lower, Middle, Upper and Uppermost Allochthons. The West Troms Basement Complex (WTBC) is shown in the black rectangle, and a black dot indicates the position of the Ersfjord Granite. Modified from Roberts (2003).*

The basement rocks of the Fennoscandian shield (fig. 4) consist of accretionary terranes younging in age from northeast to southwest as a consequence of major orogenic events during the Archean to the Mesoproterozoic (Gaál & Gorbatschev, 1987). West Troms Basement Complex (WTBC) is thought to be a part of the Fennoscandian shield (Griffin et al., 1978; Henkel, 1991; Olesen et al., 1997), uplifted and exposed during the rifting and formation of the passive continental margin outside of northern Norway during the Jurassic to mid Cretaceous (Henkel, 1987; Olesen et al., 1993; Zwaan & Bergh, 1995).

2.2 The Precambrian basement in Fennoscandia

Fennoscandia comprises the Scandinavian peninsula, Finland, Russian Karelia, and the Kola peninsula, and the Fennoscandian shield (fig. 4) refers to the Precambrian basement rocks in this region (Gorbatschev & Bogdanova, 1993).

The tectono-magmatic evolution of the Fennoscandian shield during the Precambrian involves several orogenic events, resulting in the amalgamation of Archean microcontinents in the northeast, and widespread arc accretionary growth towards the southwest, mainly during the Svecofennian orogenic event in the Proterozoic (e.g. Kärki et al., 1993; Nironen, 1997; Åhäll & Connelly, 2008). Most of the Archean crust is found in the northeast with a Paleoproterozoic cover, while Paleoproterozoic (mostly Svecofennian) crust dominates the central part of the craton (fig. 4; Lahtinen et al., 2008). In the southwesternmost regions, Meso- to Neoproterozoic crust dominates (Åhäll & Connelly, 2008). Approximately 80% of the Archean crust in the Fennoscandian shield consists of tonalitic-, trondhjemitic- and granodioritic-orthogneisses (TTG-gneisses) in addition to numerous meta-supracrustal rocks, paragneisses, granulite complexes, migmatitic amphibolites, intrusive mafic and felsic dykes, and mafic and granitoid plutons like the rapakivi granites (Lahtinen, 2012).

2.2.1 Archean provinces

The Archean part of the Fennoscandian shield can be divided into five main provinces comprising large-scale, N-S and NW-SE striking shear zones and metasupracrustal belts. These are the Murmansk, Kola, Belmorian, Karelian, and Norrbotten Provinces, (fig. 4; Holtta et al., 2008).

In the Murmansk- and Kola Provinces, Meso- to Neoarchean domains dominate, together with a few Paleoproterozoic components. Evidence is found of continental growth partially due to subduction of oceanic crust between 2.9 and 2.7 Ga, though the origin of both the subducted and the overriding crust is unclear (Holtta et al., 2008). The Lopian orogeny took place around 2.72 Ga (Lahtinen, 2012), further assembling the Archean crust towards the southwest as the Karelian craton was accreted to the existing land mass, and contributing to the buildup of the supercontinent Kenorland (Williams et al., 1991). Most of the Kola province consists of TTG rocks and other granitoids, paragneisses, greenstone belts and metavolcanic rocks, metamorphosed to upper amphibolite to granulite facies (Holtta et al., 2008). The Belmorian province is found between the two provinces of Kola and Karelia, and contains mainly Meso- to Neoarchean TTG-gneisses, paragneisses and multiple generations of greenstone belts (Slabunov et al., 2006; Holtta et al., 2008). Subduction-related Neoarchean activity is suggested based on the presence of ophiolites and eclogites in the Belmorian province (Volodichev et al., 2004), and the area in general shows evidence of high- to moderate pressure metamorphic events (Gaál & Gorbatschev, 1987).

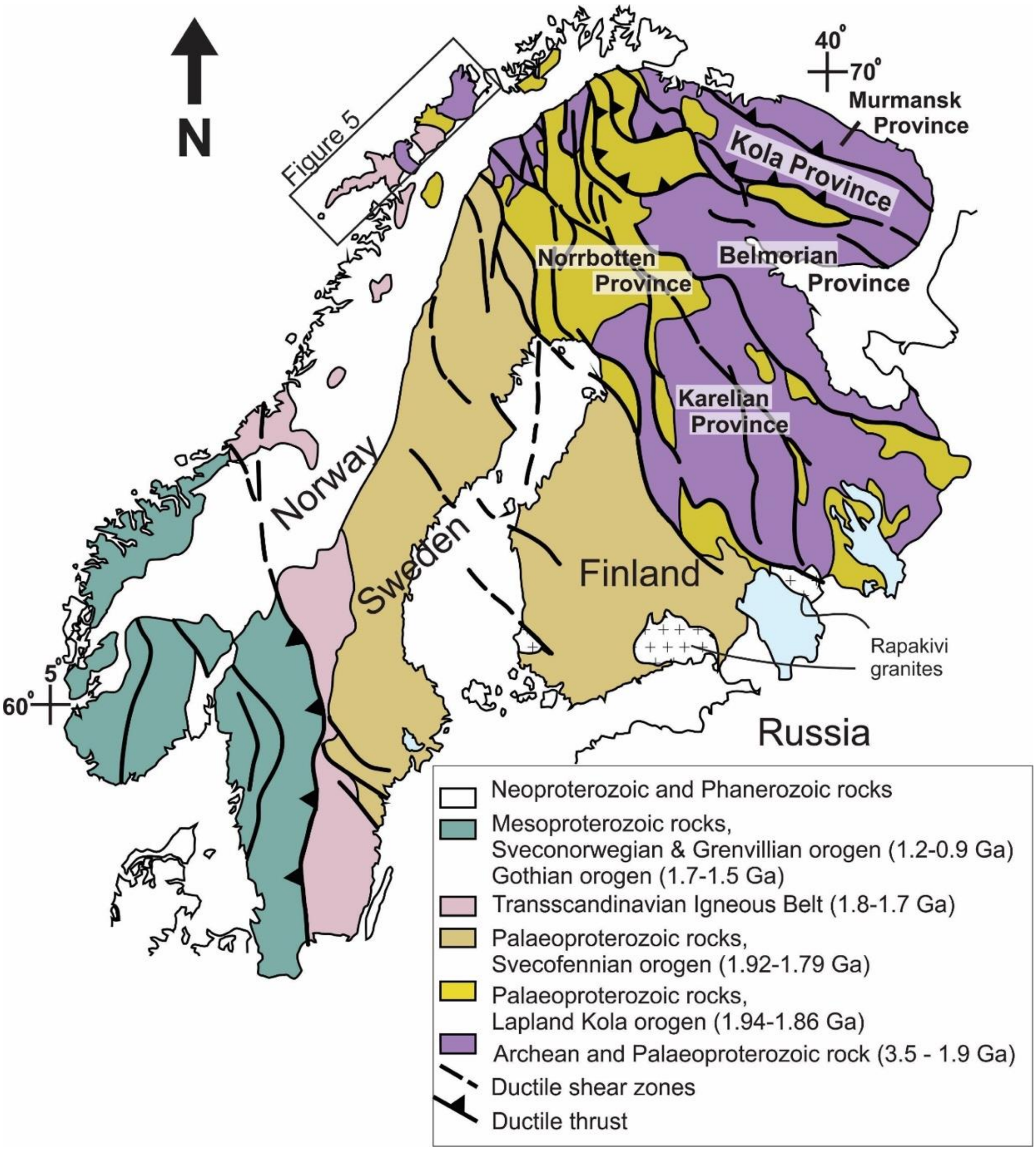

Figure 4. *Geological overview map of the Fennoscandian shield in Scandinavia, showing the extent of the Archean provinces and Proterozoic rocks. The rectangle shows the location of WTBC, and the outline of figure 5. Modified from Bergh et al. (2015) and Koistinen (2001).*

In the Karelian province, which is dominated by granitoids and greenstone belts, Mesoarchean lithologies dated to 3.2-3.0 Ga are found in the northern part, and 3.2-2.8 Ga lithologies in the west and south. The central part of the Karelian province consists of mainly Neoarchean TTG-gneisses and supracrustal units aging 2.75-2.70 Ga, as well as subduction-related granitoids (Holtta et al., 2008), deformed during tectonic thrusting in a northwestward direction (Samsonov et al., 2001). In the western parts of the Karelian province, tectonic transport of top-to-the NE and SE provides evidence that this area has been thrust eastwards over the central parts of the Karelian province, forming stacks of imbricate tectonic sheets as well as transpression around 2.7 Ga (Holtta et al., 2008). Meta-basalts with MORB composition found in this area suggest deposition in a back-arc or intra-arc rift setting (Kontinen et al., 2007). The Archean microcontinent that today constitutes the Norrbotten Province, was not accreted to the Karelian craton until well into the Paleoproterozoic at around 1.92 Ga. This was during the first stage of the Svecofennian orogeny, revised as the Lapland-Savo orogenic event by (Lahtinen et al., 2005).

2.2.2 Paleoproterozoic rocks

The beginning of the Proterozoic era was marked by incipient rifting of the supercontinent Kenorland around 2.5 Ga (Daly et al., 2006). The continental rifting took place in two stages and propagated southwestwards, initiated in northeastern Fennoscandia by a mantle plume responsible for the deposition of layered orthopyroxene-rich gabbro intrusions and dyke swarms aged 2.505-2.44 Ga (Melezhik, 2006). Further rifting took place as a consequence of reactivation of existing fault systems around 2.44 Ga, finally resulting in continental breakup and ocean formation around 2.1-2.04 Ga (Lahtinen et al., 2008).

Ensuing the breakup of Kenorland, multiple collisional events took place during the Proterozoic. The Lapland-Kola orogen at 1.86 Ga comprised the reworking of Archean and Neoarchean terrane with limited formation of juvenile crust, resulting in the accretion of the Kola and the Karelian cratons (Daly et al., 2006). The composite Svecofennian orogeny (1.92-1.79 Ga), however, included a long-lasting multiphase orogenic event, forming large parts of the Proterozoic segment of the Precambrian basement. Crust originating from the Svecofennian orogeny crops out over around one million square kilometers, and continues southwards below Phanerozoic cover rocks all the way to the Tornquist zone in the Skagerak-Poland area (Lahtinen et al., 2005). The Lapland-Savo orogen formed as the first stage of the Svecofennian orogeny, and comprised further collisions between Archean microcontinents, such as the Norrbotten craton accreting to the Karelian craton (fig. 4; Lahtinen et al., 2008). In the final stages of the Lapland-Savo event, north- and south-propagating subduction took place, the northward subduction continuing into the Fennian orogeny (the second stage of the Svecofennian orogeny) which mainly involved accretionary tectonics and local back-arc volcanism (Lahtinen et al., 2005). The 1.83-1.80 Ga Svecobaltic orogen formed as the third phase of the Svecofennian orogeny, and initiated as an oblique thrust creating E-W-striking, transpressional shear zones in the northern parts of the region. Further south, subduction was taking place simultaneously, evidenced by findings of arc magmatism in the area (Mansfeld et al., 2005). The final part of the Svecofennian orogeny is the Nordic orogeny, responsible for the intrusion of the oldest parts of the Transscandinavian Igneous Belt (1.81-1.77 Ga) as a consequence of continent-continent collision (Gorbatschev, 2004).

Together with the Svecofennian orogeny, two other Proterozoic domains are responsible for crustal growth, i.e. the Transscandinavian Igneous Belt (the TIB; 1.8-1.7 Ga) and the Gothian orogeny (1.7-1.5 Ga; e.g. Gaál & Gorbatschev, 1987; Åhäll & Connelly, 2008). The TIB is a long, NNW-SSE-striking igneous belt intruded along the southwest boundary of the Svecofennian domain. It stretches across the entire southern part of Sweden and below central parts of Norway, where it again crops out in western Norway (Högdahl et al., 2004). Multiple phases of intrusion are recorded, with variable composition and outcrop trends (Larson & Berglund, 1992). The Gothian orogen comprises the crust west of the rather undeformed TIB, and consists of mostly supracrustal and intrusive rocks (Gaál & Gorbatschev, 1987). Major reworking of this part of the crust took place during the Sveconorwegian and Grenvillian orogenies (around 1.2 - 0.9 Ga; Gorbatschev & Bogdanova, 1993).

2.3 The Precambrian basement in Troms

2.3.1 West Troms Basement Complex (WTBC)

West Troms Basement Complex (WTBC; Zwaan & Bergh, 1995), is a coastal part of the Precambrian basement in Troms in northern Norway, composed of Neoarchean and Paleoproterozoic rocks thought to be an exhumed part of the Precambrian basement found further east on the Fennoscandian shield (Griffin et al., 1978; Henkel, 1991; Olesen et al., 1997). The region is bounded in the southwest by similar aged plutonic and metamorphic rocks of Lofoten and Vesterålen (Griffin et al., 1978; Corfu, 2004), and in the east by the Caledonian nappe stack of Central Troms (e.g. Augland et al., 2014), and makes up an area of the four large islands of Senja, Kvaløya, Ringvassøya and Vanna, as well as a number of smaller islands (fig. 5). In general, the rocks of WTBC display a younging from the northeast to the southwest, and they contain various lithologies bounded my major shear zones, the largest of which is the around 30-kilometer wide Senja shear belt (Zwaan & Bergh, 1995).

The rocks of WTBC can roughly be divided into four main lithological units (Bergh et al., 2010), which will be discussed in greater detail below:

- Tonalitic-, trondhjemitic- and granodioritic (TTG-) gneisses
- Mafic dyke swarms
- Metasupracrustal units
- Granitic and mafic plutonic intrusions

The earliest work conducted in WTBC was for the most part focused on distinguishing the Precambrian basement from the Caledonian nappes. The late 20th century, however, has seen an increase in research activity in the region. Extensive mapping work in the WTBC and on Kvaløya was carried out by Landmark (1973), Andresen (1980), Binns (1983, 1984) and Zwaan (1992a, 1992b) from the 70's to the 90's, providing much of the basis for further studies in the area. The university in Tromsø has also spent a lot of time on working out the finer parts of the detailed formation and deformation history of WTBC the past years, resulting in a fairly complete understanding of the major points in the geological history of the area, as outlined in Bergh et al. (2010)'s paper.

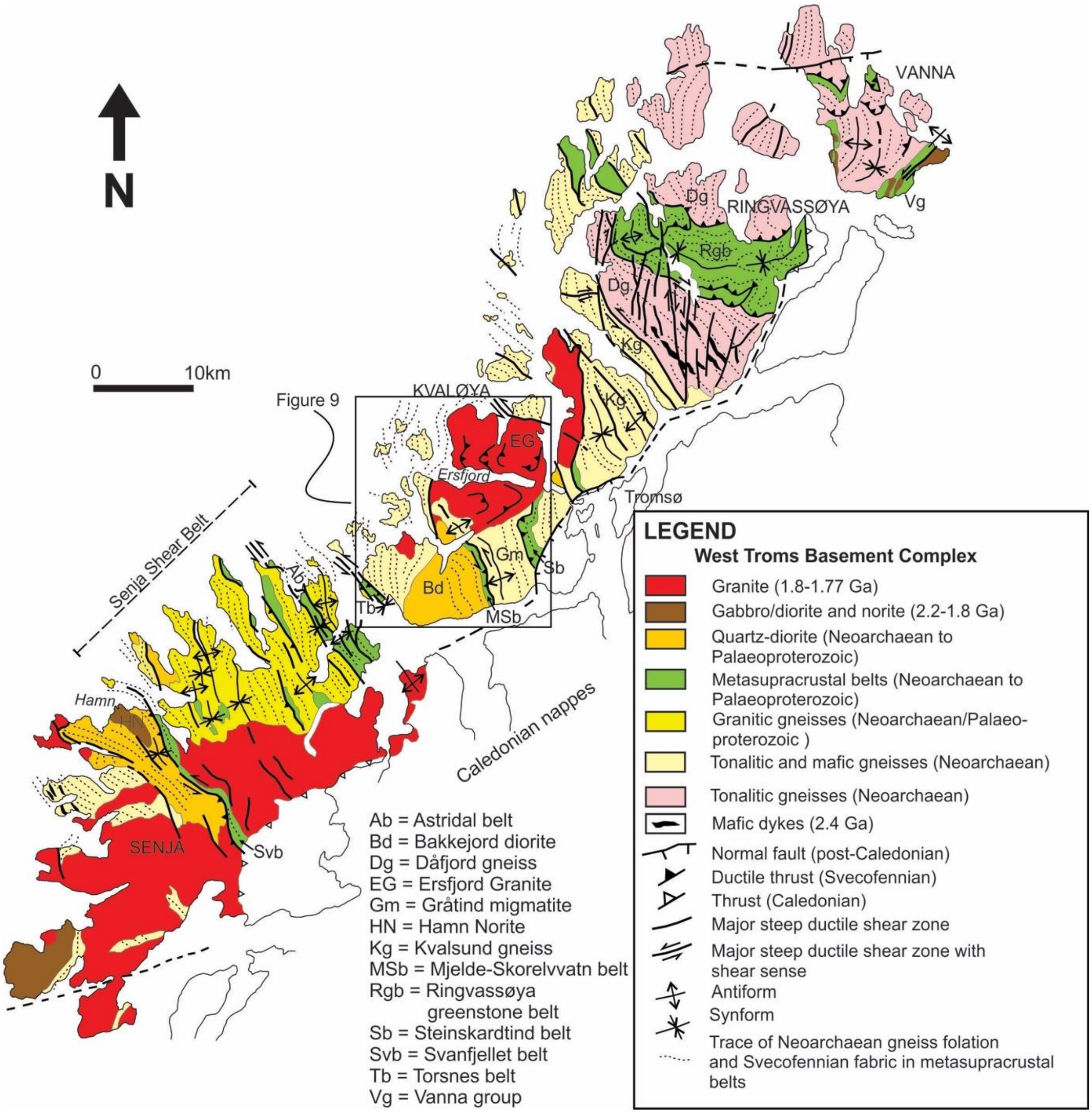

Figure 5. *Geological and tectonic map of the Precambrian basement province in western Troms, showing the different components of the West Troms Basement Complex (WTBC). Note the placement of the Ersfjord Granite (EG) on Kvaløya. Modified from Bergh et al. (2010).*

2.3.2 TTG-gneisses

Neoarchean gneisses of tonalitic-, trondhjemitic- and granodioritic origin (TTG-gneisses) are found most places in the region, the oldest and most tonalitic of them in the northeast. In the central and southwestern region, they are more heterogenic in composition, and are significantly younger than their counterpart in the north.

On Vanna and eastern Ringvassøya, tonalites from the Dåfjord gneiss (fig. 5) have U-Pb zircon ages of 2885 ±20 Ma (Bergh et al., 2007b) and 2849 ±3 Ma, respectively (Zwaan & Tucker, 1996). This makes them the oldest rocks recorded in the region, though it is assumed that they must have intruded into even older crust; no such host rock has yet been found. On southern Kvaløya, the Bakkejord diorite (fig. 5) is found to have a U-Pb zircon age of 2723 ±7 Ma (Kullerud et al., 2006a), while an age of 2800-2750 Ma (Kullerud et al., 2006a) is found in the more heterogeneous and granitic gneisses of Senja.

The main foliation in the tonalites strikes N-S to NNW-SSE, and dips gently to steeply in both directions. Multiple indicators of dip-slip to oblique-slip and ENE-WSW convergence are found within them (Bergh et al., 2010). Parallel to the foliation, shear zones and migmatite zones often separate rocks of different origin. The tonalitic gneisses mostly contain amphibolite facies metamorphic assemblages, though the Kvalsund gneiss in northern Kvaløya and southern Ringvassøya (fig. 5) displays granulite facies. The Kvalsund gneiss is a banded gneiss, commonly migmatized, and is assumed to be a high-strain ductile shear zone of Neoarchean origin (Zwaan, 1992b).

2.3.3 Mafic dyke swarms

Paleoproterozoic dyke swarms (2403 ±3 Ma (Kullerud et al., 2006b) of doleritic composition can be seen throughout most of the region of the WTBC. They most commonly strike N-S to NNW-SSE (Bergh et al., 2010). It is on Ringvassøya that the dykes are the most conspicuous, where darkly colored dykes are clearly visible against the light-colored, tonalitic host rocks. On Ringvassøya they yield a U-Pb zircon and baddeleyite crystallization age of 2403 ±3 Ma (Kullerud et al., 2006b). These dykes show local signs of mylonitization along the edges, and otherwise consist of mostly undeformed gabbros and norites (Kullerud et al. 2006b). In the Bakkejord diorite on Kvaløya (Binns, 1983, 1984; Zwaan, 1992b), a preliminary U-Pb zircon age of the dykes is around 2670 Ma (Kullerud et al., 2006b). The dyke swarm on Senja has not been dated (Zwaan, 1992b; Armitage, 2004).

2.3.4 Metasupracrustal units

Sedimentary and volcanic layers, thought to have been deposited in a rift-basin on top of the TTG-gneisses, are today seen as northwest-southeast trending metasupracrustal belts deformed during the Svecofennian orogeny. Most of these belts strike NW-SE, and bound mega-blocks of TTG-gneisses of different composition (Bergh et al., 2010). The most prominent of these are included in the Senja Shear Belt found on northern Senja and southern

Kvaløya, and are called the Svanfjellet belt (Zwaan & Bergh, 1995; Armitage, 2004), the Astridalen belt (Pedersen, 1997), and the Torsnes belt (fig. 5; Nyheim et al., 1994). The Torsnes belt is located on southern Kvaløya, and has been dated to 1970 ±14 Ma (Myhre et al., 2011) with the help of U-Pb data from detrital zircons. Two more metasupracrustal belts are found on southern Kvaløya (chapter 2.3.7), the Mjelde-Skorelvvatn (Armitage, 1999; Armitage & Bergh, 2005) and the Steinskardtind (Binns, 1983, 1984) formations. A volcanic lens in the Mjelde-Skorelvvatn belt was dated at 1.98 Ga (Kullerud et al., 2006a; Myhre et al., 2011). The Archean Ringvassøya greenstone belt is metamorphosed into greenschist to amphibolite facies, and is the oldest belt of its kind at 2.85-2.83 Ga (Zwaan, 1989; Motuza et al., 2001; Kullerud et al., 2006b).

2.3.5 Bimodal plutonic intrusions

Felsic and mafic plutonic intrusions dated to 1.8-1.7 Ga cover large areas of Kvaløya and Senja. The crystallization ages suggest that the intrusive activity is a result of the late stages of the Svecofennian orogeny. Granitic pegmatite dykes found in the same areas are presumed to be genetically related to the intrusion events (Bergh, 2010).

The Ersfjord Granite on Kvaløya and the Hamn Norite on Senja are the most prominent examples of these bimodal intrusions. The Hamn Norite has a magmatic layering, and is mainly massive and unaffected by later deformation. However, a steeply plunging fold hinge suggests it was partially affected by the late stages of the Svecofennian orogeny.

In the Ersfjord Granite, which is the target of this thesis, not much work has been carried out so far. Zwaan's mapping from 1992 (Zwaan, 1992b) provides a preliminary contact zone between the granite and surrounding lithologies, and Andresen (1980) proposed a massive texture throughout the granite, which he dated to be 1.705 Ga using the Rb-Sr whole-rock method. Corfu et al. (2003) found a well confirmed zircon age of 1.792 ±5 Ma for the granite, and suggested that it formed slightly before or during a major plutonic episode that took place across the entire Baltic shield, i.e. during early stages of the intrusion of the Transscandinavian Igneous Belt (see chapter 2.2.2). Bergh et al. (2010) suggested that the granite was intruded in pulses, and that the final stages of the intrusion could be represented by the pegmatitic veins observed in and around the granite. During the same investigation, Bergh et al. (2010) reported that the granite was not a completely massive pluton, but contained a number of localized, low-angled, ductile shear zones. The extent, timing and kinematics of these shear zones, as well as their relationships to the surrounding TTG-gneisses and other components of the WTBC, are not yet understood. Therefore, these shear zones provide the basis for this thesis.

2.3.6 Neoarchean and Paleoproterozoic deformational events

WTBC has a long and complex evolutionary history, as the oldest structures are radiometrically dated between 2.8 and 2.6. Ga (Myhre et al., 2013). A brief summary of the main tectono-thermal events is presented below.

The TTG-gneisses of the WTBC consist of heterogeneous lithologies with a variety of ductile structures throughout most of the region. They are interpreted to have originated from the juxtaposition of different crustal fragments tectonically accreted together in Neoarchean compressional regimes (fig. 6), involving E-W crustal thickening and underplating (Bergh et al., 2010). A well-defined migmatitic foliation is a presumed relict fabric from this Neoarchean stage of deformation (fig. 6a; e.g. Bergh et al., 2015). Mafic dykes were intruded in WTBC when an assumed Neoarchean supercontinent rifted, initiating a global magmatic event (e.g. Buchan et al., 1998; Mertanen et al., 1999; Corfu & Easton, 2001; Strachan et al., 2012), which in WTBC was dated to 2.4 Ga at Ringvassøya (fig. 6b; Kullerud et al., 2006b). Crustal extension and thinning formed large-scale rift basins, which collected widespread supracrustal units during the early Svecofennian (Bergh et al., 2007b; Myhre et al., 2011). These deposits were later reworked into the metasupracrustal belts described above.

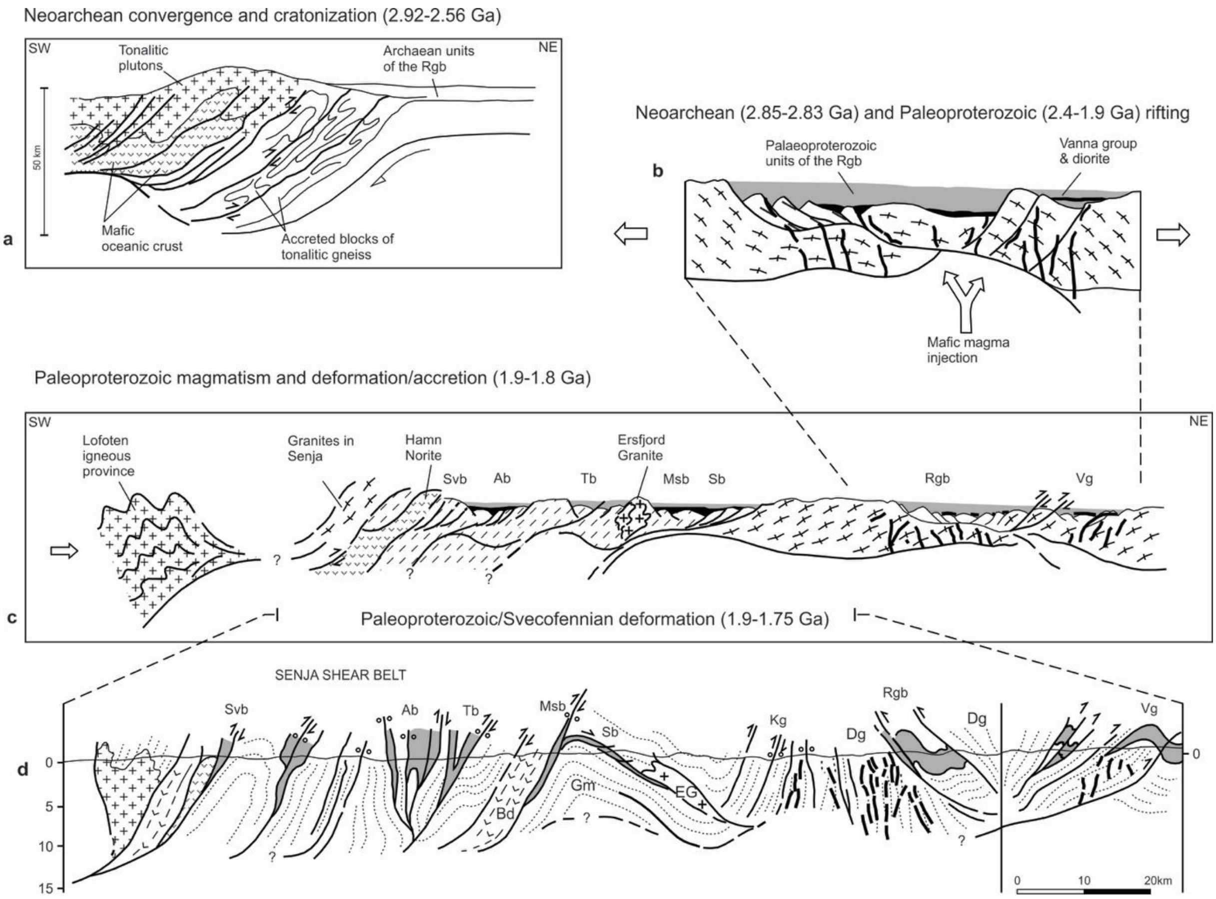

__Figure 6.__ Illustration of cross-sections through the West Troms Basement Complex (WTBC) from SW to NE, showing the Neoarchean to Paleoproterozoic evolution of the region. Modified from Bergh et al. (2010). a) Neoarchean accretion of microcontinents involving juxtaposition of tonalitic plutons, oceanic crustal fragments and the formation of tonalitic gneisses. b) Early Paleoproterozoic crustal extension led to the formation of rift basins and (global) injection of mafic magma in dykes. c) Paleoproterozoic crustal shortening and bimodal plutonism as a consequence of accretionary tectonics during the

Svecofennian orogeny. d) Detailed cross-section showing the composite result of the Archean and Proterozoic crust-forming events. Abbreviations are the same as for figure 5.

During the Svecofennian orogeny, a highly active stage of bimodal plutonism was followed by compressional tectonics (fig. 6c), including low-angle thrusts and the formation of a main foliation in metasupracrustal units (D1-event; fig. 7a) during medium- to high-grade metamorphic conditions in the WTBC (Bergh et al., 2010). A second Svecofennian deformation event (D2; fig. 7b) refolded the metasupracrustal belts and thrust zones into large-scale NW-SE trending, tight to open folds. Later, a third deformation (D3; fig. 7c) folded the preexisting fabrics into vertical folds that produced steep, NW-SE striking shear zones with mostly sinistral strike-slip deformation (Armitage & Bergh, 2005). This final deformational event comprised low-angled, SE-directed thrust zones and steeply dipping, ductile shear zones in Ringvassøya and Vanna (fig. 6d).

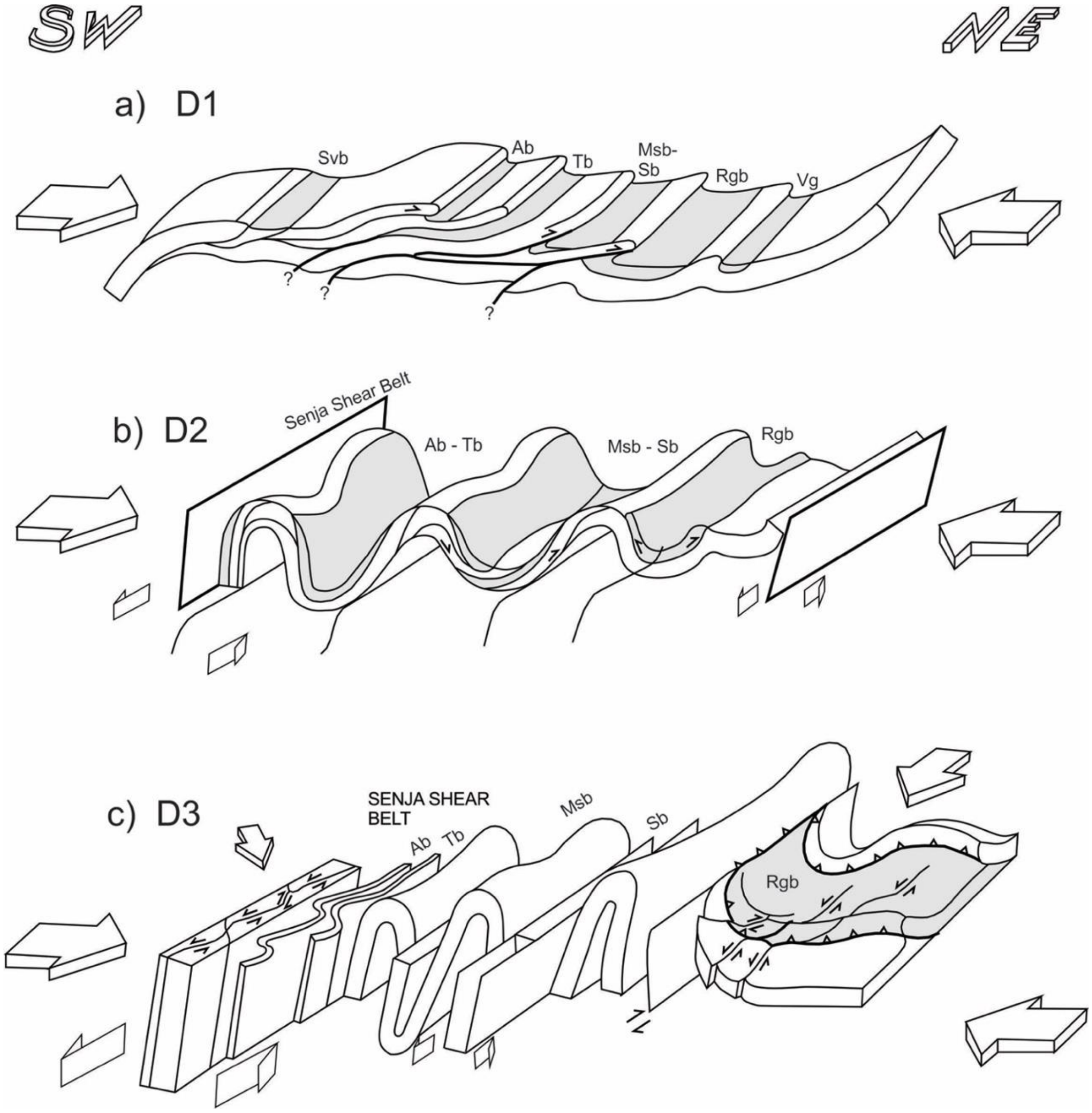

Figure 7. *Schematic illustration of Svecofennian deformation in the West Troms Basement Complex (WTBC) in a SW-NE directed cross-section, modified from Bergh et al. (2010). a) NE-directed accretion and formation of low-angled thrust-zones throughout the region. b) Crustal shortening in a NE-SW direction forming upright, closed to open folds. c) Continued crustal shortening comprising slip along fold limbs and forming steeply plunging folds. Abbreviations are the same as for figure 5.*

2.3.7 Geology of Kvaløya

A number of lithologies surround the Ersfjord Granite on Kvaløya (figs. 2, 5). The Gråtind Migmatite, which has been closely studied in this investigation, lies directly south of the Ersfjord Granite, and is delimited by the metasupracrustal belts of the Skorelvvatn- and Steinskardtind Formations to the west and east, respectively. An intensely sheared transpressive shear zone to the west of the Skorelvvatn Formation constitutes its contact to the plutonic complex of the Bakkejord Diorite, which borders to the Kattfjord Gneiss further west. The Kvalsund Gneiss lies to the east of the Steinskardtind Formation (Zwaan, 1992a, 1992b; Bergh et al., 2010). The exact boundaries between the Ersfjord Granite and these surrounding lithologies are not yet well investigated.

The metasupracrustal rocks of the Steinskardtind- and the Skorelvvatn Formations consist of amphibolite facies meta-sedimentary and mafic volcanic rocks, retrograded into greenschist facies (Zwaan, 1992b; Zwaan et al., 1998; Armitage, 1999; Armitage & Bergh, 2005). In the Skorelvvatn Formation, Armitage and Bergh (2005) found mainly coarse-grained, foliated amphibolites, marbles, actinolite-plagioclase schists, and banded meta-psammites. The Steinskardtind Formation consists of paragneisses with mafic, silicic and calc-silicate lithologies (Myhre et al., 2011).

The Gråtind Migmatite is an anorthositic to quartz-feldspathic, intensely foliated gneiss, including intermittent bands and lenses of amphibolites, very coarse-grained biotite schists, and green serpentinites assumed to be retrograded ultramafic rocks. The Kattfjord Complex consists of a biotite-rich, well-foliated, partly migmatized orthogneiss of tonalitic composition (Zwaan, 1992b). The composite plutonic complex of the Bakkejord Diorite comprises metagabbro, metadiorite dated at 2.72-2.66 Ga (Myhre et al., 2013), and metatonalite. It is cut by a set of metadiabase dykes and is weakly deformed throughout its extent, apart from a gneissic texture near the contact to the Skorelvvatn Formation (Armitage & Bergh, 2005). The Kvalsund Gneiss is a reworked, tonalitic, banded gneiss with high-strain fabrics showing evidence of anatexis (Zwaan, 1992b).

2.4 The Caledonides

In the early Palaeozoic, the supercontinent Pangea was created, in Fennoscandia through the E-W directed collision of the Baltic and Laurentic continental plates (fig. 8). This collision resulted in the formation of the Caledonian orogen, and comprised closing of the Iapetus ocean and finally subduction of the Baltic margin below the Laurentian plate during the Silurian to the early Devonian (fig. 3; Roberts & Gee, 1985). The resulting tectonostratigraphy recognized today comprises the Lower, Middle, Upper, and Uppermost Allochthons (fig. 3; Roberts, 2003).

The Caledonian mountain chain in northern Norway and central Troms (figs. 1, 3) comprises components from all four allochthons. The Tromsø nappe in the uppermost allochthon, is bounded to the WTBC by a Mesozoic normal fault system (Forslund, 1988; Indrevær et al., 2013).

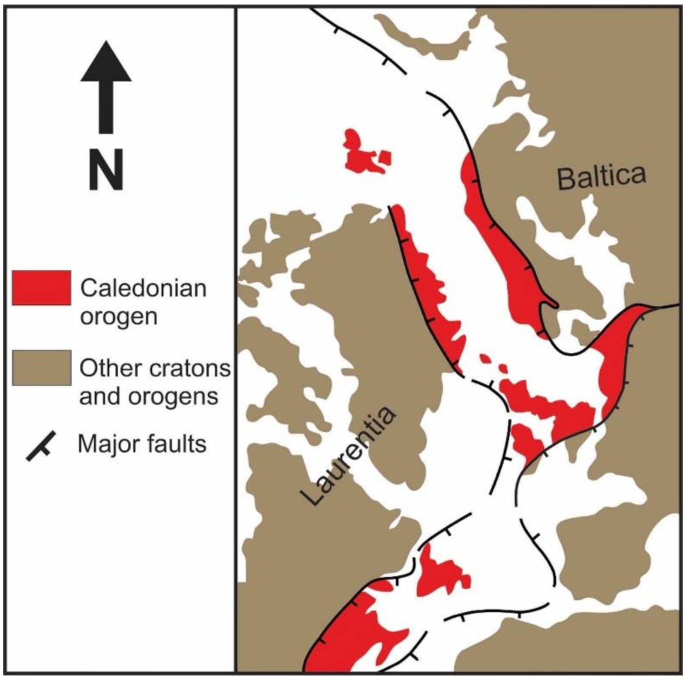

Figure 8. *Simplified map showing the extent of the Caledonian orogenic event, which took place in the early Paleozoic by collision of the two continental plates of Laurentia and Baltica. Modified from Gee et al. (2008).*

Generally in Norway, Lower and Middle Allochthons comprise mostly shelf and continental rise-associated material derived from the Baltic margin (Roberts, 2003). Upper Allochthon consists of ophiolitic material, primitive and evolved magmatic arc successions, and marginal basin material presumably from the Iapetus Ocean or nearby terranes (Stephens & Gee, 1985; Grenne et al., 1999). The Uppermost Allochthon is considered to be exotic terrane from the Laurentic continent (Stephens & Gee, 1989; Roberts et al., 2002).

In the Devonian the collapse of the Caledonides began, many places as a consequence of reactivation of old thrust faults. During the final stages of the collapse in the Mesozoic and Cenozoic, the Atlantic Ocean began to open, and uplift took place along the margin of Norway. The rotation of fault blocks and creation of horst-graben structures resulted in juxtaposition of Precambrian basement next to Caledonian nappes along much of the present-day coastal regions of northern Norway. This uplift, together with multiple tectonic windows in a belt parallel to the coastline, makes it possible to study the Precambrian basement in Norway, and is assumed to be the main contributor of the uplift of the WTBC (figs. 2, 3, 4; e.g. Bergh et al., 2007a; Faleide et al., 2008; Indrevær et al., 2013).

3 Results

3.1 Overview

Most of the Ersfjord Granite consists of fairly homogeneous, coarse-grained, massive granite, some places with a weak, distributed foliation, and numerous, localized ductile shear zones. A number of structural elements are present within the granite, often related to these shear zones, and in particular near the contacts to the surrounding TTG-rocks of the Gråtind Migmatite (Zwaan, 1992b; Bergh et al., 2010). Shear zones in the Ersfjord Granite seem to have formed during different deformational events, and reflect heterogeneous evolutionary histories. They also seem to have some genetic relationship to those of the Gråtind Migmatite (table 1; fig. 9). For example at Tverrfjellet, a steeply dipping migmatite foliation in the TTG-gneisses of the Gråtind Migmatite is cross-cut by a low-angle, migmatite shear zone fabric that strongly resembles shear zones in the Ersfjord Granite. The contact between the Ersfjord Granite and the Gråtind Migmatite (Zwaan, 1992b) is mapped structurally above the Tverrfjellet shear zone in the Tverrfjellet-Middagstind area (fig. 11).

The most prominent shear zones within the Ersfjord Granite, which also are the main focus of this study, are low-angled, ductile, localized migmatite zones. They crop out in most mountain sides, making up a repeating, gently dipping, planar fabric throughout the granite. Internally they display composite fabrics, including isoclinal and asymmetric folds, boudinage, sigmaclasts, duplexes and secondary foliations. They are also folded in large-scale, and cross cut by a younger set of steeply dipping to subvertical, ductile shear zones.

In this chapter, a description of the localities will be provided, followed by a presentation of petrographic and structural data from the Gråtind Migmatite and Ersfjord Granite. A summary of the results and tentative interpretations is presented in table 1 below, and a compiled geological map in figure 9. A selection of structural data from within the Ersfjord Granite is shown in figure 10.

3.2 Main study areas

Ductile shear zones were studied in three main areas where most of the fieldwork was conducted, including the mountains of Hatten and Buren within the eastern contact of the Ersfjord Granite, and at Tverrfjellet in the Gråtind Migmatite, where the contact zone between the Ersfjord Granite and the Gråtind Migmatite is found. Additional structural and petrographic data were collected from Middagstind and Store Blåmann (fig. 9). Data were also provided from previous work in the area (e.g. Andresen, 1980; Zwaan, 1992a, 1992b; Zwaan & Bergh, 1995; Armitage, 1999; Armitage & Bergh, 2005; Bergh et al., 2010), as well as from own field work in a few additional places within and around the Ersfjord Granite.

Table 1. Summary of deformational events and related structures identified in the Ersfjord Granite and surrounding rocks of the Gråtind Migmatite, with tentative interpretations and correlation of deformational events.

Deformational events in the Ersfjord Granite					
		D0^{EG} intrusion event	D1^{EG}	D2^{EG}	D3^{EG}
Lithology		Ersfjord Granite, containing mainly quartz, biotite, albite and microcline	Migmatitic gneisses with mafic inclusions and pegmatitic veins.		Biotite-rich orthomylonite.
Internal fabrics		Weak, distributed foliation (S0^{EG}) in the Ersfjord Granite	Isoclinal folds (F1a^{EG}), producing axial-planar shear zone foliation of low-angle ductile shear zones (S1^{EG}). Intrafolial asymmetric shear folds (F1b^{EG}) refolding the S1^{EG}-foliation.	Large-scale gentle to open, upright to asymmetric F2^{EG}-folding of S1^{EG}-shear zones.	Steep, mylonitic, ductile shear zones (S3^{EG}) cross-cut the S1^{EG}-fabrics. Associated with drag folding.
Fabric orientation data		N-S strike, alternating gentle to moderate dip to the E and W	S1^{EG}-shear zones striking variably N-S and dipping subhorizontally to gently to the NW and SE. Intrafolial asymmetric shear folds (F2b^{EG}) with fold axes plunging to the N to NW	Fold axes plunge subhorizontally to gently to the NNW.	S3^{EG}-foliation strikes NNE-SSW and dips steeply to the ESE.
Sense-of-shear			Top-to-the WNW; NNE-SSW shortening	Top-to-the W (?)	Oblique shortening and strike-slip
Interpretation		Magmatic foliation due to 1) Intrusion of Ersfjord Granite as major magma chamber, or 2) partial migmatization, i.e. melting of TTG-gneisses, supra-crustal rocks and/or para-gneisses, or 3) combined intrusion event and partial melting/migmatization of surrounding host rocks during early-stage crustal shortening and/or accretion	Main fold-thrust forming event. Subduction/ accretion-related (?) oblique-reverse imbricate thrusting. D1-Svecofennian deformation (cf. Bergh et al., 2010). Shear zone rocks formed due to crustal accretion, shearing and partial melting of Ersfjord Granite and surrounding TTG-gneisses of the Gråtind Migmatite (?)	Continued coaxial folding and thrusting. D2-Svecofennian deformation (cf. Bergh et al., 2010)	Orogeny-oblique shearing? D3-Svecofennian deformation (cf. Bergh et al., 2010)
Deformational events in the Gråtind Migmatite (TTG-gneisses)					
	D1^{GM}		D2^{GM}	D3^{GM}	D4^{GM}
Lithology	Migmatitic TTG-gneisses		Migmatitic gneisses and mylonites with intrusions of pegmatite and inclusions of mafic lenses		
Internal fabrics	Well-developed, banded migmatitic foliation and internal, isoclinal folds (axial-planar foliation, F1^{GM})		Open to tight, asymmetric folds (F2^{GM}) producing axial planar low-angle shear zones (S2^{GM}, e.g. Tverrfjellet shear zone). Isoclinal to tight asymmetric, intrafolial folds (F2a^{GM}-F2b^{GM}) and other asymmetric structures within shear zones.	Open to tight, subhorizontal asymmetric folds of low-angle shear zones	Steeply plunging, macro-scale closed to tight folds
Fabric orientation data	On average NW-SE strike, steeply and variably SW and NE- dipping		Tverrfjellet shear zone, S2^{GM}-foliation: strike NE-SW, dip SE (225/25). F2^{GM}-fold axes: 090/30. Intrafolial shear folds within Tverrfjellet shear zone, F2b^{GM} fold axes: 135/25.	Not observed	Steeply NE-plunging fold axes
Sense-of-shear			Top to the WNW; NNE-SSW shortening	Not observed	Not observed
Interpretation	Neoarchean (?) deformational event including partial melting of crust and ductile shortening and shearing		Tverrfjellet shear zone is interpreted as a W-SW-directed, oblique, imbricate thrust zone. May correspond to Svecofennian D1^{EG}-deformational event.	Progressive coaxial refolding of S2^{GM}-shear zones. Corresponds to D2^{EG}-deformation (?)	Axial-planar shearing formed D3^{EG}-shear zones.

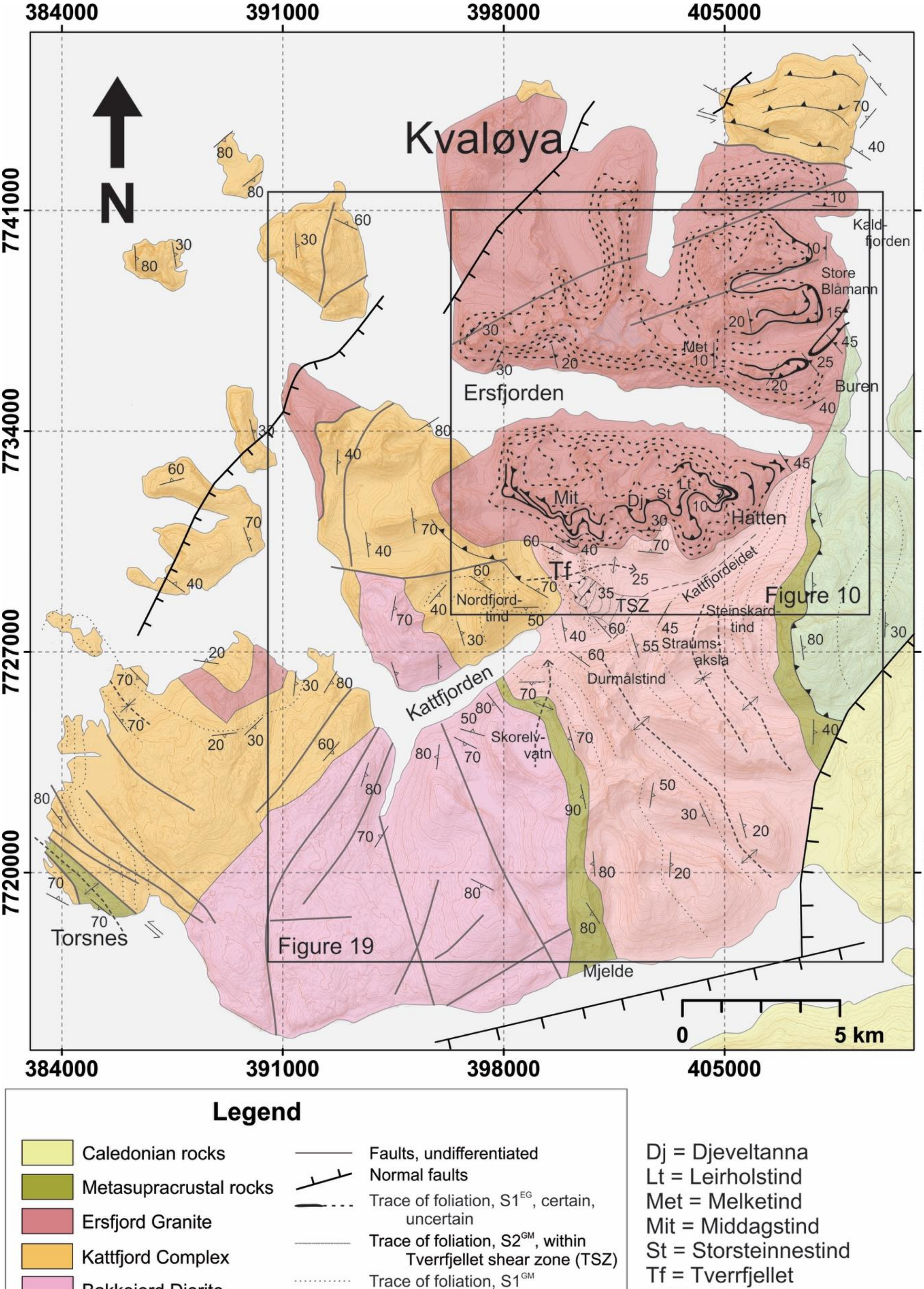

Figure 9. *Geological overview map of Kvaløya showing the main structural elements and geological domains.*

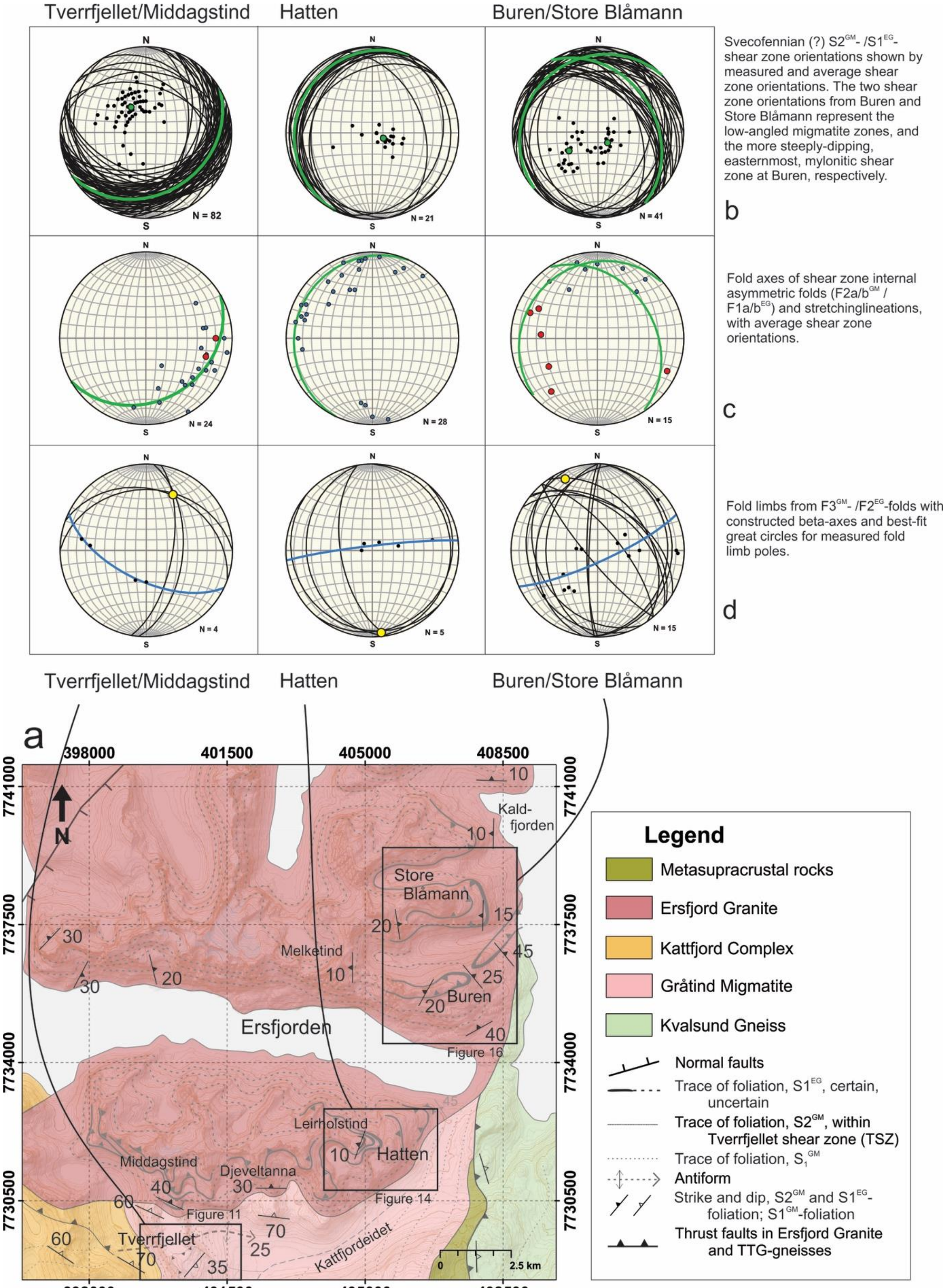

Figure 10. *Geological map showing the main study areas of Tverrfjellet, Hatten, Buren and Store Blåmann. Inset are lower-hemisphere stereonets presenting a selection of structural data, where black great circles are measured orientations of $S2^{GM}$ and $S1^{EG}$-shear zones, black dots are poles to the shear zones, green great circles are average shear zone orientations for each locality, and green dots are poles to the average shear zone orientations. Blue dots are measured $F2^{GM}$ and $F1^{EG}$-fold axes,*

and red dots are measured stretching lineations. Yellow dots are constructed beta-axes, and blue great circles are best-fit circles for measured fold axes.

3.2.1 Tverrfjellet and Middagstind

Tverrfjellet lies within the Gråtind Migmatite (Zwaan, 1992b), just outside the southwesternmost part of the Ersfjord Granite in the valley of Kattfjordeidet, and summits at 675 meters above sea level (fig. 9). During Zwaan et al. (1998)'s mapping of the Ersfjord Granite, Tverrfjellet was placed within the southernmost part of the granite (fig. 2). It was proposed that the contact between the granite and the surrounding Gråtind Migmatite was located approximately along the valley of Kattfjordeidet, and a lake southwest of the summit of Tverrfjellet, some places higher up in the mountainside opposite the lake (Zwaan et al., 1998).

Our remapping, however, shows that the lower sections of Tverrfjellet are composed dominantly of migmatitic gneisses with a steep foliation resembling the Gråtind Migmatite (see chapter 3.3.1). The upper part of the mountain contains a gently dipping migmatitic shear zone termed Tverrfjellet shear zone (see figs. 11, 12, and chapter 3.3.2) that cross cuts the steeply dipping foliation of the underlying Gråtind Migmatite (fig. 13). The proposed contact to the Ersfjord Granite is located structurally above and subparallel to Tverrfjellet shear zone, in the mountainside leading up to Middagstind (fig. 11).

Rocks of the Tverrfjellet shear zone display a low-angle, NE-SW striking, SE-dipping ductile, migmatitic gneiss fabric (fig. 12) which is well exposed along the southeast shore of the lake Tverrfjellvatnet. The shear zone consists of a heterogeneous assemblage of foliated granites, interlayered mafic gneisses and occasional lenses of seemingly massive granite rocks (fig. 11). More detailed petrographic and structural data will be provided in chapter 3.3.2.

The foliation of the Gråtind Migmatite at Tverrfjellet (fig. 11) below the Tverrfjellet shear zone, comprises a well-developed, gneissic texture with a composite, heterogenous, steeply E-dipping and folded foliation. In the transect northwards towards Middagstind, Ersfjord Granite rocks substitute the steeply dipping gneisses of the Gråtind Migmatite along a contact that is subparallel to the foliation of the Gråtind Migmatite rocks (see more detailed description in chapter 3.5). Above the contact, massive Ersfjord Granite dominates, though several migmatitic ductile shear zones repeatedly crop out. These shear zones strike NE-SW and dip gently to the SE (see description in chapter 3.4.2).

Narrow, steep to subvertically dipping planar fabrics interpreted to be shear zones are visible in outcrops at Tverrfjellet (see details in chapter 3.4.4). They strike NNE-SSW and truncate the Tverrfjellet shear zone described above (fig. 12). These features crop out on the surface of the bed rocks along linear depressions, often covered by glacial debris, water, soil, or thin vegetation.

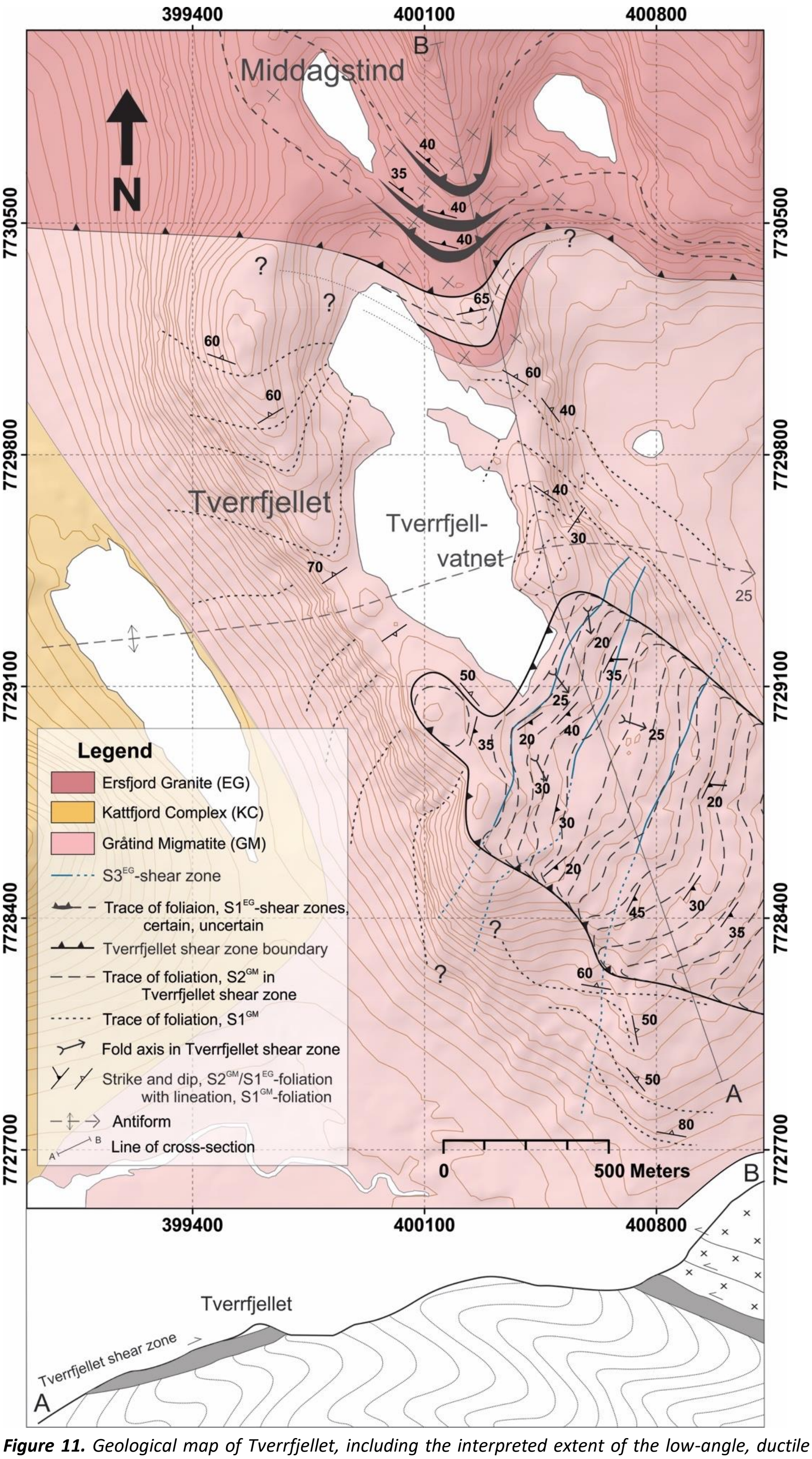

Figure 11. *Geological map of Tverrfjellet, including the interpreted extent of the low-angle, ductile Tverrfjellet shear zone which is well-exposed along the southeast shore of the lake Tverrfjellvatnet. The proposed boundary to the Ersfjord Granite is included, as well as certain internal foliations within the Ersfjord Granite. Inset is a schematic profile of the study area.*

Figure 12. *Overview image of Tverrfjellet, showing the well-exposed Tverrfjellet shear zone near the lake Tverrfjellvatnet (left-hand side of the image). The Tverrfjellet shear zone comprises a low-angled foliation, which is cross cut by steeply dipping shear zones.*

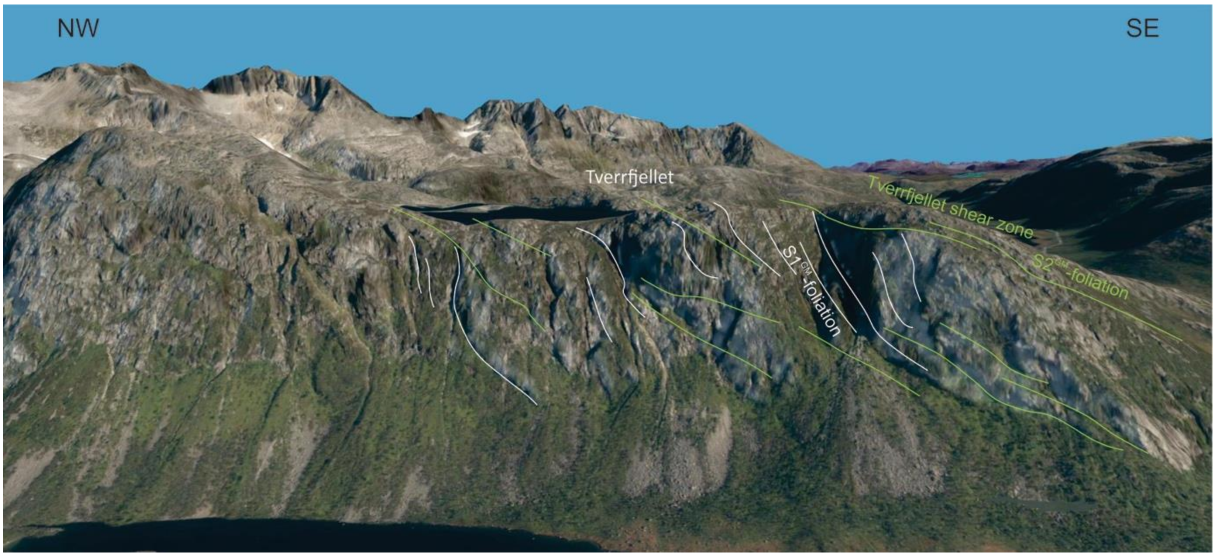

Figure 13. *View of the west face of Tverrfjellet, showing the interpreted position of Tverrfjellet shear zone (green lines) cross cutting the steep, southeast-dipping foliation of the Gråtind Migmatite (white lines). Image is downloaded from Norigeibilder.no.*

3.2.2 Hatten

Hatten is a 657-meter-high mountain lying near the east end of Ersfjorden, well inside the Ersfjord Granite. Most of the field work carried out in Hatten was conducted in the saddle between the summit of Hatten and its neighboring peak, Leirholstind (fig. 9). The mountain is characterized by a host rock of massive, coarse-grained Ersfjord Granite, and numerous, subhorizontal, repeating zones of foliated gneisses and migmatites making up ductile shear zones (fig. 14).

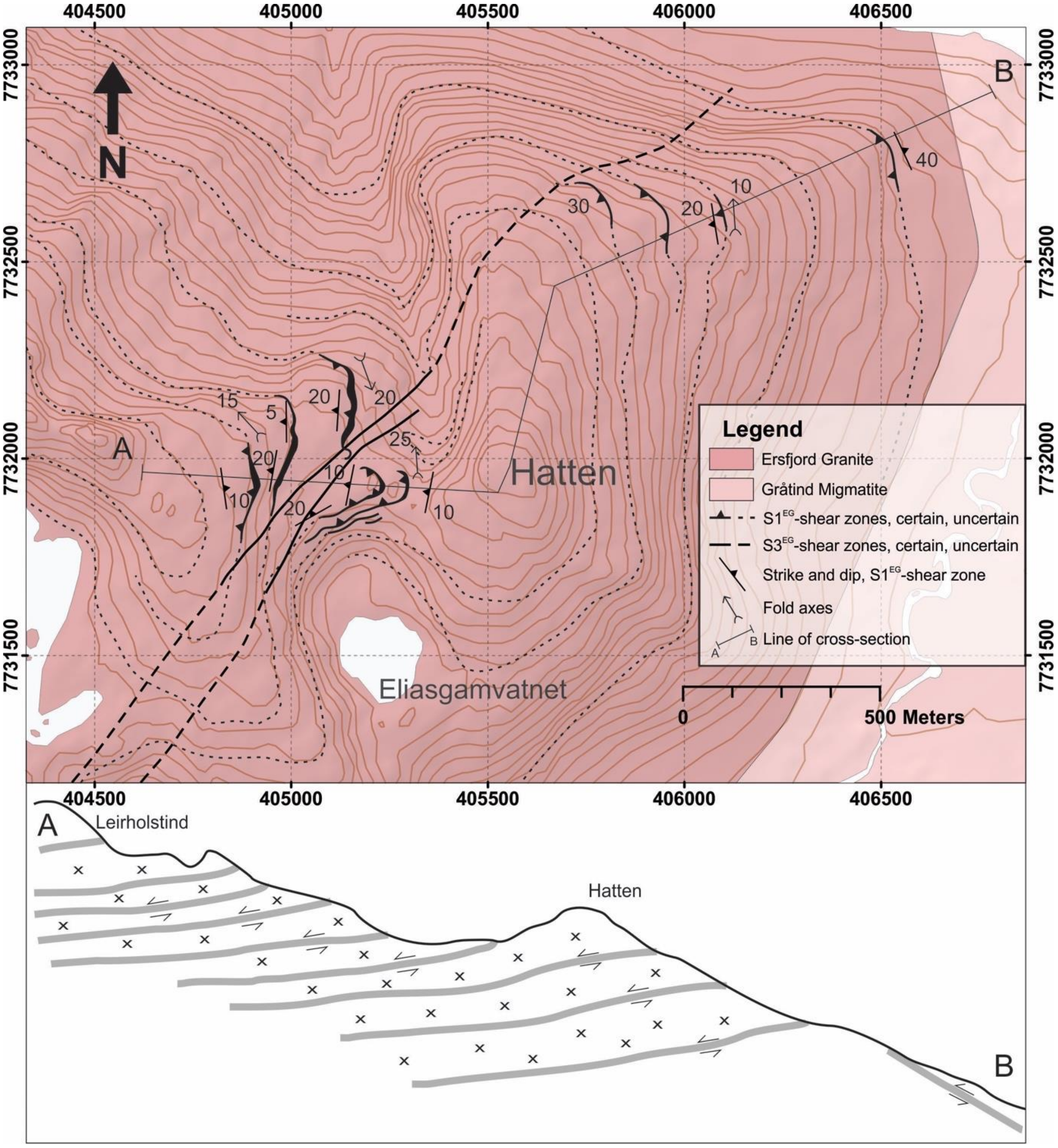

Figure 14. *Geological and topographical map of Hatten, showing low-angled shear zones and cross-cutting, steeply dipping fabrics (S3^{EG}). Inset is a schematic profile showing the low-angled shear zones at Hatten.*

These low-angle shear zones are generally 1-5 meters thick, and divided by tens of meters-thick packages of mostly undeformed Ersfjord Granite rocks (fig. 15). Internally, a number of different fold geometries and structural elements are found. For instance, the shear zone foliation is refolded into open to isoclinal asymmetric folds, partially boudinaged asymmetric clasts and lenses are common, and pegmatitic veins locally interlayer with the shear zone fabric. On average, the shear zones strike N-S, and consistently dips subhorizontally to gently (5-20^{o}) to the W. Five of these low-angle shear zones were mapped in detail at Hatten, though similar repeating shear zones are visible both from a distance and on aerial photographs in most of the study area (fig. 15).

Steep and (in map view) linearly arranged shear zones, similar to those at Tverrfjellet, are found at Hatten as well (figs. 14, 15). They strike approximately NE-SW, are steeply (70-90^o) dipping, and clearly cross-cut the low-angled shear zones. Internally, the steep shear zones comprise a well-defined mylonitic foliation (see chapter 3.4.2). Fabric from the low-angled shear zones steepens as it approaches the subvertical foliation of these cross-cutting shear zones, showing important geometric and kinematic data that will be described in chapter 3.4.4.

Figure 15. *Overview image showing cyclically repeating shear zones exposed in bench-like scarps in the saddle between the mountains of Hatten and Leirholstind. Steeply dipping (S3^{EG}) shear zones cross cut the low-angled S1^{EG}-shear zones from north to south. View is to the west.*

3.2.3 Buren

Buren is an 802 meters high mountain situated between the peaks of Hatten and Store Blåmann, with the fjords of Kaldfjorden to the east and Ersfjorden to the south (fig. 16). The east face of Buren is well exposed and comprises, in addition to massive granite, an approximately 5-10 m thick sheet of foliated granite that dips moderately to the east, and resembles a ductile shear zone (fig. 17). This presumed shear zone, which is parallel to the mountainside, is mylonitic and appears to be steepening towards the fjord to the east. Closer to the scarp of Burshammaren at 540 meters above sea level (fig. 16) it dips more gently. Above Burshammaren, a more gently, NW-dipping, migmatitic shear zone fabric crops out, which is traceable almost to the top of Buren (fig. 16). A more detailed description of these shear zones is given in chapter 3.4.2.

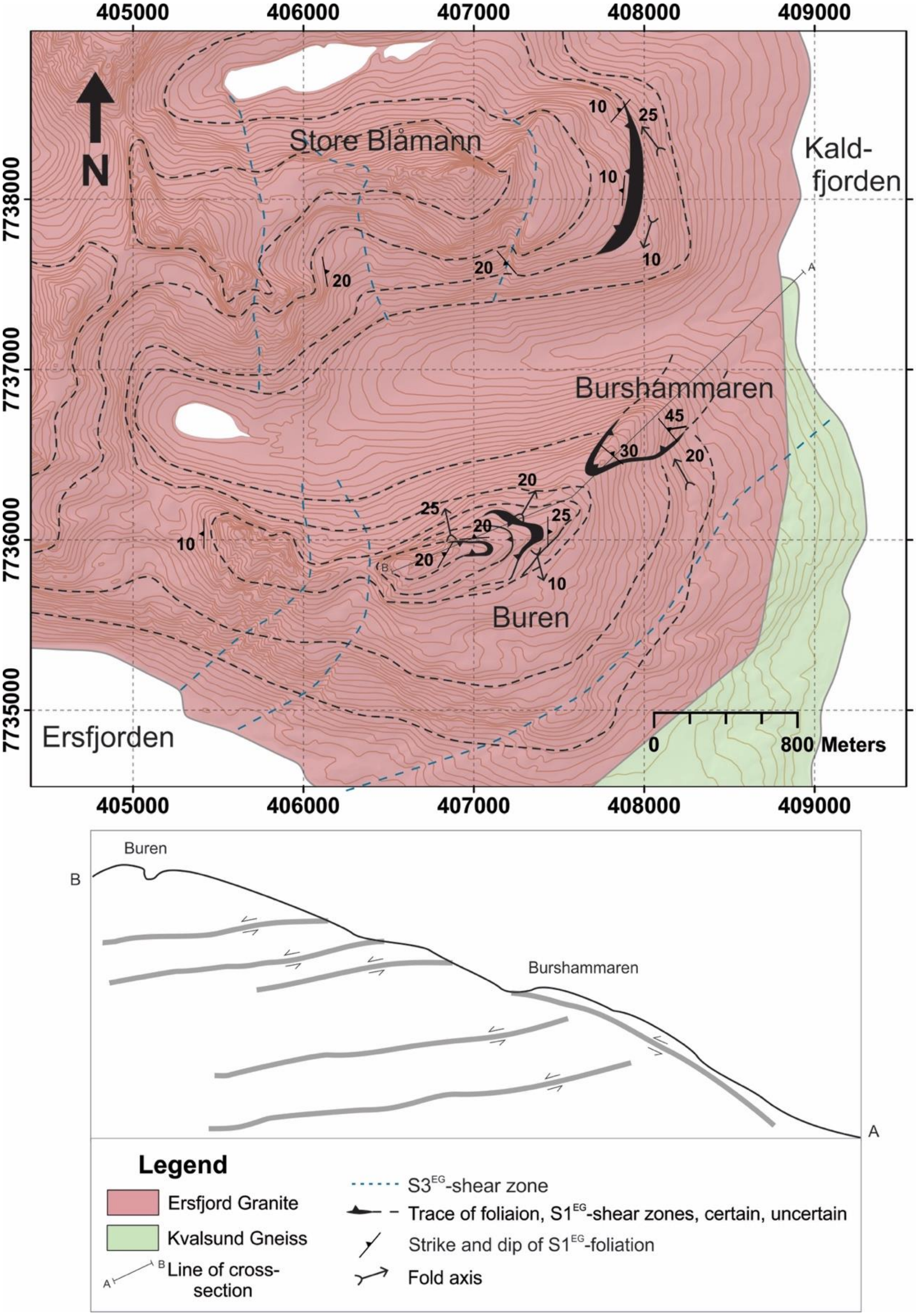

Figure 16. *Geological map showing the shear zone at Store Blåmann, the steeply ESE-dipping mylonitic shear zone on the east face of Buren, and the low-angled, W- and NW-dipping migmatitic shear zones above Burshammaren. Selected structural data is also included, as well as cross-cutting, steeply dipping shear zones interpreted from aerial photos. Inset schematic cross-section shows low-angled, migmatitic shear zones, and the steeply dipping, mylonitic shear zone at Buren.*

Figure 17. *Image of steeply dipping, mylonitic shear zone on the east face of Buren. Low-angled, mylonitic shear zones from Store Blåmann visible in the background.*

3.2.4 Store Blåmann

Store Blåmann is located by Kaldfjorden, near the eastern border of the Ersfjord Granite (fig. 9). The peak is 1044 meters above sea level, making it the highest mountain on Kvaløya, and thus also in the granite.

Along the mountainside of Store Blåmann, a series of low-angled, ductile shear zones crop out (figs. 16, 17, 18). They consist of 2-20 m thick, evenly distributed and well-foliated migmatite zones, with varying mafic and felsic banded gneisses and a few lenses of seemingly massive granite. Mafic lenses and pods, from 10-60 cm long, are particularly common in the shear zones at Store Blåmann. The shear zones are repeated up-section, with lenses of undeformed granite between them, like those described at Hatten (chapter 3.2.2).

Figure 18. *Store Blåmann displays a massive A clearly visible synform in the low-angled fabric of the Ersfjord Granite, which becomes apparent when viewed from a distance. The fabric is made up of gently dipping, ductile shear zones, here seen in the south side of Store Blåmann. Note massive and unfoliated texture in the topmost section of the peak.*

3.3 Petrography and deformation structures in the Gråtind Migmatite

The Ersfjord Granite is surrounded by TTG-gneisses of the Gråtind Migmatite (see fig. 9 and chapter 2.3.7; Zwaan, 1992b, 1992a; Bergh et al., 2010), where a number of different lithologies and textures are present (table 1). The Gråtind Migmatite comprises Neoarchean TTG-gneisses, and has a main fabric consisting of a steeply dipping migmatitic foliation (Armitage, 1999). The gneisses are complexly deformed during Neoarchean deformation events (Myhre et al. 2013), and variously folded by intrafolial, isoclinal folds, and younger, both upright and asymmetric antiforms and synforms striking on average N-S (fig. 9; Armitage, 1999; Armitage & Bergh, 2005). In addition, steeply plunging, open to tight folds are interpreted to belong to the youngest generation of deformational structures in the Gråtind Migmatite (Armitage & Bergh, 2005).

At Tverrfjellet, the steep, migmatitic foliation of the Gråtind Migmatite rocks is truncated by the moderately SE-dipping Tverrfjellet shear zone. Similar shear zones are also present within the Ersfjord Granite itself (see chapter 3.4.2), with comparable characteristics like geometry, petrography and internal structural elements.

3.3.1 $D1^{GM}$-deformation structures and petrography

The main gneiss foliation in the Gråtind Migmatite surrounding the Ersfjord Granite is termed $S1^{GM}$-foliation, as it is interpreted to originate from the first deformational event within the Gråtind Migmatite, the $D1^{GM}$-event (fig. 19). It is composed of a steeply dipping foliation that is parallel to axial surfaces of intrafolial isoclinal folds, $F1^{GM}$-folds (fig. 20; Armitage & Bergh, 2005).

In the Gråtind Migmatite, this $S1^{GM}$-foliation consists of a relatively large proportion of mesosomes interlayered between continuous, mm-thick melanosomes, mostly composed of amphibolitic bands, alternating with quartz-feldspathic leucosomes of approximately the same thickness (fig. 20a). Sporadic, discontinuous lenses of irregularly shaped and cm-thick, amphibole-rich, possible resisters (cf. Pawley, 2013) make up the final part of the foliation, which overall is interpreted to be a stromatic metatexite migmatite fabric (cf. Sawyer, 2008).

The $S1^{GM}$-foliation in the Gråtind Migmatite strikes on average N-S, and dips steeply to the E and W (figs. 9, 19; Zwaan, 1992b, 1992a). In the Kattfjord Complex further west (fig. 9), a similar foliation strikes on average WNW-ESE, with the same variable dip as in the Gråtind Migmatite, to the NNE and SSW (figs. 19, 20a, b, c).

At Tverrfjellet, the Gråtind Migmatite comprises a migmatitic gneiss texture. Irregular, continuous, centimeter to decimeter thick, coarse-grained quartz-feldspathic leucosomes alternate with more fine-grained, also continuous, amphibolitic melanosomes (fig. 20c), making up a stromatic metatexite fabric (Sawyer, 2008). Thin section studies show that the

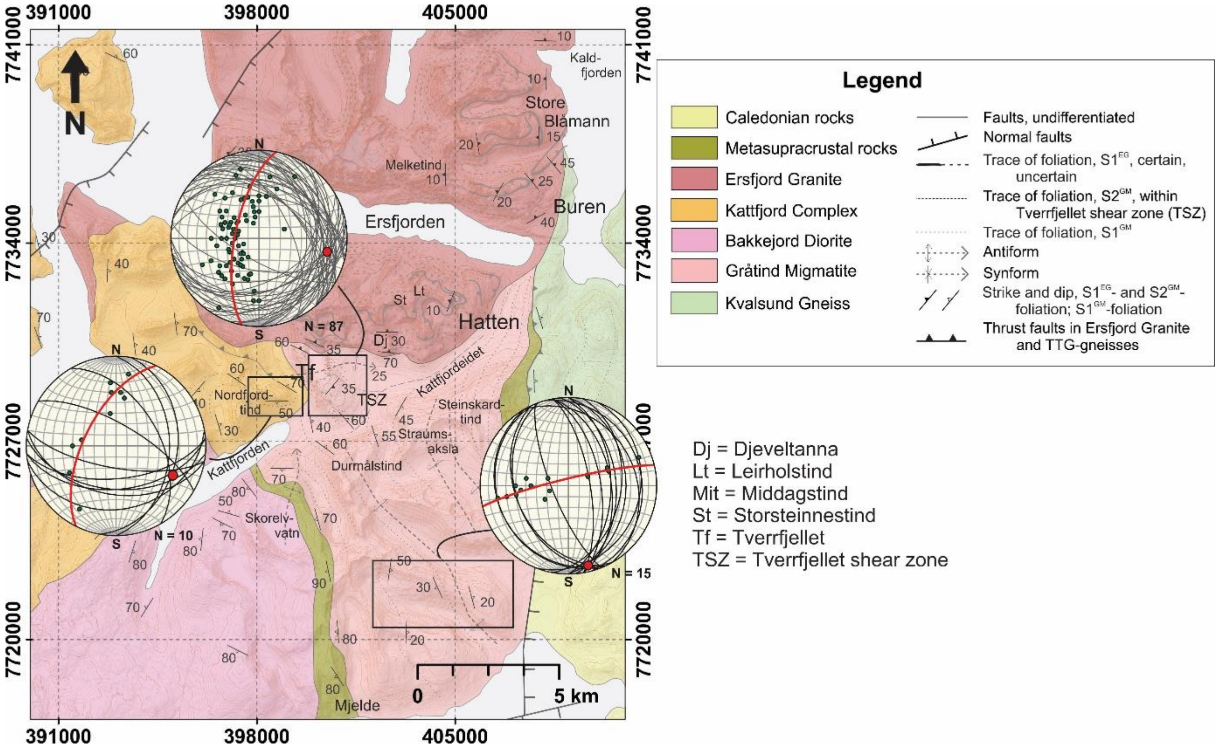

Figure 19. *Geological map showing orientation data from the S1^{GM}-foliation in the Gråtind Migmatite, as well as selected data from the nearby Kattfjord Complex further west. Inset are lower-hemisphere stereonets showing measured foliation orientations as black great circles, and poles to the foliation as green dots. Red dots are constructed beta-axes, and red great circles are best fit circles for the poles to the foliation.*

melanosomes are composed of biotite, amphibole, chlorite, and local porphyroblastic garnets, whereas leucosomes contain mostly quartz, plagioclase and K-feldspar. White micas and chlorite are preserved as small inclusions within the garnets (figs. 20d, e). The S1^{GM}-foliation at Tverrfjellet strikes on average E-W, and dips variably from 20 to 80° towards the north through east to south (fig. 19), and when plotted in a stereonet, poles to the foliation spread along a N-S striking great circle girdle.

3.3.2 D2^{GM}-deformation structures (Tverrfjellet shear zone)

At Tverrfjellet, a second generation of folds is observed in the Gråtind Migmatite fabric (fig. 11). These F2^{GM}-folds have hardly been measured, but are observed to be open to tight asymmetric folds of around 100 meters in amplitude, with fold axes trending E-W and plunging around 30° to the W.

The steeply dipping S1^{GM}-fabric of the Gråtind Migmatite is well outlined in the west cliff of the mountain Tverrfjellet, where a gently dipping fabric truncates this TTG-gneiss foliation in the uppermost section near the peak (fig. 13). Southwest of the lake Tverrfjellvatnet, a large area exposes this gently dipping fabric (fig. 12), which is axial planar to the F2^{GM}-folds, and makes up an S2^{GM}-shear zone.

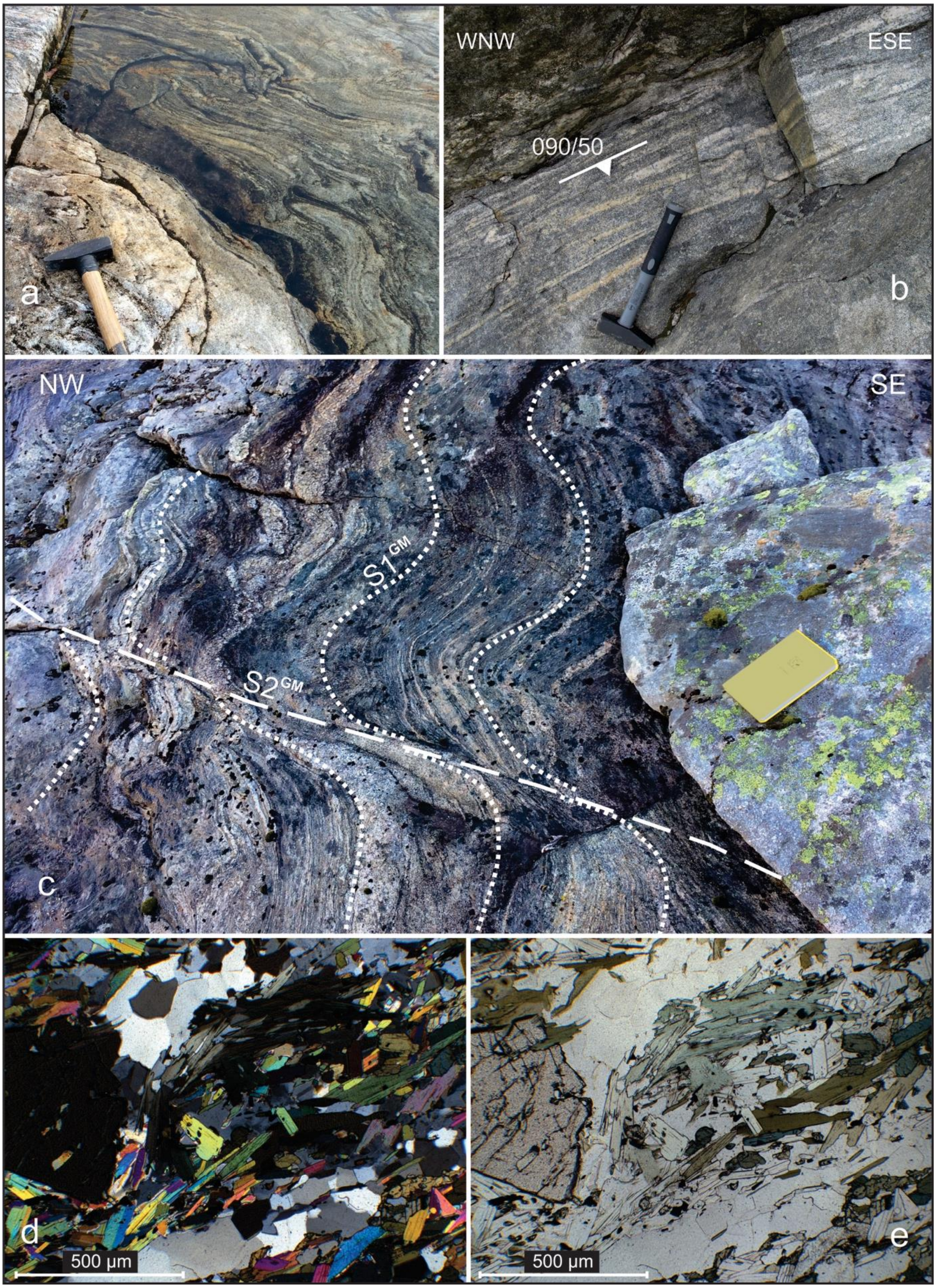

Figure 20. *Textures of foliation and thin section images of the S1^{GM}-fabric of the Gråtind Migmatite. a) Isoclinally folded, banded gneiss with alternating, mm-thick melanosomes and leucosomes, as well as a possible resister directly to the right and above the hammer. The fabric is interpreted to be a stromatic metatexite foliation. b) Well-foliated S1^{GM}-fabric from rocks of the Kattfjord Complex west of the Gråtind Migmatite. Note mm to cm-thick leucosomes alternating with thicker bands of*

mesosomes, suggesting a stromatic metatexite fabric. c) Migmatitic $S1^{GM}$-foliation of the Gråtind Migmatite, cross-cut by $S2^{GM}$-fabrics of the Tverrfjellet shear zone. Note folded nature of the $S1^{GM}$-foliation, and how axial traces are parallel to the $S2^{GM}$-foliation. d) and e) Images of thin section showing chlorite- and biotite-rich melanosomes with porphyroblastic garnets containing internal inclusions. Leucosomes are quartz-feldspathic. Sampled from the $S1^{GM}$-foliation of the Gråtind Migmatite. Depicted in cross-polarized light (d) and plane-polarized light (e).

The $S2^{GM}$-Tverrfjellet shear zone is approximately 50 meters thick, and comprises a well-foliated, migmatitic, texture (fig. 21). The rocks often display complex internal folds and foliation patterns, as well as a number of different internal structural elements (see below).

Geometric characteristics of Tverrfjellet shear zone

Tverrfjellet shear zone consistently strikes NE-SW, dips gently (20-30°) to the SE (fig. 10b), and has an overall laterally planar geometry in the studied area (fig. 11). The exact boundaries of the shear zone are difficult to pinpoint precisely, except in areas where the low angle shear zone fabric ($S2^{GM}$) truncates the underlying steep $S1^{GM}$-TTG-gneiss foliation (fig. 13). In small-scale, this truncating relationship can be seen where gently SE-dipping axial surfaces of asymmetric folds ($F2^{GM}$) of the TTG gneisses truncate the steep $S1^{GM}$-gneiss foliation and make up a new $S2^{GM}$-fabric. This fabric is subparallel to the Tverrfjellet shear zone (fig. 20c).

Figure 21. *Image of the fabrics in the Tverrfjellet shear zone. Note folded nature of the internal foliation, and boudinaged lenses. The height of the outcrop is approximately two meters, and the view is towards the NE.*

Internal Structures in the Tverrfjellet shear zone

Bed rocks and fabrics of the Tverrfjellet shear zone consist of composite banded amphibolites and intercalated, foliated felsic gneisses (fig. 22a). Multiple internal folds and shear zone fabrics are commonly found within the shear zone, including stretching lineations on $S1^{GM}$-foliation surfaces (fig. 23b), asymmetric sigmoidal lenses and clasts (fig. 23c), and duplexes (fig. 23d), many of which have been used as shear-sense indicators (see later subchapter). Migmatitic parts of the shear zone show metatexite fabrics interlayered with meter-thick lenses of more homogenous granites, interpreted to be diatexites (fig. 22b; Brown, 1973).

Most of the shear zone architecture is characterized by a composite, well-developed migmatitic fabric ($S2^{GM}$; fig. 22a). Axial surfaces of partially dismembered, isoclinal to tight, near-recumbent folds ($F2a^{GM}$) make up this main shear zone foliation, and relics of hinge zones from these $F2a^{GM}$-folds are preserved in isolated lenses (fig. 23a) throughout the shear zone. In addition, this axial planar foliation ($S2^{GM}$) is commonly refolded by open to tight, asymmetric, W-verging and locally disharmonic folds ($F2b^{GM}$; fig. 22b).

In addition to the different types of folds, a number of internal structural elements are incorporated in the shear zones. Mafic lenses (fig. 22b), consisting mostly of fine-grained amphibolites are seen throughout the shear zone, varying in size from 5-50 cm thick, and typically pinching out laterally. Large-scale lenses, 1-20 meters long, of seemingly undeformed, granitoid rocks arranged parallel to the main foliation ($S2^{GM}$) are also common (fig. 22b). Their lack of internal structures and seemingly homogeneous composition suggest that they are diatexites (cf. Sawyer, 2008). In addition, numerous granitic to pegmatitic veins of a reddish color, around 5-15 cm in thickness, are intruded parallel to the shear zone foliation (fig. 22c). They consist of equigranular alkali feldspars and quartz, and have straight to stepped, sharp edges. Boudins crop out locally (fig. 21), for instance as boudinaged quartz veins, mafic lenses or shear zone foliation.

Figure 22. *a) Stromatic metatexite fabrics in the Tverrfjellet shear zone. Hammer for scale. b) Disharmonic folding and chaotic foliation. On the left-hand-side of the image, a lens of presumed diatexite is shown, and a folded, mafic lens to the right. c) Pegmatite vein intruded into the Tverrfjellet shear zone, parallel to the foliation.*

Structures used as kinematic indicators in Tverrfjellet shear zone

The isoclinal and asymmetric folds ($F2a^{GM}$ and $F2b^{GM}$-folds) described in the section above, are the main structural elements used as sense-of-shear indicators (fig. 23a). Although the use of folds as shear-sense indicators is slightly ambiguous (Passchier & Trouw, 2005), the great number of measured structural orientations produced enough data to infer a tectonic transport direction. Less ambiguous kinematic indicators like stretching lineations, sigmoidal clasts and duplexes were also used, and compared with the results obtained from the fold data.

Asymmetric and isoclinal folds were measured, either by recording fold limbs and constructing a fold axis, or by measuring the fold axis directly. In both cases, the vergence of the fold was recorded as well. All the fold data collected are presented in a lower-hemisphere stereonet in fig. 10c. The fold axes on average trend NW-SE, plunge 10-30° to the SE, and verge to the southwest. Interestingly, the fold axes fall into a great circle girdle that overlaps well with the average orientation of the main Tverrfjellet shear zone.

Figure 23. *Internal deformation structures within Tverrfjellet shear zone. a) Intrafolial, isoclinal F2a^{GM}-folds that make up the S2^{GM}-shear zone foliation of Tverrfjellet shear zone. F2a^{GM}-folds are commonly dismembered, though localized relics are preserved in lenses. Inferred sense of shear is top-to-the SSE. Short edge of the blackboard is 10 cm long, for scale. b) Local lineations defined by elongated mineral grains and small crenulations in the surface are interpreted to be stretching lineations. Here, showing a trend to the east. c) Asymmetrically shaped clast with "tails" entrained in the surrounding foliation is interpreted to be a sigmaclast that shows a top-to-the ESE sense of shear. d) Duplex shows thickened beds indicating a top-to-the N sense of shear.*

Sigmoidal-shaped clasts (fig. 23c) range in size from 3 to 20 cm. They are typically elongated asymmetrically with "tails" entrained in the surrounding matrix. In addition, asymmetric lenses of partially thickened and curved layers of rock were interpreted to be duplexes (fig. 23d). They commonly occur in mafic lenses or melanosome bands of up to a meter in thickness. Both sigmoidal clasts and duplexes show shear senses of top-to-the N through W to S, and most commonly to the W. In fig. 23c, a typical example of a sigmoidal clast is shown, indicating a top-to-the WNW sense of shear. The duplex in fig. 23d shows a top-to-the N sense of shear.

Stretching lineations on S2^{GM}-foliation surfaces in Tverrfjellet shear zone were recognized as elongated mineral grains and small crenulations in the foliation surfaces, as shown in fig. 23b. The few measurements of stretching lineations that were obtained are presented in fig. 10c. They commonly trend E-W, and plunge gently, around 20-30° to the E. The stretching lineations indicate a movement in one of two directions, in this case to the east or to the west.

Thin section studies

Thin section studies show that the melanosomes in the Tverrfjellet shear zone fabric contain biotite, white micas, amphibole, local porphyroblastic garnets and possible epidote. Chlorite is also present, often surrounding biotite crystals, but is not in equilibrium with the remaining mineral assemblage (fig. 24).

Internally in the garnet porphyroblasts, a preserved mineral assemblage of white mica, amphibole and minor apatite and zoisite, as well as suspected epidote is found. Opaque minerals seem to make up a relict foliation within the garnet crystal, and rutile is an accessory mineral (fig. 24). A possible interpretation of this is that the internal mineral assemblage within the garnet crystals is a preserved, older fabric that has been altered into the second mineral assemblage outside of the garnet crystal, likely during the D2^{GM}-deformational event.

On the basis of this, the thin section depicted in figure 24 can be interpreted to have a crystallization history as follows: the chlorite and white mica within the garnet porphyroblast crystallized pre-D2^{GM}-deformation. The garnet grew syn-D2^{GM}, enclosing parts of the S1^{GM}-foliation within it. Biotite, amphibole and white mica crystallized syn-D2^{GM}-deformation, but after the beginning crystallization of garnet. Biotite was chloritisized syn- to post-D2^{GM} in retrograde metamorphic conditions.

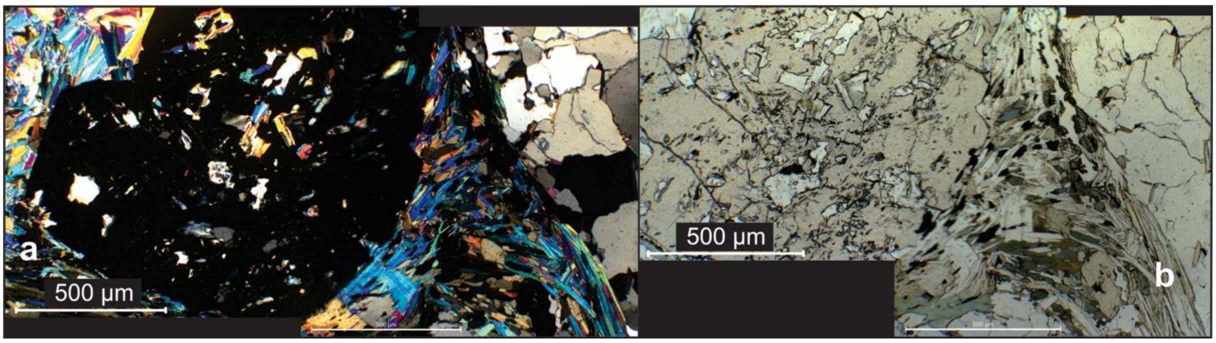

Figure 24. *Thin section images showing foliation in and around local garnet porphyroblasts found in the S2^{GM}-foliation at Tverrfjellet. Images have been stitched together from two separate photos, and are taken in cross-polarized light (a) and plane-polarized light (b).*

3.4 Petrography and deformation structures in the Ersfjord Granite

The Ersfjord Granite is mainly a massive, coarse-grained granite, some places with a weak and well-dispersed foliation. Multiple ductile structures are identified within and along migmatitic and some places mylonitic shear zones. These shear zone structures are interpreted to have formed due to mid-crustal deformation during and after the emplacement of the granite (see discussion). A brief summary of deformation structures within the Ersfjord Granite (see table 1) will first be given, before more detailed descriptions are provided below.

The Ersfjord Granite, in particular in undeformed areas, often contains a weak foliation (termed $S0^{EG}$ as it is within the Ersfjord Granite; table 1). This early stage foliation is truncated by low-angle, migmatitic and partly mylonitic, ductile shear zones, present both in the surrounding TTG-gneisses near the contact to the Ersfjord Granite (e.g. at Tverrfjellet), and within the granite itself ($D1^{EG}$-deformation). A variety of deformation structures have been observed internally in these shear zones, e.g. isoclinal to tight as well as open, asymmetric folds ($F1^{EG}$), boudinage, stretching lineations, and sigmoidal clasts. Describing and analyzing these low-angled, migmatitic ductile shear zones in the Ersfjord Granite, and internal structures within them, is the main focus of this master's study.

In addition, large-scale open folding of the shear zone is locally observed ($D2^{EG}$-deformation), as well as a younger fabric recognized as a system of steep, ductile shear zones that cross-cut all other fabrics in the Ersfjord Granite ($D3^{EG}$-deformation).

3.4.1 $D0^{EG}$-deformation structures

Most commonly, the Ersfjord Granite has a light grey to reddish-color and a massive texture (fig. 25a). It is generally equigranular, and coarse- to medium grained. Thin section studies indicate major mineral constituents to be biotite (10-15%), microcline, albite and quartz. Plagioclase is generally sericitized, and thin shear bands appear within the granite containing chlorite, epidote, plagioclase and alkali feldspars, suggesting a greenschist facies mineral assemblage (figs. 25c, d).

However, a weak foliation termed $S0^{EG}$ is present throughout most of the Ersfjord Granite, although it is not always apparent (figs. 25e, f). It consists of weakly aligned, flaky minerals, and light- and darker-colored layers of more fine-grained granite (fig. 25e). It is consistently truncated by low-angle shear zones ($D1^{EG}$; see fig. 25f) and related foliations ($S1^{EG}$), as well as all of the other structural elements within the granite. Notably, when the $S0^{EG}$-foliation approaches the cross-cutting foliation of the $D1^{EG}$-shear zones (see chapter 3.4.2), it is bent into parallelism with the ($S1^{EG}$) shear zone foliation (fig. 25f).

The $S0^{EG}$-foliation was not studied in detail, but some orientation measurements were taken from Buren, Hatten and Djeveltanna (fig. 25b). From the sparse data set, the distributed foliation in general strikes N-S and dips gently to moderately in two main directions, NE and W to NW.

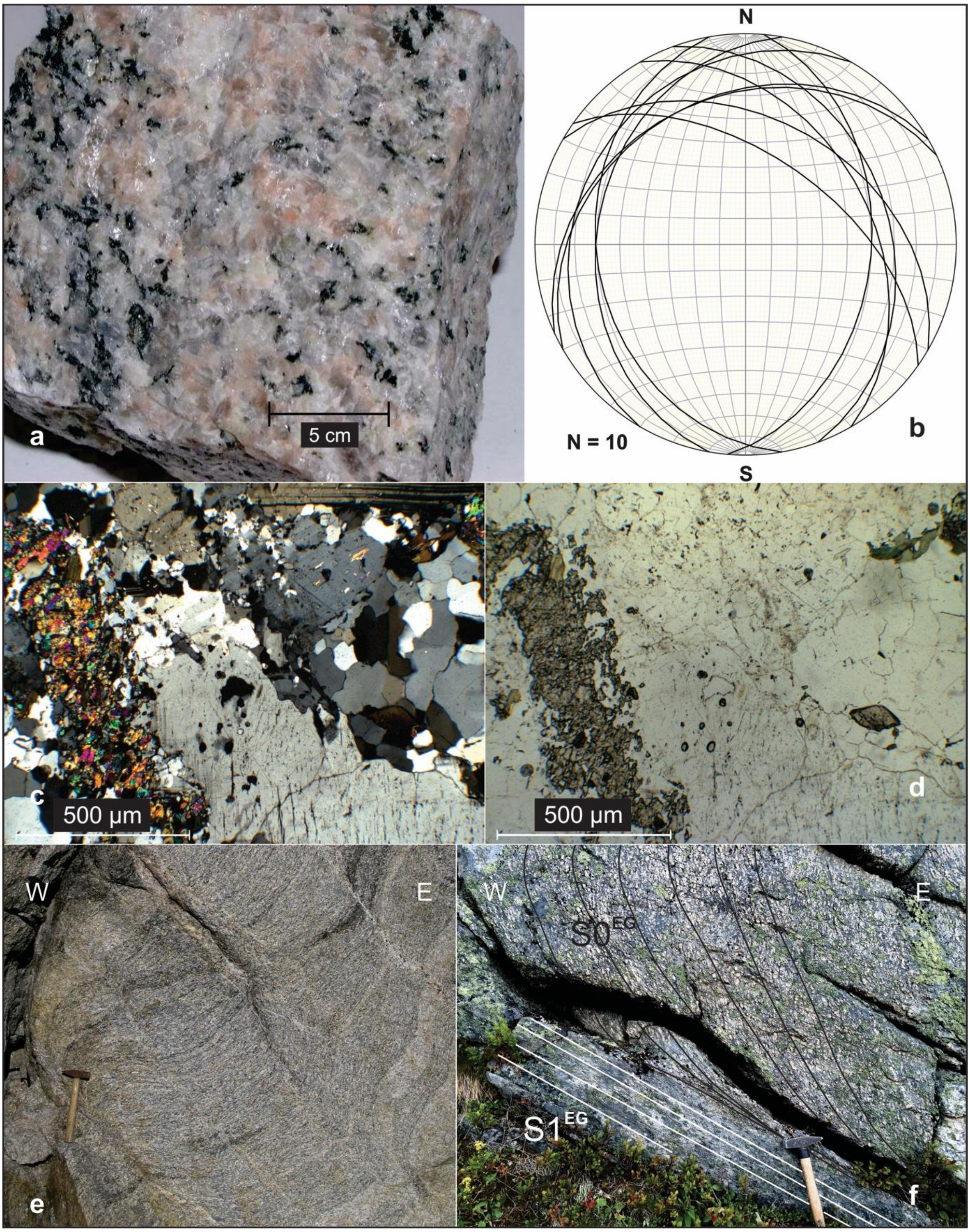

Figure 25. *a) Hand sample of massive, unfoliated Ersfjord Granite. Note equigranular quartz, K-feldspars, plagioclase and amphibole crystals. b) Lower-hemisphere stereonet showing orientation of the distributed $S0^{EG}$-foliation in the Ersfjord Granite. Note the variable dip to the east and west. Data are achieved from Hatten, Buren and Djeveltanna. c and d) Thin section images of massive granite sampled at Buren shows a mineral content of mainly microcline, albite and quartz, with sericitized plagioclase. Thin shear bands within the sample contain chlorite, epidote, plagioclase and alkali feldspars. Images*

taken in cross-polarized (c) and plane-polarized (d) light. e) Distributed, $S0^{EG}$-foliation in the Ersfjord Granite is made up of rotated flaky and needle-shaped minerals like biotite and amphiboles. f) Distributed, $S0^{EG}$-foliation is cross-cut by the planar $S1^{EG}$-fabric. Note that the $S0^{EG}$-foliation is bent into parallelism with the cross-cutting foliation.

3.4.2 $D1^{EG}$-deformation structures

The main fabrics of the Ersfjord Granite are a set of low-angle ductile, mostly migmatitic shear zones with a well-developed foliation ($S1^{EG}$). They consistently truncate the $S0^{EG}$-foliation (fig. 25f), and are themselves truncated by other structural elements (see chapter 3.4.3 below) in the Ersfjord Granite. Therefore, these shear zones are termed $S1^{EG}$-structures, and they belong to the $D1^{EG}$-deformation.

$S1^{EG}$-shear zones comprise well-defined, banded gneisses in otherwise massive host rocks, with mm-thick leucosomes with sharp to diffuse edges, interlayered with slightly thinner, more fine-grained melanosomes. Based on the banded nature of alternating leucosomes and melanosomes, the texture of the foliation is interpreted to a stromatic metatexite migmatite fabric (cf. Sawyer, 2008).

Geometric characteristics

These low-angled, ductile shear zones exist throughout the granite, though they vary strongly in appearance. As a rule, they occur in extensive, sheet-like geometries, and are localized and surrounded by massive granite rocks. Most often, the shear zones appear repeatedly over large areas like those described at Hatten (fig. 15), though commonly they are more widely spaced.

The shear zones are far more conspicuous in some areas than others, e.g. in the mountainsides of Hatten, Buren and Store Blåmann, where they display thicknesses from 2 to 20 meters. Where shear zones are less conspicuous, the granite contains a massive or weakly foliated texture that dominates the exposed portion of the granite (chapter 3.4.1). Irregular, thinner shear zones are, however, found throughout most of the pluton. Often these zones are no thicker than 10-60 cm, displaying fewer internal deformation structures, and commonly pinching out laterally along strike. When these shear zones are viewed in combination from a distance, they make up a clearly defined, gently-dipping to subhorizontal fabric throughout the Ersfjord Granite (fig. 18). Locally, shear zones vary in geometry from horizontal to more steeply dipping, and with internal truncations (fig. 26). This mainly low-angled fabric is interpreted to reflect the overall geometry of the $S1^{EG}$-shear zones.

The orientation of the shear zones is fairly uniform throughout the main study areas. They strike on average N-S (fig. 10b), and have a subhorizontal to gentle dip of around 5-30° to the WNW, with the exception of the east side of Buren where two dip directions are observed (fig. 16). A low-angled, 20-25° northwestern dip characterizes migmatized shear zones in the topmost part of Buren, whereas a steeper, easterly dipping shear zone of around 30-60° is present in the lower parts of the mountain side furthest east (fig. 16). A steeper dip is also found at Middagstind, where the shear zone strikes ENE-WSW and dips 35-40° to the NNE (fig. 11).

Limited shear zone-orientation data are collected from the northernmost parts of the granite, but sporadic measurements, DEMs and aerial photos indicate a gentle, 20-30° dip to the NW and to the E (see fig. 10a).

Figure 26. *Gently dipping fabric of the Ersfjord Granite becomes clear when seen from a distance. Foliation is mostly planar, but locally it dips more steeply. This fabric is interpreted to reflect the large-scale geometry of S1^{EG}-shear zones in the Ersfjord Granite. Here shown from a view of the northern side of Ersfjorden.*

Internal structures

The main foliation (S1^{EG}) that makes up the shear zone fabrics of the D1^{EG}-shear zones, is axial-planar to intrafolial isoclinal folds (F1a^{EG}; fig. 27a). This foliation is locally refolded by open to tight, asymmetric folds (F1b^{EG}; fig. 27b), and incorporates a number of different internal structures such as asymmetric and sigmoidal clasts (figs. 27c, d), mafic lenses and pods (fig. 27e), pegmatite veins (fig. 27f), secondary foliations, boudins and duplexes (see further descriptions below). The main S1^{EG}-foliation is generally migmatitic, although mylonitic foliation crops out locally, for example in the shear zone on the east face of Buren (fig. 28a, b). Lenses of seemingly undeformed granite are also commonly included in the shear zones (fig. 28c).

The S1^{EG}-foliation that makes up the shear zones consists of dismembered or partially intact, tight to isoclinal, recumbent folds (F1a^{EG}), with axial surfaces aligned into parallelism with the shear zone fabric. Irregular remnants of these fold hinges are common as lenses within the $S1^{EG}$-foliation (fig. 29a), and locally they connect to isoclinal or tight fold limbs as well (figs. 27a, 29). These folds display shear-like, similar style fold geometries (Ramsay, 1980), with thickened hinges and thinned limbs.

Small-scale intrafolial folds that refold the $S1^{EG}$-foliation (figs. 29b, c), are ubiquitous throughout the $S1^{EG}$-shear zones. They display asymmetric, similar, shear-like fold geometries (Ramsay, 1980), are most often open to tight (figs. 29c, d), and locally disharmonic (fig. 29e). Axial surfaces are aligned obliquely to the shear zone fabrics, and verge mainly westwards. Locally these folds close in both directions (fig. 29c), indicating that they are sheath folds (Passchier & Trouw, 2005). Kinematic implications of fold data will be discussed below.

In addition to the different fold-types, other various internal structures are incorporated in the shear zones. Mafic pods and lenses (fig. 27e) included in the shear zone consist for the most part of composite gneiss banding in amphibolitic gneisses. They are usually 5-40 cm wide, from a half to a meter in length, and pinch out laterally. Thin section studies show a mineral assemblage of euhedral amphibole, fine-grained biotite and quartz-feldspars, suggesting amphibolite facies deformation (fig. 30b). They often have strain shadows filled by dilational leucosomes, or appear boudinaged, some places asymmetrically (fig. 27e).

Veins of pegmatitic to coarse-grained, light-colored granite, much like the ones found outside the Ersfjord Granite at Tverrfjellet, are commonly seen injected into surrounding fabrics, usually parallel to the foliation (fig. 27f). Edges of the veins are typically sharp and stepped, and quartz and feldspars make up the mineral content of the veins.

Seemingly less deformed lenses of granitic rocks are commonly found within the $S1^{EG}$-shear zones. They are often larger than the mafic lenses, up to a couple of meters in width and several meters in length, and pinch out laterally (fig. 28c). Their lack of internal fabrics and granitic composition suggest that they are diatexites in the otherwise metatexic fabric of the shear zones (cf. Sawyer, 2008).

The E-dipping ductile shear zone at Buren that can be traced downhill toward Kaldfjorden below the Burshammaren scarp (fig. 16), displays very different internal characteristics from those described so far. It has a texture comprising asymmetric, lense-shaped, porphyroclasts surrounded by a matrix of flaky minerals oriented in two main directions, making up a mylonitic fabric (fig. 28b). The ratio of porphyroclasts to matrix varies from a proto- to ortho- to ultramylonitic texture throughout the shear zone. Ultramylonites commonly occur within the very center of the shear zone, whereas ortho- and protomylonites are distributed in a slightly wider area, where lenses of massive granitic rocks are present in between (fig. 28b).

Figure 27. *a) Intrafolial isoclinal F1a^{EG}-folds, intact within shear zones between the summits of Hatten and Leirholstind. Inferred sense of shear is top-to-the SSW. b) F1b^{EG}-folds are ambiguous within the migmatitic S1^{EG}-shear zones, showing open to tight fold geometries. The shortest edge of the little blackboard in the photo is 10 cm long. c) Asymmetric feldspar clast making up a sigmaclast showing top-to-the W sense of shear. d) Mafic lens in the migmatitic foliation with asymmetric geometry suggests a shear sense to the west. e) Asymmetrically shaped, boudinaged mafic lenses within S1^{EG}-shear zones at Hatten. Note dilational metatexites between the amphibolitic lenses. f) Pegmatite vein at Hatten. Note parallel direction to shear zone foliation.*

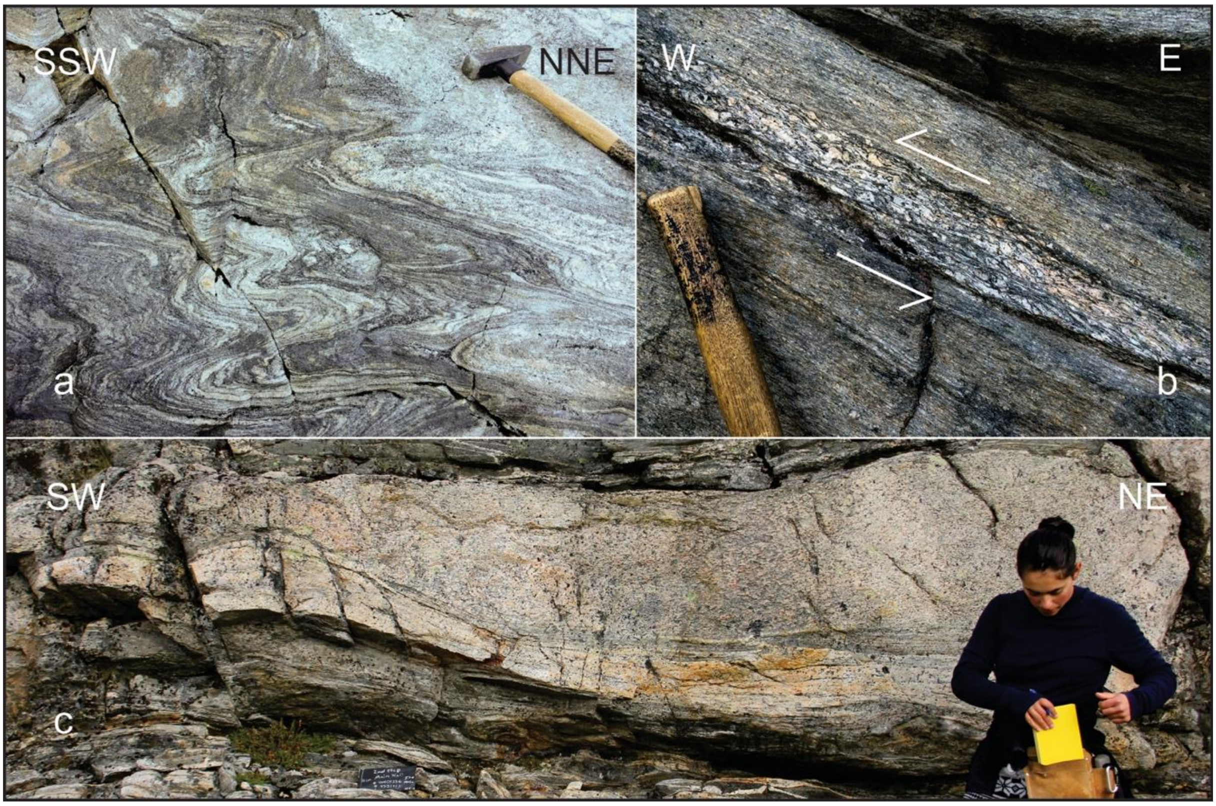

Figure 28. *a) Continuous, alternating bands of melanosomes and leucosomes make up a migmatitic texture in most of the S1^{EG}-shear zones in the Ersfjord Granite. b) Mylonitic shear zone from the steeply dipping shear zone at Buren showing mainly ultramylonitic texture, with a diagonal protomylonite band in the center of the image. Within the protomylonitic texture, S-C structures can be made out, suggesting a top-to-the W sense of shear. Handle of hammer for scale. c) Lens of fairly massive granite within the S1^{EG}-shear zones. Lack of foliation suggests diatexite migmatite texture.*

Structures used as kinematic indicators

Asymmetric shear folds and isoclinal folds (F1^{EG}) are by far the most abundant structures within the S1^{EG}-shear zones, and were for that reason used as the primary kinematic indicators. Few direct observations were made of other, more reliable shear-sense indicators, which still proved useful to compare with the fold data, like for the Gråtind Migmatite.

Fold data was attempted subdivided by area, fold characteristics and folding phase (F1a^{EG} or F1b^{EG}), but no correlation was seen in the plots. Fold axes plunge on average gently N-NW throughout most of the S1^{EG}-shear zones in the Ersfjord Granite (fig. 10c). Shear zones in Hatten have the largest variation in trend, from 270 to 60°. The vergence of the folds is also variable, mostly towards the west but also north, and the fold axes plunge gently to moderately, from 10-40°. Interestingly, plotted F1^{EG}-fold axes from the shear zones spread along great circle girdles that largely overlap with the orientation of respective ductile shear zones at each locality (fig. 10c). The data show an overall top-to-the WSW sense of shear for the majority of studied shear zones in the Ersfjord Granite.

Stretching lineations on S1^{EG}-foliation surfaces were measured at Buren. The main trend is W-E and a gentle plunge of 20-30° to the west is recorded (fig. 10c). Asymmetric lenses and clasts commonly pinch out along the main foliation on either side of the clast. The two "tails" that make up the ends of the crystal or lens are asymmetric to one another, one comes out above the crystal, and the other below. The "tails" are parallel to the shear zone foliation. These observations suggest that they are sigma clasts, and can be used as a kinematic indicator (figs. 27c, d), in this case indicating a top-to-the W sense of shear.

The mylonitic foliation of the shear zone at Buren comprises lens-shaped porphyroclasts of quartz and feldspars, with a main foliation in two directions oblique to one another (fig. 28b). These two directions can be used as S-C structures (cf. Lister & Snoke, 1984), indicating a top-to-the W shear sense.

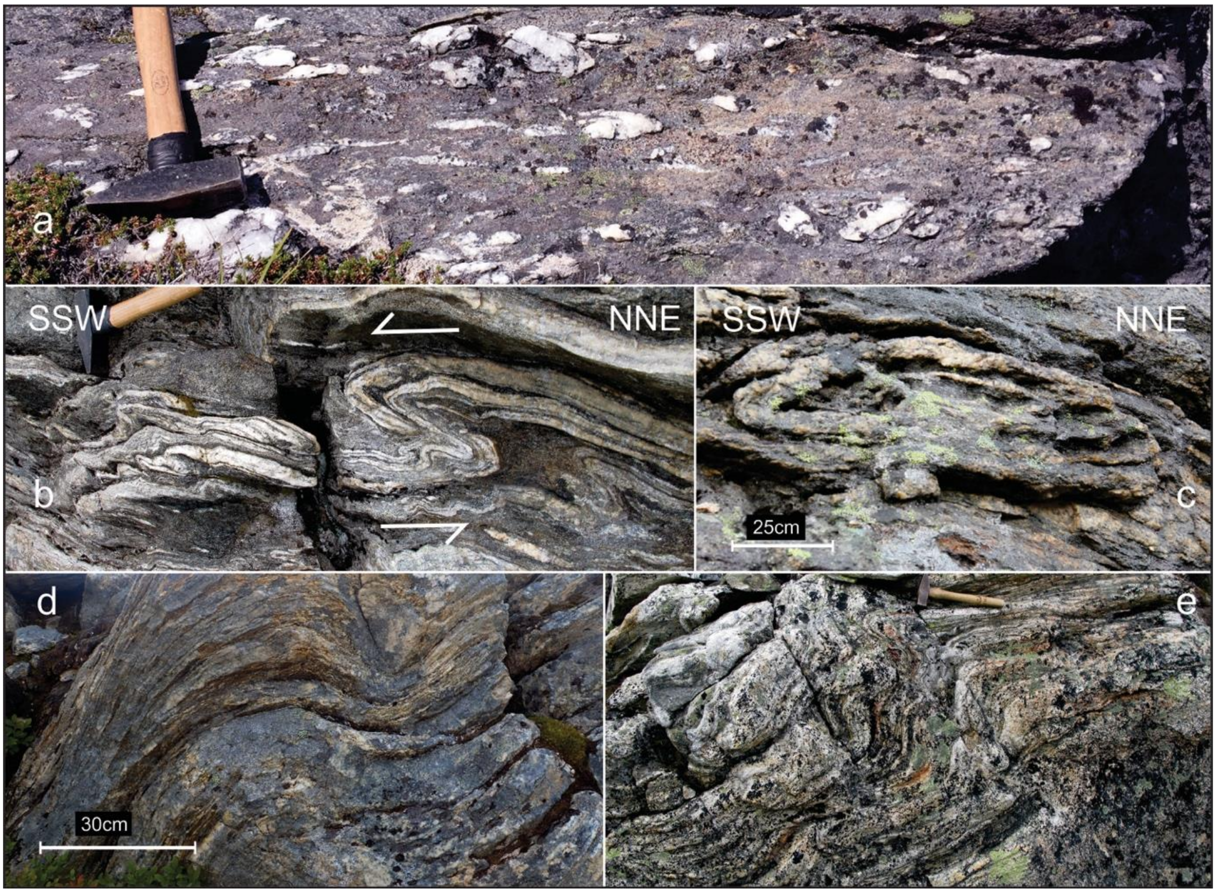

Figure 29. *a) Hydrothermal quartz-vein showing dismembered fold limbs and hinge zones of isoclinal F1a^{EG}-folds making up the S1^{EG}-foliation within shear zones in the Ersfjord Granite. b) Refolded F1a^{EG}-folds make up asymmetric, tight F1b^{EG}-folds within the S1^{EG}-shear zones in the Ersfjord Granite. c) F1b^{EG}-folds locally close in both directions, suggesting a presence of sheath folds. d) Open, asymmetric F1b^{EG}-folds in the Ersfjord Granite. e) Chaotic foliation and disharmonic F1b^{EG}-folds in the S1^{EG}-shear zones. Hammer in upper part of the photo for scale. All images are taken from Hatten.*

Thin section studies

Migmatitic S1^{EG}-shear zone foliation (table 1; fig. 9) in the Ersfjord Granite consists of leucosomes containing coarse-grained quartz and feldspars, and melanosomes of oriented, subhedral biotites and quartz. Sericitized plagioclase truncates the biotite foliation, and euhedral, oriented epidotes are found throughout the melanosome fabric (fig. 30a). A possible crystallization history based on these observations is discussed in chapter 4.3.2. Mafic lenses are commonly included in the $S1^{EG}$-shear zones in the Ersfjord Granite. They consist of mostly epidotes as well as biotite, plagioclase and amphiboles (fig. 30b).

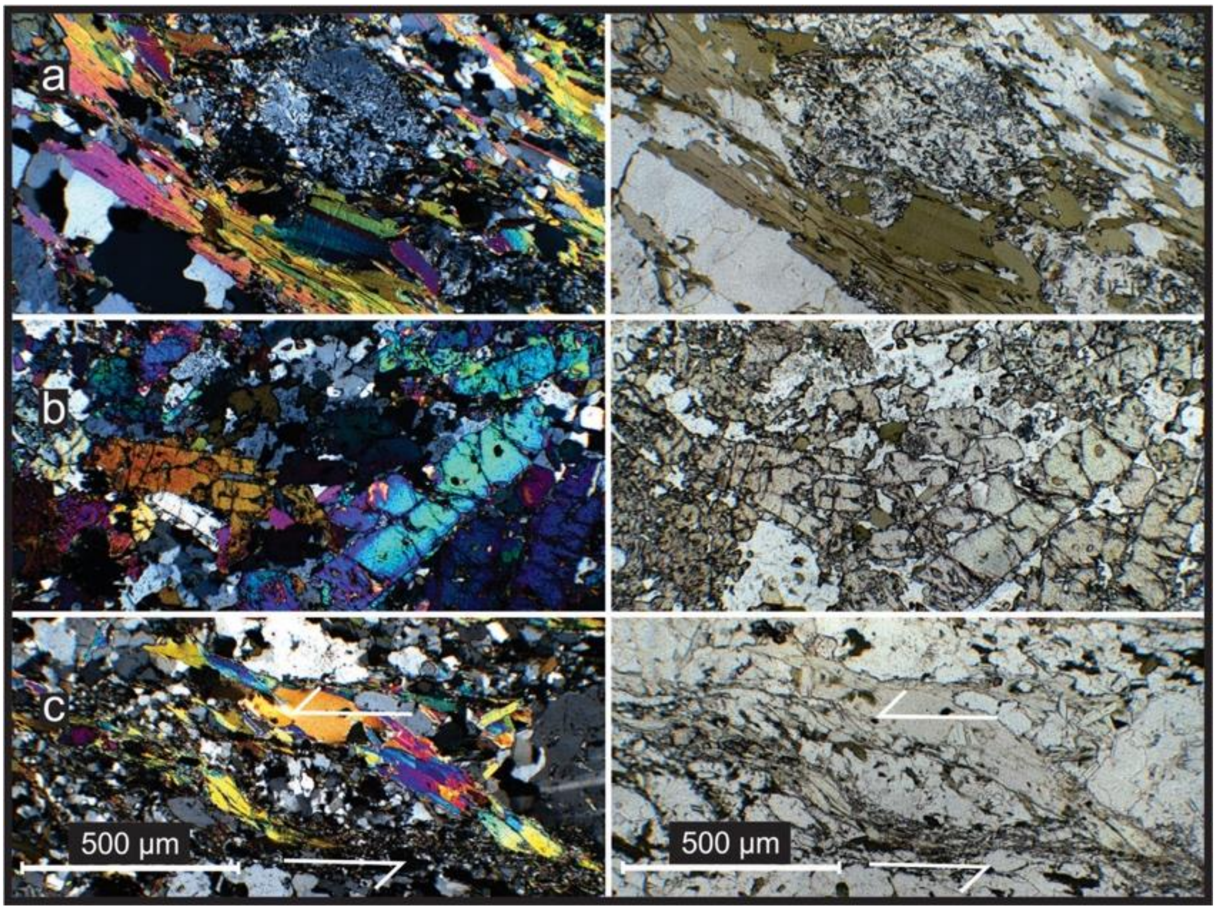

Figure 30. *Thin sections images of different textures and lithologies in the Ersfjord Granite. Images are taken with cross-polarized light are to the left, and same structures in plane-polarized light to the right. a) A sample of massive granite shows a mineral content of mainly microcline, albite and quartz, with sericitized plagioclase. Thin shear bands within the sample contain chlorite, epidote, plagioclase and alkali feldspars. b) Mafic lenses in the Ersfjord Granite consist of mostly epidotes with minor to moderate contents of biotite, plagioclase and amphibole. c) Recrystallized feldspar constitutes an asymmetric lens in a matrix of white mica and biotite. The mylonitic fabric makes up S-C structures showing a top-to-the W shear sense. Image is oriented W-E. Sampled from the easternmost, steeply dipping shear zone at Buren.*

Specifically within the steeper-dipping mylonitic shear zone furthest east at Buren, thin sections of the protomylonitic foliation (fig. 30c) show internal asymmetric lenses consisting of sericitized feldspar clasts, recrystallized quartz and feldspars, or mica fish. The surrounding matrix is made up of bands of oriented white micas and biotite, or bands of recrystallized quartz-feldspars, oriented in two main directions. Randomly oriented, euhedral epidote is common within the matrix, as well as accessory magnetite, calcite and opaque minerals (fig. 30c). The feldspars and quartz are most likely porphyroclasts crystallized pre-$D1^{EG}$, although they seem to have recrystallized syn-$S1^{EG}$. These minerals are oriented in two main directions, indicating that they are S-C-structures (cf. Lister & Snoke, 1984) with a top-to-the W sense of shear. Mica fish are interpreted to have grown as porphyroblasts syn-$D1^{EG}$, and epidote crystals post-D1^{EG}, as they overprint the rest of the mineral assemblage, and are randomly oriented.

Ultramylonite is sampled from the same site as the protomylonitic sample, and is characterized by a much finer grain size, with smaller and fewer porphyroclasts preserved (fig. 28b). The same mineral assemblage is found in thin section, though the C-bands of the mylonitic texture are more closely spaced than within the protomylonite, making the S-bands less apparent.

3.4.3 D2^{EG}-deformation structures

Structures that are superimposed onto, and thus younger than, the dominant S1^{EG}-shear zones in the Ersfjord Granite, are classified as D2^{EG}-structures (see table 1). The most pronounced structures include larger-scale folds (F2^{EG}), 5-10 meters in amplitude, that refold the S1^{EG}-shear zones as well as their internal structures (fig. 31). F2^{EG}-folds are mostly tight to open, upright, and symmetric or asymmetric in geometry, and they vary in size from meter-scale (fig. 31) to macro-scale (figs. 18, 35). Fold axes generally trend N-S to NW-SE (fig. 10d). At Middagstind, the folds are less open than observed at Hatten and Buren, and they plunge moderately (around 40°) to the NE, also in contrast to the nearly upright folds at Hatten and Buren (fig. 31).

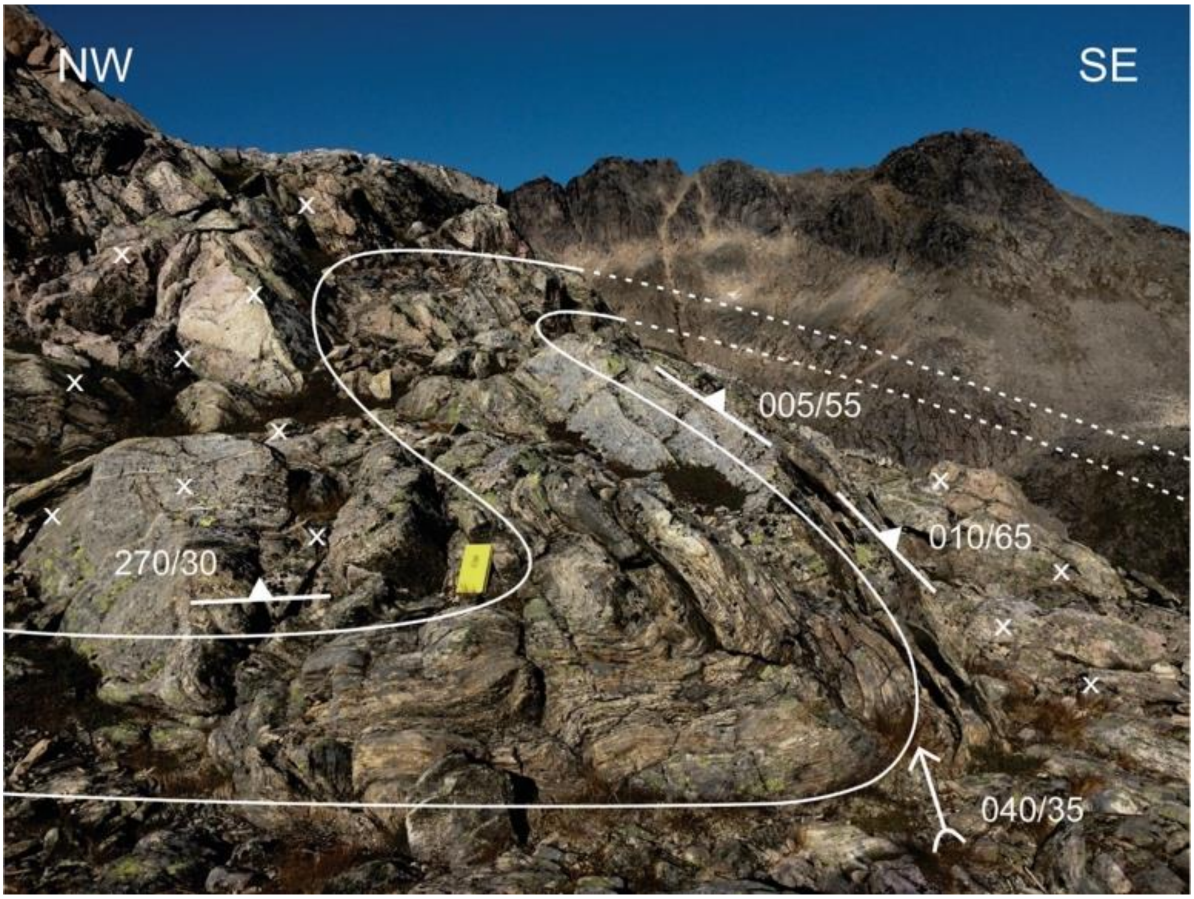

Figure 31. *S1^{EG}-shear zone refolded by tight, asymmetric F2^{EG}-folds and surrounded by massive granite. From Middagstind.*

3.4.4 D3^{EG}-deformation structures

Narrow, linear, and well-defined depressions are visible on the ground surface in many of the studied localities. These depressions are 3-5 meters wide, and often filled with soil, thin vegetation or water. When bed rocks are exposed, they define steep planar foliated mylonitic fabrics (S3^{EG}) that cross-cut the main S1^{EG}-shear zones in the Ersfjord Granite (fig. 32). The mylonitic zones strike NE-SW at Hatten (chapter 3.2.2; fig. 32), and make up steeply dipping planar, ductile foliations. The mylonitic fabric consists of a biotite-rich orthomylonite with vertical to steeply dipping foliation.

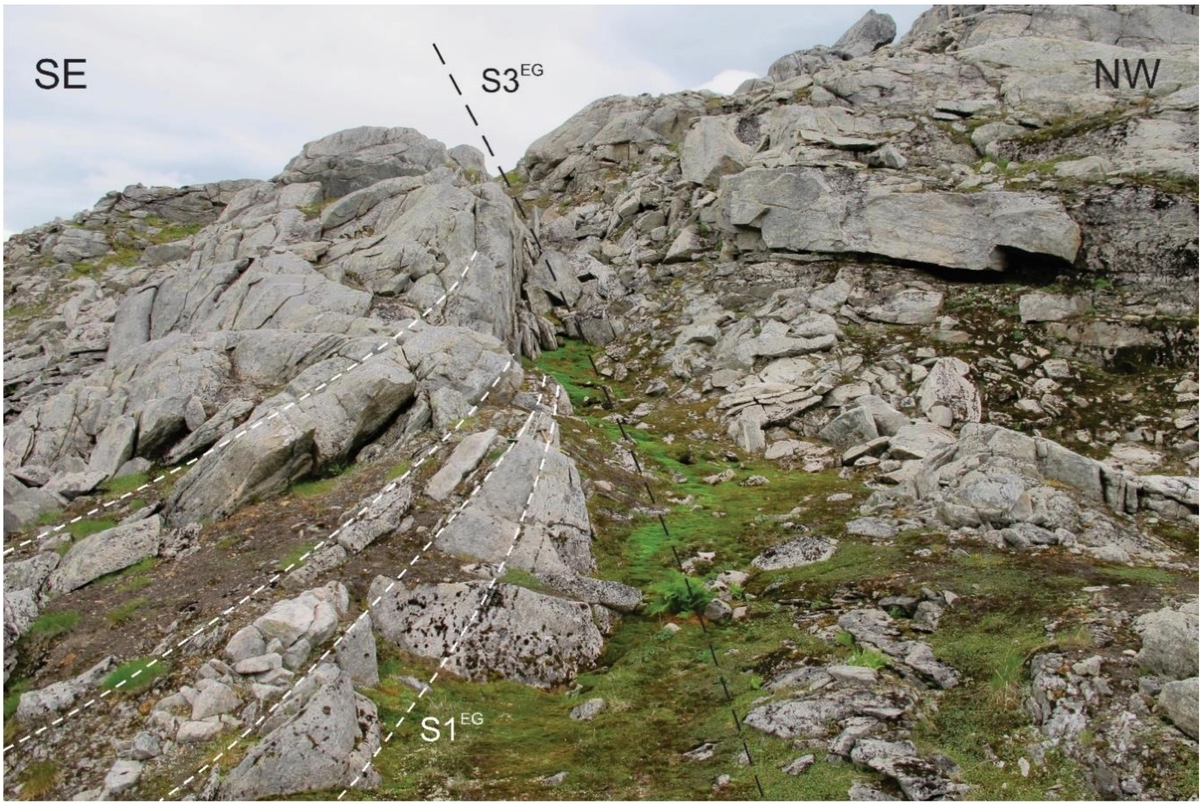

Figure 32. *Steep, S3^{EG}-shear zones in the Ersfjord Granite show surrounding foliation bent into parallelism along the boundaries of the shear zone. Many of the same characteristics of these shear zones are found in similar structures at Tverrfjellet.*

The orientation of the shear zones can be subdivided into two slightly differently-striking sets (fig. 33). One set strikes NNE-SSW (from 10 to 30°) and dips from 60-80° to the ESE, whereas the other set strikes ENE-WSW (from 60-70°), with a similar dip angle of 60-80° to the SSE.

Along the contacts of the steep shear zones where they cross-cut the low-angled S1^{EG}-shear zones, the adjacent S1^{EG}-foliation bends into parallelism with the steeply dipping S3^{EG}-foliation, asymmetrically on either side (fig. 32). The mostly subhorizontal to gently dipping S1^{EG}-foliation steepens a few meters away from the S3^{EG}-shear zone, and dips nearly parallel to the steep S3^{EG}-foliation along the contact. The asymmetrically bent foliation of the S1^{EG}-shear zones makes up folds, notably with axial surfaces aligned parallel to the S3^{EG}-shear zones (fig. 32), and fold axes plunging moderately to steeply to the NE.

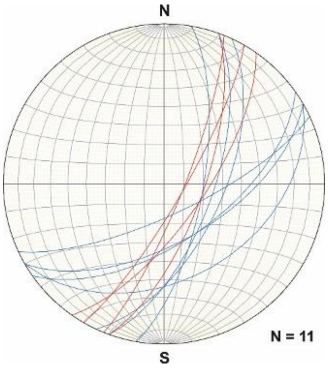

Figure 33. *Lower-hemisphere stereonet showing the orientation of $S3^{EG}$-shear zones at Hatten (blue great circles) within the Ersfjord Granite, and the orientation of similar structures from Tverrfjellet (red great circles) directly outside the Ersfjord Granite. Note two sets of strike and dip, one striking NNE-SSW and dipping steeply to the WSW, and one striking WNW-ESE and dipping steeply to the SSW.*

Interpreting the bent foliation of the $S1^{EG}$-shear zone into the $S3^{EG}$-shear zone at Hatten as dragfolding, a sense of shear can be estimated. As shown in fig. 32, the southeast side of the $S3^{EG}$-shear zone is dragged up and to the north, indicating a dextral-oblique strike-slip movement.

Similar $S3^{EG}$-shear zones crop out throughout the Ersfjord Granite, e.g. at Tverrfjellet (figs. 11, 12). The orientation of the $S3^{EG}$-shear zones at Tverrfjellet is also parallel to one of the sets at Hatten, with an average strike and dip of around 030/70 (fig. 33).

Thin section studies

Thin section studies show that the $S3^{EG}$-foliation consists of asymmetric lenses of saussuritized plagioclase (an estimated 10%), fine-grained epidote (an estimated 50%) pseudomorphing plagioclase, and presumably biotite (around 10%). The remaining 30% are unidentified minerals. The lenses are surrounded by a matrix of biotite (around 80%) and epidote (around 20%), oriented in two main directions (fig. 34). The asymmetric lenses are interpreted to be porphyroclasts in the recrystallized or rotated matrix, suggesting a mylonitic texture. Randomly oriented white micas locally cross-cut the mylonitic fabric.

A crystallization history can be inferred from the observations above: Plagioclase crystallized pre-$S3^{EG}$, and partially recrystallized, rotated and was epidotized syn-$S3^{EG}$. Biotite and epidote were rotated syn-$S3^{EG}$, and white mica crystallized after the rest of the phases post $S3^{EG}$.

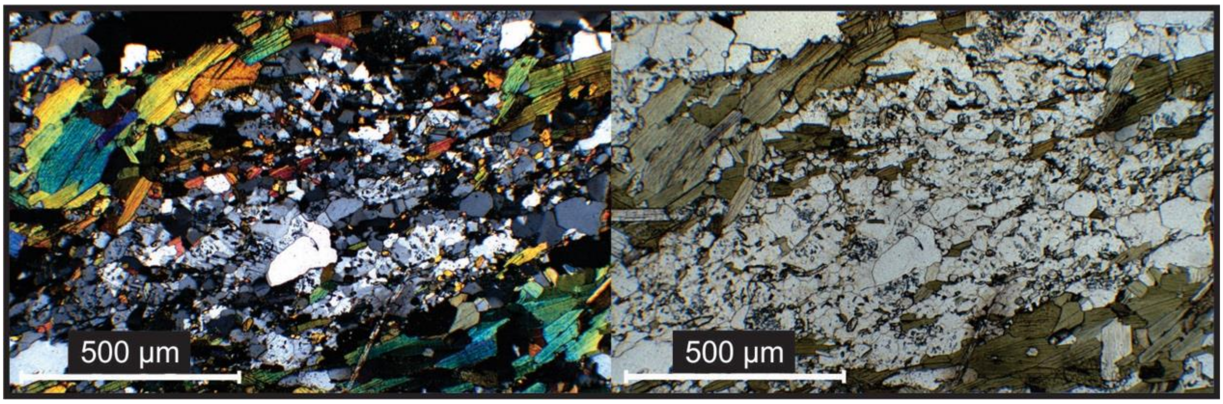

Figure 34. *Images of thin sections sampled from the $S3^{EG}$-shear zones show a mylonitic texture. Plagioclase and epidote make up asymmetric lenses, surrounded by a biotite-rich matrix oriented in two main directions. Image to the left is taken in cross-polarized light, and to the right in plane-polarized light.*

3.5 Contact relationships between the Ersfjord Granite and the TTG-gneisses of the Gråtind Migmatite

Along the transect from Tverrfjellet and up towards Middagstind (figs. 11, 35), a systematic change in the strike and dip of the $S1^{GM}$-foliation is recorded, apparently due to macro-scale antiformal folding (fig. 35). Northwards, the steeply dipping foliation of the Gråtind Migmatite is truncated by a section of massive granite, followed by a section consisting of a moderately north-dipping, well-foliated migmatite with multiple internal folds and asymmetric features. This last section shows signs of thrusting and similar geometry and internal characteristics as the Tverrfjellet shear zone. Beyond this shear zone, massive granite again dominates. Following the transect upwards toward Middagstind, multiple shear zones repeatedly crop out with packages of massive granite in between each shear zone. This pattern in the topmost part of the section towards Middagstind is much like the one described at Hatten (fig. 15). The uppermost section consisting of massive granite and repeated shear zones is interpreted to be Ersfjord Granite with internal $S1^{EG}$-shear zones. Below the granite the transition into the moderately dipping, shear-like foliation is considered to be the contact between the Ersfjord Granite and the Gråtind Migmatite, subparallel to the surrounding foliation.

Figure 35. *View of the Tverrfjellet – Middagstind transect with interpreted geometry of the contact between the Ersfjord Granite and the surrounding TTG-gneisses of the Gråtind Migmatite and its relationship to Tverrfjellet shear zone.*

In general, shear zones within the Ersfjord Granite are low-angled, dipping around 5-20° to the NW (see chapter 3.4.2). Near the proposed contact to the Gråtind Migmatite at Tverrfjellet, however, the strike is NW-SE, and the dip is steeper, 35-40°, to the NE (fig. 11). A view of the southwest face of Middagstind (fig. 36) shows this steepening tendency nearer the contact.

Based on the observations above, a generalized, schematic tectonostratigraphic model is drawn of the area, see fig. 37.

Figure 36. *Interpreted S1^EG-shear zones in the south face of Middagstind show a steepening tendency as they approach the contact to the Ersfjord Granite located structurally below them. View is to the north.*

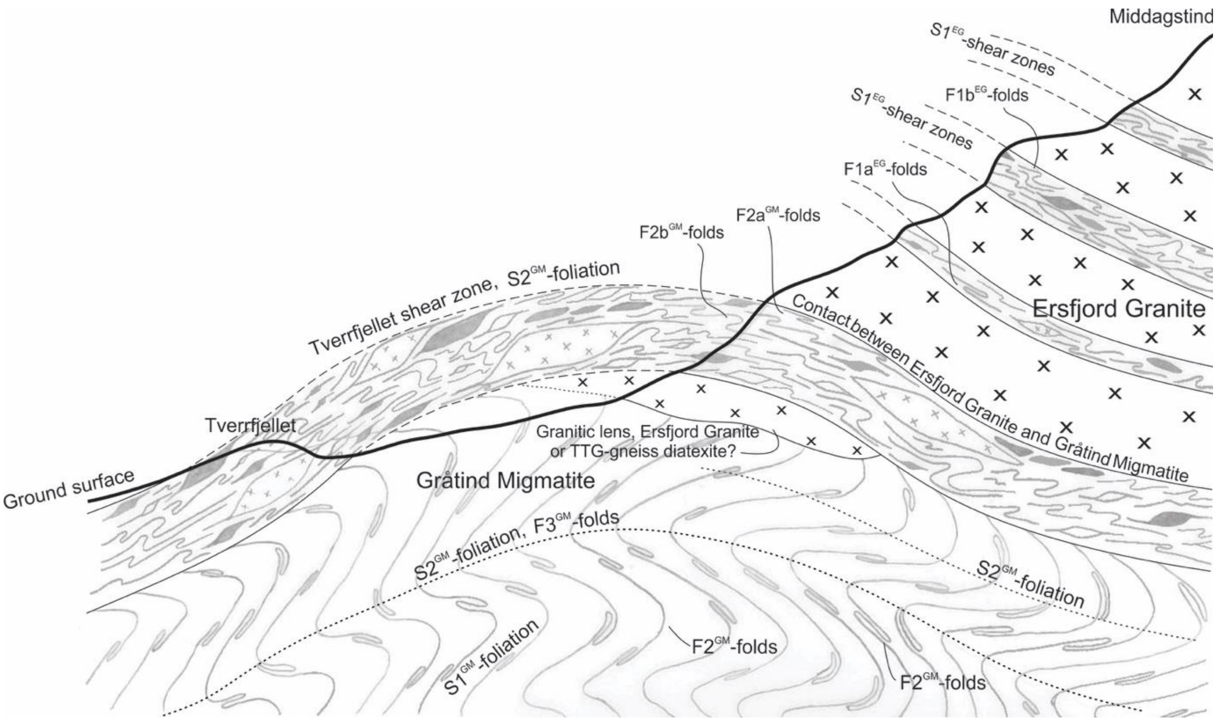

Figure 37. *Schematic tectomostratigraphic model of deformation structures in the Ersfjord Granite and surrounding TTG-gneisses. Within the Gråtind Migmatite, $F1^{GM}$-folds are intrafolial isoclinal folds, refolded by the $D2^{GM}$-event. $F2^{GM}$-folds have axial planes parallel to Tverrfjellet shear zone. Intrafolial elements within Tverrfjellet shear zone comprise isoclinal $F1a^{GM}$-folds, asymmetric open to tight $F2b^{GM}$-folds, asymmetric clasts and boudins and diatexic lenses. The contact to Ersfjord Granite lies above Tverrfjellet shear zone, and multiple low-angled, ductile, $S1^{EG}$-shear zones alternate with massive granite in the rocks of the Ersfjord Granite. Shear zones in the Ersfjord Granite contain intrafolial isoclinal $F1a^{EG}$-folds that are refolded by open to tight, asymmetric $F1b^{EG}$-folds. Also incorporated in $S1^{EG}$-shear zones are asymmetric clasts, boudins, mafic lenses, diatexic lenses and pegmatitic veins. Slip direction in shear zones is highly oblique to indicated directions in the figure. See fig. 35 for comparison.*

4 Discussion

The aim of this project has been to map, analyze and discuss the origin and kinematics of structural elements within the Ersfjord Granite, and to propose a tectonic model for the evolution and emplacement of the granite based on the findings. This tentative model should then provide the basis for a comparison with structures elsewhere in the West Troms Basement Complex. In order to achieve these goals, the study has included not only the Ersfjord Granite, but also nearby areas of the surrounding rocks of the Gråtind Migmatite. This chapter starts with a brief summary of the data and results (also summarized in table 1). The origin and kinematic character of structures in the Gråtind Migmatite and Ersfjord Granite will then be discussed, followed by an analysis of the contact relations between the Gråtind Migmatite and Ersfjord Granite. Finally, a tectonic model is proposed, as well as its regional implications.

4.1 Summary of data and results

The Ersfjord Granite on Kvaløya is surrounded by Neoarchean and Paleoproterozoic TTG-gneisses of the WTBC (Bergh et al., 2010). Among these TTG-gneisses is the Gråtind Migmatite, which is located structurally below the contact to the Ersfjord Granite at Tverrfjellet and Middagstind (fig. 13). Here, a main gneissic foliation comprises $F1^{GM}$-isoclinal folds that form a steeply dipping, axial-planar $S1^{GM}$-foliation. This foliation is refolded by macro- and mesoscale, tight, asymmetric $F2^{GM}$-folds with gently dipping axial surfaces, which are parallel to a major, low-angled shear zone studied at Tverrfjellet. This Tverrfjellet shear zone contains a number of structural elements, including tight intrafolial folds, asymmetric clasts and boudins, stretching lineations and duplexes. The main $S2^{GM}$-foliation is axial-planar to intrafolial isoclinal $F2a^{GM}$-folds, which is itself internally refolded by tight, asymmetric, mainly W-verging $F2b^{GM}$-folds. The entire Tverrfjellet shear zone is refolded by gently E-plunging macro- and mesoscale $F3^{GM}$-folds, and cut by steeper ductile shear zones ($S4^{GM}$). Between the mountains of Middagstind and Tverrfjellet, the shear zone is subparallel to the contact to the Ersfjord Granite (figs. 35, 37).

Within the mainly massive Ersfjord Granite body, a weak, distributed foliation ($S0^{EG}$) made up of aligned, flaky mineral grains is present in most exposed areas. In addition, localized, low-angled, migmatitic $S1^{EG}$-shear zones repeatedly crop out in the granite. These shear zones comprise a main shear zone fabric ($S1^{EG}$) consisting of a composite foliation of alternating, biotite-rich melanosomes and felsic leucosomes, and which is subparallel to the axial surface of foliation-internal isoclinal folds ($F2a^{EG}$). The axial-planar $S1^{EG}$-foliation is refolded by asymmetric, open to tight folds ($F2b^{EG}$), and includes multiple other internal structural elements. The shear zones themselves are refolded by large-scale, open upright, symmetric and asymmetric folds ($F2^{EG}$), and are truncated by steep to subvertical $S3^{EG}$-shear zones.

4.2 Discussion of structural and petrographic data from the Gråtind Migmatite

4.2.1 Discussion of D1^{GM}-deformation structures

The mapped rocks of the Gråtind Migmatite are considered to be parts of the Neoarchean TTG-gneisses of the West Troms Basement Complex (Zwaan, 1992b; Zwaan & Bergh, 1995), with leucosome crystallization ages dated in Senja to be around 2.75-2.70 Ga, and gneiss-forming events at around 2.70 and 2.67 Ga (Myhre et al., 2013). The well-defined foliation in the Gråtind Migmatite dips steeply to the E and W, though it was considered to be an originally flat-lying foliation by Bergh et al. (2010).

Within the study area, these rocks have a main migmatitic S1^{GM}-foliation that is composed of quartz-feldspathic leucosomes alternating with amphibolitic and locally biotite-rich melanosomes, producing a composite foliation (Armitage & Bergh, 2005). The field and textural data (see chapter 3.3.1) suggest they formed due to partial melting of either a magmatic tonalite or felsic meta-sedimentary rocks. A sedimentary origin is favored by the often km-thick and well-laminated sequences of TTG gneisses in the area surrounding the Ersfjord Granite (Bergh et al., 2010). Also, straight to diffuse leucosome edges relative to the often banded melanosome in the Gråtind Migmatite rocks, indicate that the felsic component crystallized in a partially solid crust (cf. Sawyer, 2008).

As the main S1^{GM}-foliation is made up of similar-style isoclinal F1^{GM}-folds, a shear-induced event involving a thrust-type movement is likely to have formed the fabric. On the basis of this it is reasonable to conclude that Neoarchean thrusting associated with crustal shortening has taken place. Although upper amphibolite to granulite facies metamorphism has been proposed further west in Senja and Lofoten (Corfu, 2007; Bergh et al., 2010), metamorphic conditions during this event are uncertain, as the minerals defining the foliation have been thoroughly recrystallized, retrograded, and overprinted by later deformational and metamorphic events. The S1^{GM}-foliation displays a steep and varying dip (fig. 19) throughout the Gråtind Migmatite, indicating a later tilting of the fabrics.

Based on these observations, it can be concluded that the D1^{GM}-deformational event involved crustal shortening and possibly shearing or thrusting, likely during the Neoarchean (around 2.6 Ga; Myhre et al., 2013), which produced a widespread TTG gneiss foliation. Some degree of partial melting might have taken place during the D1^{GM}-deformational event.

4.2.2 Discussion of D2^{GM}-deformation structures and Tverrfjellet shear zone

Structural data obtained for the Tverrfjellet shear zone (figs. 11, 12) clearly show that the shear zone truncates the steeply dipping S1^{GM}-foliation of the Gråtind Migmatites, and must for that reason be younger. Fabric orientation data further show that in the study area, the shear zone dips gently to the southeast (fig. 11), and is axial-planar to F2^{GM}-folds, which are macro- to meso-scale, open to tight folds that refold the S1^{GM}-fabric. It comprises a main, migmatitic foliation (S2^{GM}) which is also axial-planar to foliation-internal, asymmetric isoclinal folds (F2a^{GM}; fig. 23a), and has numerous internal fabrics and structures that allow the kinematics to be determined (fig. 23).

Since the main, low-angle, southeast-dipping foliation (S2^{GM}) of the Tverrfjellet shear zone is axial-planar to F2^{GM}-folds, this suggests that the shear zone formed synchronously with a D2^{GM}-folding event that also involved low-angle shearing (see kinematics below). The intrafolial asymmetric and isoclinal F2a^{GM} and F2b^{GM}-folds may reflect different stages of the shearing event, or heterogenous movement or strain intensity within the shear zone. Measured fold axes of F2a^{GM}- and F2b^{GM}-folds plotted together in stereonets (fig. 10c) vary a lot, and cannot easily be separated into two sets of trend. This makes it reasonable to assume that they were formed during the same shortening event, but due to variable internal shearing. A stage of intense shearing producing isoclinal F2a^{GM}-folds could for instance have been followed by a less active strain stage, before renewed activation again took place and refolded the S2^{GM}-foliation into the intrafolial, asymmetric F2b^{GM}-folds, making the later stage a coaxial, progressive folding event (figs. 38A, B). Alternatively, the asymmetric F2b^{GM}-folds formed due to low strain shearing, and where the strain was locally higher, tight to isoclinal F2a^{GM}-folds were formed (figs. 38C, D). A third option could be that the isoclinal F2a^{GM}-folds formed during the main D2^{GM}-shearing event, and the asymmetric F2b^{GM}-folds formed during a later D3^{GM}-macro folding event, as parasitic folds within the folded shear zone (figs. 38C, D). If the assumption that the F2a^{GM}-folds are part of a ubiquitous, transposed S2^{GM}-foliation is correct, the second of the three models (figs. 38C, D) is unlikely, as it is shown that shear zone foliation (F2a^{GM}) in fact is refolded by the asymmetric folds (F2b^{GM}). The third model is unlikely if the axial surfaces of the parasitic F3^{GM}-folds (F) are not parallel to the macro-scale folds (E). The first model is favored, however, not enough data exist to reliably conclude on one of the three models.

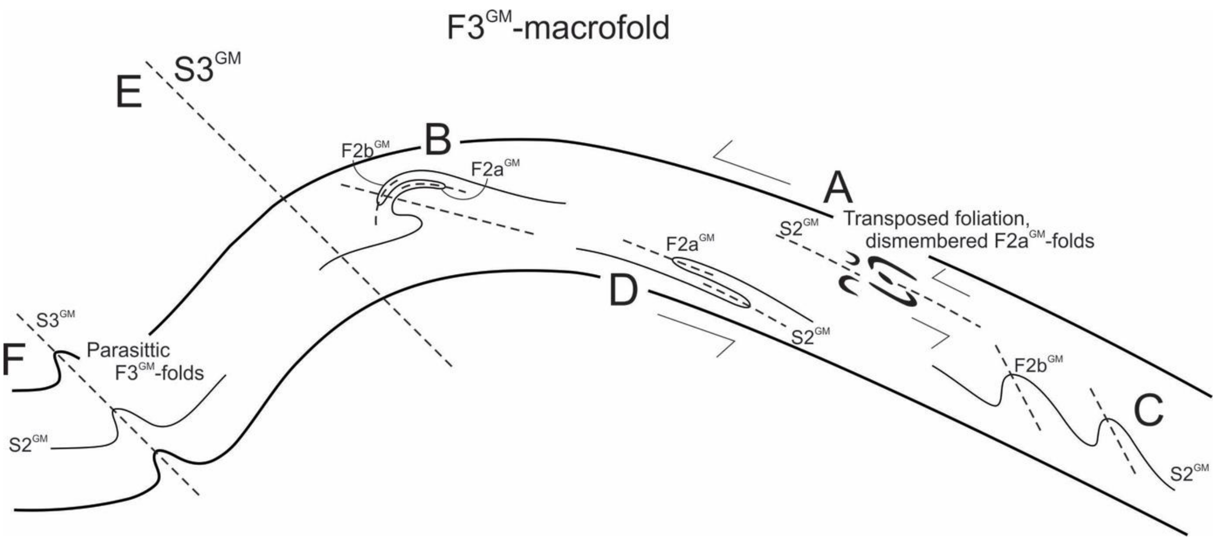

__Figure 38.__ Possible formation of different fold types progressive evolution. The internal S2^{GM}-foliation in Tverrfjellet shear zone could have formed by an intensive phase of deformation creating isoclinal, partially dismembered F2a^{GM}-folds in a transposed foliation (A), followed by a less active stage of deformation and refolding of the transposed foliation into asymmetric, open

F2b^{GM}-folds (B). Another option is that asymmetric F2b^{GM}-folds formed during shearing (C), and that areas affected by the highest amount of strain were progressively folded into isoclinal F2a^{GM}-folds (D). A third possibility is that the F2a^{GM}-folds formed during the D2^{GM}-deformational event, whereas the asymmetric folds could be F3^{GM}-folds (F) formed as small-scale, parasitic folds to the macro-scale folding D3^{GM}-event (E).

Geometric and kinematic data show that the Tverrfjellet shear zone strikes NE-SW and dips gently to the SE (fig. 11). Asymmetric and isoclinal F2a^{GM}- and F2b^{GM}-fold axes recorded within the shear zone vary a lot in orientation, from NE-, E-, SE- to S-plunging, but on average, they fall into a great circle girdle that overlaps well with the average orientation of the shear zone itself (fig. 11). The dominant plunge direction is ESE (fig. 11), subparallel to a stretching lineation (fig. 10c; only two measurements). This spread in fold axes suggests a non-uniform shearing direction with possible rotation of fold axes toward a common shear direction (cf. Bell et al., 1992), which is either NW or SE depending on sense-of-shear (fig. 10c). Additional observed kinematic data, such as sigmaclasts and duplexes (figs. 23c, d) show dominant thrust-type of movements with shear senses from north through west to south, and most commonly to the west. Due to the few stretching lineations, it is difficult to know whether or not outcrops are oriented normal to the sense-of-shear, and both sigmaclasts and duplexes can possibly (or even probably) be oriented up to 90° from their true direction (cf. Passchier & Trouw, 2005). In other words, they can only indicate apparent transport directions. If internal folds alone are used as kinematic indicators, fold vergence to the SW (figs. 21, 23) suggests the movement is oblique, normal down-to-the-SW with a dominant dextral strike-slip component. W-verging folds, however, compared with the ESE-plunge of the measured stretching lineations indicates a fairly certain sense-of-shear to the WNW, and sigmaclasts and duplexes reinforce a western sense-of-shear. Based on the kinematic data, an overall transport direction in the Tverrfjellet shear zone is top-to-the WNW.

The migmatitic fabric that makes up the Tverrfjellet shear zone is composed of highly sheared, dark colored biotite-rich amphibolitic melanosome and light-colored felsic leucosome components. The absolute age of the Tverrfjellet shear zone is unknown, so these composite gneisses may have originated either from the same melts as those that formed the Neoarchean S1^{GM}-fabric of the Gråtind Migmatite rocks, or they could be much younger and formed by partial melting of the Ersfjord Granite or the surrounding TTG gneisses. The latter explanation is favored, as shown in chapter 4.5.3. The mineral and textural data (see chapter 3.3.2) indicate that the host rocks of the Tverrfjellet shear zone underwent prograde, moderate to high-grade metamorphism, with partial melting and ductile deformation during the D1^{GM} and D2^{GM}-events (cf. Bergh et al., 2010). This is supported by mineral assemblages of amphibole and local garnets along the S2^{GM}-foliation. Later retrograde metamorphic conditions are evidenced by growth of chlorite (fig. 24).

As the Tverrfjellet shear zone is axial-planar to the F2^{GM}-folds in the Gråtind Migmatite, it is reasonable to assume that the internal kinematics of the Tverrfjellet shear zone reflect the overall crustal kinematics of the D2^{GM}-deformational event. This event most probably took place during the Svecofennian orogeny (Zwaan & Bergh, 1995; Bergh et al., 2010), and may have involved crustal shortening and accretionary tectonics (see later discussion). The Tverrfjellet shear zone likely formed in this scenario as an oblique-reverse, dextral top-to-the WNW thrust, possibly also involving anatexis.

4.3 Discussion of structural and related petrographic data from the Ersfjord Granite

4.3.1 Discussion of D0^{EG}-deformation structures

A crystallization age of 1.79 Ga is obtained for the Ersfjord Granite (Corfu et al., 2003), which is consistent with emplacement of the granite during the Svecofennian orogeny (Bergh et al., 2010). Most of the granite is massive and non-foliated, or the granite contains a weakly foliated texture, termed S0^{EG}. This texture is distributed throughout the granite, and it is itself consistently truncated by widespread and localized ductile shear zones containing a number of other structural elements (figs. 25e, f). Thus, this distributed fabric is considered the oldest fabric within the Ersfjord Granite.

Based on the aligned texture of flaky minerals, the S0^{EG}-foliation is interpreted to have originated either as a magmatic layering in a magma chamber or as a tectonic fabric during the emplacement of the melt in combination with an early episode of deformation (cf. Barbey, 2009). In favor of a magmatic fabric is the presence of lens-shaped, partly relic quartz-feldspar phenocrysts in the massive host rock (figs. 25e, f; cf. MacKenzie et al., 1982).

In general, the S0^{EG}-fabric strikes approximately N-S, dips gently to moderately to the E and W (fig. 25b), and is mostly subparallel to the S1^{EG}-shear zones. This variation in strike and dip could be due to fluctuations in the magmatic flow during the emplacement of the granite, or it could reflect a later stage of large-scale folding around a N-S-trending fold axis (fig. 39). A combination of the two processes could also be responsible for the varying orientations.

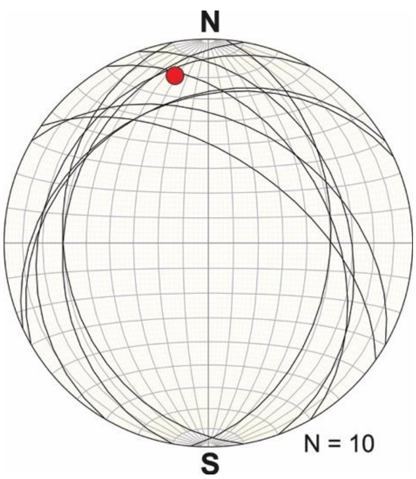

Figure 39. *Lower-hemisphere stereonet showing orientation of magmatic S0^{EG}-foliation (black great circles) and the constructed beta-axis (red dot). In general, the S0^{EG}-foliation strikes approximately N-S, and dips to the east and west. The constructed beta-axis plunges gently to the NNE.*

An alternative possibility for the emplacement, is that the entire Ersfjord Granite body is a product of in situ partial melting of the crust (cf. Sawyer, 2008), due to extensive and/or localized concentration of heat. The melanosomes of the shear zones in the granite might then be relict structures, formed prior to the melting event. Alternatively, the metatexite fabrics in the shear zone could be relict shear zones. Both of these suggestions are considered unlikely, as the distributed $S0^{EG}$-foliation, interpreted to be a magmatic foliation from the intrusion of the granite, is clearly cut by the younger shear zones in the Ersfjord Granite. It is, however, possible that the $S0^{EG}$-foliation is misinterpreted as a magmatic foliation. Further studies are necessary to confidently conclude on an option.

4.3.2 Discussion of $D1^{EG}$-deformation structures

Low-angle, planar and continuous $S1^{EG}$-shear zones make up a localized subhorizontal to gently dipping $S1^{EG}$-fabric throughout the Ersfjord Granite (figs. 18, 26). Since these shear zones truncate the $S0^{EG}$-foliation described above, it can be concluded that they are younger than the magmatic foliation and may be linked to a separate deformation event ($D1^{EG}$). In addition, the superimposed refolding on macro- and mesoscale of $S1^{EG}$-shear zones by $F2^{EG}$-folds, and later truncation by steeply dipping to subvertical ductile shear zones ($S3^{EG}$) support the Ersfjord Granite was affected by two more deformational events ($D2^{EG}$ and $D3^{EG}$; see table 1).

On a large scale, the $S1^{EG}$-shear zones define a system of repeated, mostly foliation-parallel to slightly foliation-oblique systems (fig. 26) that can be interpreted as a low-angle, imbricate thrust system formed due to crustal shortening and stacking of thrust-generated nappes including enclosed granite slivers (cf. Boyer & Elliott, 1982). Low-angle imbricate thrusts may have propagated upward into the granite in the direction of tectonic transport. This tentative interpretation is partly supported by shear zone-internal structures and kinematic data as outlined below.

Within individual $S1^{EG}$-shear zones, the metatexite fabric contains a number of different structural elements, such as isoclinal and asymmetric folds, asymmetric clasts, and boudins (fig. 27). These structures are interpreted to be a product of solid state compressional tectonics associated with thrust-type movements (cf. Butler, 1982). The majority of the structures show a top-to-the W and WNW sense of shear, though the measurements vary widely from NE to NW through W, SW and S displacement (fig. 27). Isoclinal $F1a^{EG}$-folds make up the main $S1^{EG}$-shear zone fabric, which is often refolded by more open, asymmetric $F1b^{EG}$-shear folds. This indicates either multiple phases of deformation, or a progressive, coaxial deformation history similar to that described at Tverrfjellet (fig. 38; chapter 4.2.2)

Orientation data for fold axes of shear folds and isoclinal folds in $S1^{EG}$-shear zones of the Ersfjord Granite are arranged nicely along a great-circle girdle that overlaps with the average orientation of the $S1^{EG}$-shear zones in the areas they are measured from (fig. 10c). This is an indication that the fold axes may have been rotated away from their original orientation, i.e. from perpendicular to the transport direction towards a direction more parallel to the transport direction (fig. 10c). In the presumed most highly strained parts of the $S1^{EG}$-shear zones, such folds close on both sides (fig. 29c) producing sheath folds (Passchier & Trouw, 2005). Most of the shear folds have axes trending in a WNW direction, thus, an overall top-to-the WNW directed kinematic transport direction can be inferred for the $S1^{EG}$-shear zones in the Ersfjord Granite based on the data and discussion above. This estimate is confirmed by a few measurements of stretching lineations with a main ESE-WNW trend (fig. 10c). On the other hand, since the main strike of the shear zones, e.g. in Hatten and Store Blåmann, is on average NE-SW and the dip is gently to the NW, a down-to-the-WNW oblique-slip type of movement is displayed for these shear zones. This is in contrast to the thrust-type of movement inferred from the character of the deformation structures described above. Possible reasons will be further discussed in chapter 4.3.3.

The mineral assemblage of melanosomes of the $S1^{EG}$-foliation is made up of aligned, irregular biotite, and lens-shaped sericitized plagioclase with minor, idioblastic epidote grains (fig. 30a), whereas coarse-grained quartz and feldspars dominate in the leucosomes. From this mineral assemblage, it may be inferred that phenocrysts of lens-shaped plagioclase, quartz and alkali-feldspars crystallized pre-$D1^{EG}$, based on their lack of alignment. This could also be due to recrystallization at a later stage, although this is unlikely, as triple-points and straight crystal boundaries are not observed. Within the melanosome, biotite and polygonal quartz crystallized syn-$S1^{EG}$, as the grains are parallel to the melanosome foliation. Plagioclase truncates the biotite and quartz, but is also aligned parallel to $S1^{EG}$, indicating it crystallized syn- to post-tectonically with biotite and quartz in $S1^{EG}$. Veins and clusters of granitic, quartz-feldspathic leucosome locally truncate and obliterate the melanosome fabric, which is an indicator of melting of the host rock in the shear zones. In this case it may support partial anatexis of the original rock, with separation and migration of a leucosome (cf. Sawyer, 2008). Later on, epidote crystallized syn- to post- $S1^{EG}$, as it is also oriented, but grew across all the other minerals in the $S1^{EG}$-foliation.

The more steeply east-dipping shear zone on the east side of Buren (fig. 17) differs from the $S1^{EG}$-shear zones described from the rest of the granite. At Buren, this shear zone dips around 30° near the scarp of Burshammaren (fig. 16), whereas a dip of nearly 60° is found at the foot of the mountain closer to the fjord, in stark contrast to the gentle NW-dip elsewhere in the granite. The reason for this steep, opposite dip might be that the $S1^{EG}$-shear zone is folded by a second generation of large-scale antiformal folds, with a NW-SE-trending fold axis near the Burshammaren scarp. The east-dipping shear zone, however, has a noticeable mylonitic fabric, as opposed to the consequently migmatitic fabric of the $S1^{EG}$-shear zones elsewhere in the granite. It is suggested that this shear zone formed separately, for example during a later event, or when the Ersfjord Granite was at a different crustal level. This could for instance be if it formed as an out-of-sequence thrust (Butler, 1987; Morley, 1988) much later in the $D1^{EG}$-

event than the migmatitic shear zones, at a higher level in the crust when the P-T conditions were lower. This is supported by the solid state mylonitic fabric containing quartz, K-feldspar and plagioclase porphyroclasts that likely crystallized pre-$S1^{EG}$, whereas elongated mica porphyroblasts formed syn-$S1^{EG}$, and epidote crystals post-date $S1^{EG}$, as they overprint the rest of the mineral assemblage and are randomly oriented. Another option is that the east-dipping shear zone was located closer to the steep contact of the granite relative to the surrounding TTG gneisses, and for that reason, the temperature was cooler. Such a location would also explain the lack of migmatization, as well explain the steep dip of the shear zone which is expected near a steep contact.

The kinematic character of the mylonitic shear zone at Buren is determined from where the $S0^{EG}$-magmatic foliation is cross-cut by the $S1^{EG}$-shear zone (fig. 25f), and the foliation is bent into parallelism with the $S1^{EG}$-shear zone. This bending is interpreted to be dragfolding, which yields a reliable top-to-the W tectonic transport direction for the steep, $S1^{EG}$-thrust at Buren. Also in thin section, S-C-structures support this sense-of-shear (fig. 30c), which is in the same direction as the estimated transport direction for the migmatitic shear zones, although the migmatitic shear zones are far more gently dipping.

4.3.3 Discussion of $D2^{EG}$-deformation structures

Macro-scale $F2^{EG}$-folds are most pronounced when viewed from a distance, and affect the $S1^{EG}$-shear zone systems in the entire Ersfjord Granite. Examples include the areas of Middagstind and Store Blåmann, where the nearly planar, $S1^{EG}$-foliation is seen to be gently folded over large areas (figs. 18, 36). The $F2^{EG}$-folds consistently refold the main $S1^{EG}$-shear zone foliation, and for that reason are interpreted to postdate these shear zones, as well as the oldest, distributed $S0^{EG}$-foliation. These macro-scale $F2^{EG}$-folds may explain the contrasting shear zone characteristics for the $S1^{EG}$-shear zones that show oblique-normal fault geometry, but thrust-type internal structures. If the $F2^{EG}$-folds refolded the $S1^{EG}$-shear zones, initially SE-dipping thrust zones are now NW-dipping, since the folded $S1^{EG}$-shear zones are now situated on different $F2^{EG}$-macroformal fold limbs.

Orientation data for the $F2^{EG}$-folds are mostly achieved from meso-scale folds observed in outcrops, whereas orientation data for the larger-scale folds are revealed from plots of folded $S0^{EG}$- and $S1^{EG}$-foliation (fig. 40). These orientation data, when analyzed together, show a calculated beta-fold axis trending NNW-SSE and plunging gently NNW. Meso-scale $F2^{EG}$-folds from Hatten, Buren and Store Blåmann show a similar orientation of fold axes (fig. 10d), indicating an E-W directed shortening of the Ersfjord Granite during the $D2^{EG}$-event. At Middagstind, however, the calculated beta-fold axis trends NE-SW and plunges 35° to the NE (fig. 10d). This difference in trend and plunge of the fold axis at Middagstind could be due to a local, oblique tilting of the shear zone as it approaches the Ersfjord Granite contact (see further discussion in chapter 4.4 and 4.5.5).

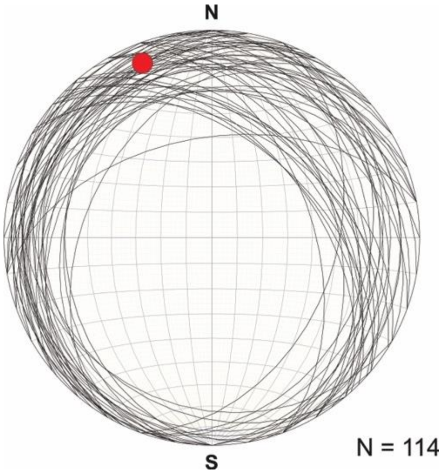

Figure 40. *Lower-hemisphere stereonet showing orientations of $S0^{EG}$ and $S1^{EG}$-foliations combined (black great circles). Constructed beta-axis (red dot) plunges gently to the NNW.*

4.3.4 Discussion of $D3^{EG}$-deformation structures

The youngest ductile structures observed in the Ersfjord Granite are NE-SW striking and steeply dipping mylonitic $S3^{EG}$-shear zones that truncate all of the other described structures. Where this fabric intersects with the low-angled $S1^{EG}$-shear zones, the lower-dipping foliation is bent into parallelism with the $S3^{EG}$-shear zone (fig. 32). This bending is interpreted to be dragfolding related to shear movement along a younger set of shear zones. In combination, these data can be used to infer the $S3^{EG}$-shear sense. However, the only shear-sense estimate made is from a dragfolded foliation at Hatten, and based on limited data. There, the foliation on either side of the shear zone is folded around a moderately to steeply NE-plunging fold axis, indicating that the west side has moved up and north compared to the east side, suggesting an oblique-dextral, strike-slip movement sense.

The observed $S3^{EG}$-shear zones at Hatten have very similar geometric characteristics as the steep shear zones at Tverrfjellet, with a steep mylonitic foliation, suggesting that they originated during the same deformational event. In other words, the late stage $D3^{EG}$-deformation is interpreted to affect both the Ersfjord Granite rocks, as well the surrounding Gråtind Migmatite rocks (see chapter 4.5.5).

The mineral assemblage in the $S3^{EG}$-shear zones contains syn-tectonic chlorite, indicating that this late stage of deformation took place at lower metamorphic conditions than the $D1^{EG}$ and $D2^{EG}$-events, i.e. higher up in the crust, and also after a significant cooling of the intrusion. This could explain the mylonitic texture of the shear zone rocks, in contrast to the predominantly migmatitic texture of the $S1^{EG}$-shear zones in the Ersfjord Granite.

4.4 Discussion of the contact relationships between the Ersfjord Granite and the Gråtind Migmatite

Between Tverrfjellet and Middagstind, the mapped and interpreted contact between the Gråtind Migmatite and the Ersfjord Granite is located (fig. 35). The gneisses with a steeply dipping, migmatitic foliation described in the southernmost parts of the transect are interpreted as the Gråtind Migmatite host rocks with $S1^{GM}$-foliation, and the massive portion of granite to the north of this is assumed to be a granitic lens included in the Neoarchean gneisses. The highly sheared, moderately north-dipping foliation further north is interpreted to be a part of the Tverrfjellet shear zone, which must be macro-folded about a gently E-plunging fold axis. Therefore, the north-dipping shear zone below the contact is from an opposite fold limb compared to the part of the shear zone mapped at Tverrfjellet. This macro-fold is interpreted as a result of the $D3^{EG}$-event, and thus an $F3^{EG}$-fold (fig. 37). Directly above the $F3^{EG}$-folded Tverrfjellet shear zone at Middagstind lies the contact to massive Ersfjord Granite rocks, which contain a number of repeating, ductile shear zones interpreted to be $S1^{EG}$-shear zones. They have a slightly different orientation compared to the $S1^{EG}$-shear zones in the rest of the granite, and are more parallel to northeast limb of the Tverrfjellet shear zone (see chapters 4.2.2 and 4.3.2). These observations indicate that the shear zones in Middagstind and Tverrfjellet were deformed during the same event, which could have had a slightly oblique shortening direction compared to the $S1^{EG}$-shear zones in the Ersfjord Granite. A favored interpretation is that these shear zones were refolded by a later folding event (see chapter 4.5.5).

4.5 Nature, origin and relative timing of deformation events in the Ersfjord Granite and the Gråtind Migmatite

The nature and relative timing of deformation structures in the Ersfjord Granite and Gråtind Migmatite rocks will be discussed in this chapter, in order to better correlate deformation events, and evaluate the origin of the migmatites, possible melting processes and metamorphic conditions. This discussion, however, suffers from the lack of radiometric age dating in the area.

4.5.1 $D1^{GM}$-event

The oldest structure in the study area is the main migmatitic foliation ($S1^{GM}$) of the TTG-gneisses that makes up the Gråtind Migmatite, thought to be Neoarchean in age (Armitage & Bergh, 2005; Bergh et al., 2010; Myhre et al., 2013). This fabric is generally steeply dipping and consistently truncated by younger shear zones including the Tverrfjellet shear zone and the Ersfjord Granite contact. The main $S1^{GM}$-foliation of the Gråtind Migmatite rocks is migmatitic, with neosomes and possible paleosomes, formed axial-planar to isoclinal folds that makes up the dominant migmatitic fabric. This presumed shortening and thrusting event (cf. Myhre et al., 2013) took place well before the intrusion or emplacement of the Ersfjord Granite (1.79 Ga; Andresen, 1980), and for that reason, no structures from this event are present in the granite.

4.5.2 D0^{EG}-event

The presumed oldest structure in the Ersfjord Granite is the magmatic foliation formed as the granite intruded into the crust. It is possible that the intrusion took place shortly prior to or during the D2^{GM} and D1^{EG}-deformation (see below).

4.5.3 D2^{GM} and D1^{EG}-events

The shear zone at Tverrfjellet is formed parallel to the axial surface of upright, asymmetric NE-SW trending F2^{GM}-folds, and has many similar macro-scale and internal characteristics as the S1^{EG}-shear zones in the Ersfjord Granite. For instance, internal fold-patterns are the same, where isoclinal folds make up the shear zone fabric (S2a^{GM}/S1a^{EG}), which is likely refolded by foliation-internal, asymmetric shear folds (F2b^{GM}/F1b^{EG}). Asymmetric clasts and lenses, boudins and lineations are found in both shear zones, which also are low-angled and migmatized, and show a transportation direction of top-to-the WNW. In addition, the shear zones are macro-folded by corresponding F3^{GM}- /F2^{EG}-folds, which explains why the two shear zone sets do not have the same strike and dip directions; i.e. the S1^{EG}-shear zones dip gently to the northwest, whereas the S2^{GM}-Tverrfjellet shear zone dips gently to the southeast. Since the estimated shear-senses vary accordingly, it is suggested that the deformational events of D2^{GM} and D1^{EG} occurred at the same time, producing initially oblique top-to-the WNW thrusts, prior to the F3^{GM}- /F2^{EG}-folding, due to regional NNE-SSW crustal shortening.

If the D2^{GM}- and the D1^{EG}-events are the same event, it must have taken place sometime after or during the late stages of the emplacement of the Ersfjord Granite, i.e., in the Svecofennian Orogeny (cf. Andresen, 1980; Bergh et al., 2010). As the two lithologies were juxtaposed, it is likely that any deformation taking place within one of the lithologies, also took place within the other. Although no other shear zones similar to that of the Tverrfjellet shear zone are observed elsewhere within the Gråtind Migmatite rocks, the F2^{GM}-folds with axial surfaces parallel to the Tverrfjellet shear zone are ubiquitous in the migmatites. It is possible that the rigid and competent Ersfjord Granite was deformed along large-scale thrusts, while the less competent and well-foliated Gråtind Migmatite gneisses were mainly folded into asymmetric folds (F2^{GM}; fig. 37). The Tverrfjellet shear zone could be an exception, formed in the close proximity to the contact with the intruding Ersfjord Granite, and where some of the rigidity was transferred to the rocks near the contact. The migmatitic texture of the S2^{GM} and S1^{EG}-fabrics suggests at least local anatexis during this deformation event, possibly as a consequence of the increase in temperature as the granite intruded into and melted the surrounding TTG-gneisses. It is also possible that S2^{GM}-shear zones like the Tverrfjellet shear zone, and S1^{EG}-shear zones in the Ersfjord Granite were formed elsewhere in the Gråtind Migmatite on Kvaløya, even though later Svecofennian deformation may have obliterated these structures (cf. Bergh et al., 2010). Macro-scale tight to isoclinal $F2^{GM}$-folds and shear zones similar to the Tverrfjellet shear zone are mapped in the West Troms Basement Complex, for instance on Senja and Ringvassøya (Zwaan et al., 1998; Armitage, 1999; Bergh et al., 2010).

The migmatitic texture of these shear zones indicate some degree of partial melting in the crust during deformation, possibly due to excess heat associated with the intrusion of the granite. If the $D1^{EG}$-deformation took place during or shortly after the emplacement of the granite, $S2^{GM}$ and $S1^{EG}$-shear zones could have formed along preexisting weaknesses made up of injected melts from mixing between the granite and the TTG-gneisses. Alternatively, the deformation itself could have entrained TTG-melts and rafts into the granite along the shear planes, or TTG-melts could have been injected into the granite along the shear zones after they formed. All of the above options would explain the melanosome content in the otherwise massive granite. Mafic pods and lenses are possibly unmelted resisters, or they could have crystallized out of a mafic melt incorporated in the granite as described above. Internally within the shear zones ($S2^{GM}$ and $S1^{EG}$), lenses of seemingly massive diatexites are found, and are assumed to be a product of progressive anatexis of the same lithologies that make up the metatexic shear zones (cf. Sawyer, 2008). Pegmatitic veins in the shear zones could be the products of melts from the Ersfjord Granite or the TTG-gneisses, showing increased melt differentiation as it migrated within the host rocks. However, it is more likely that the pegmatites represent the last stages of the injection of the Ersfjord Granite (chapter 2.3.5; cf. Bergh, 2010; Bergh et al., 2015), as the sharp and stepped edges of the veins indicate that they must have intruded in a late phase of the crystallization of the host rock (cf. Sawyer, 2008). These veins are mostly parallel to the $S3^{GM}$- /$S2^{EG}$-foliation, indicating that they formed synchronously.

4.5.4 $D3^{GM}$ and $D2^{EG}$-events

The $D3^{GM}$ and $D2^{EG}$-deformation events both comprised macro-scale folding ($F3^{GM}$ and $F2^{EG}$) of the $S2^{GM}$ and $S1^{EG}$-foliations. In the Gråtind Migmatite, this deformation is expressed as it refolds the $F2^{GM}$-folds and their axial-planar $S2^{GM}$-Tverrfjellet shear zone (fig. 37).

In favor of the two deformations being the same folding event, is also the fact that the two lithologies were in contact with one another during deformation. The shortening direction for this $D3^{GM}$- /$D2^{EG}$-macrofolding event is inferred based on orientation data from the $S0^{EG}$ and $S1^{EG}$-fabrics, plotted together in a stereonet (fig. 40). The data yield an overall NNW-SSE trending beta-axis for the macro-scale $F2^{EG}$-folds, which slightly deviates from the approximate N-S shortening direction estimated for the folding of the Tverrfjellet shear zone. Specifically at Middagstind, fold axes trend more NE-SW, subparallel to the general NNW-SSE trending $F2^{EG}$-fold axes in the Ersfjord Granite. This NE-SW-trending fold axis is also subparallel to the $F3^{GM}$-fold axis, possibly suggesting a later realignment or rotation of the fold axes (see section 4.5.5).

4.5.5 D4^{GM} and D3^{EG}-events

If the Ersfjord Granite and surrounding Gråtind Migmatite host rocks are all deformed by the same deformational events (see table 1), it is also likely that the steep, presumed oblique-strike-slip shear zones of the D3^{EG}-event (see chapter 3.4.4) affected the Gråtind Migmatite. Partial evidence of this is found in similar geometry and orientation of steeply dipping shear zones in the Gråtind Migmatite at Tverrfjellet, and the S3^{EG}-shear zones in the Ersfjord Granite at Hatten. Armitage and Bergh (2005) reported the D4^{GM}-event in the Gråtind Migmatite to have produced steeply NE-plunging folds, as well as moderately to steeply dipping, strike-slip shear zones along the Mjelde-Skorelvvatn unit southwest of Tverrfjellet (fig. 9). Observed S3^{EG}-shear zones in the Ersfjord Granite strike on average NE-SW to NNE-SSW and dip steeply (fig. 17), which is subparallel to the axial surfaces of F4^{GM}-folds (Armitage & Bergh, 2005). It is possible that these two events also are from the same deformation event, but expressed differently due to the differences in rheology of the bed rocks. For example, F4^{GM}-folds could have formed in the anisotropic, well-foliated TTG-gneisses, involving sporadic slip along axial surfaces, whereas S3^{EG}-shear zones formed, possibly parallel to the F4^{GM}-axial surfaces in the more competent Ersfjord Granite. If this is the case, a link must be drawn to the D2^{GM}- /D1^{EG}-deformational event, where F2^{GM}-folds developed ubiquitously in the Gråtind Migmatite, only involving occasional slip along axial surfaces (at Tverrfjellet shear zone). The same deformation in the Ersfjord Granite, however, formed F2^{GM}-axial planar S1^{EG}-shear zones.

The axial trace of F3^{GM}-folds in the Gråtind Migmatite, and related steep shear zones, differ systematically in orientation (fig. 19), suggesting they may be refolded by younger, steeply plunging to subvertical F4^{GM}-folds. However, a reliable connection between the D4^{GM} and the D3^{EG}-events cannot be made, since too few orientation data of F4^{GM}-axial surfaces and S3^{EG}-shear zones exist. On the other hand, both sets of shear zones have a NE-SW strike and steep dip, suggesting that the two events are related. This folding event could then be responsible for the later rotation of the southernmost limb of the Tverrfjellet shear zone, as well as the S1^{EG}-shear zones at Middagstind (section 4.5.4; figs. 11, 36)

4.6 Structural and tectonic model

Based on the discussion above, a generalized tectono-magmatic model for the studied structures in the Ersfjord Granite and Gråtind Migmatite is presented below (fig. 41):

1) The oldest structures in the study area belong to the Gråtind Migmatite rocks and are characterized by TTG-gneisses with a well-developed gneissic to migmatitic foliation (S1^{GM}). This fabric pre-dates the intrusion of the Ersfjord Granite, and is thought to be Neoarchean in age (Bergh et al., 2010). It may have formed during a D1^{GM}-thrusting event at moderate to high-grade metamorphic conditions, associated with partial melting, and producing isoclinal F1^{GM}-folds and an axial-planar foliation (fig. 41a). The original orientation of the foliation is

unknown, but it may have been tilted to a steep attitude, most likely prior to the intrusion of the Ersfjord Granite.

2) The next event included the emplacement of the Ersfjord Granite, likely to be a combined intrusion and crustal deformation event. The excess heat from the intrusion of the melt might have contributed to partial melting in the surrounding TTG-gneisses, which could to some extent have been mixed with melts from the Ersfjord Granite during the emplacement of the granite into the crust.

3) The $D2^{GM}$ and $D1^{EG}$-events may have occurred synchronously with, or shortly after the intrusion of the Ersfjord Granite. These events produced macro- and meso-scale asymmetric folding of the steep $S1^{GM}$-foliation in the Gråtind Migmatite rocks, and an axial-planar migmatitic fabric ($S2^{GM}$) which is parallel to the major, Tverrfjellet shear zone (fig. 41b). This deformation is assumed to be the same as the $D1^{EG}$-deformation in the Ersfjord Granite, which formed low-angle $S1^{EG}$-thrusts between imbricate tectonic slices during multiple and progressive phases of tight to isoclinal folding and ductile shear deformation (fig. 41b). Local to regional anatexis took place during the deformation, possibly as a consequence of the intrusion of the granite. The $S2^{GM}$ and $S1^{EG}$-shear zones likely entrained melt material from the surrounding TTG-gneisses into the shear zones during deformation, or otherwise produced zones of weakness that were easily injected by melt at a later stage. Analysis of kinematic indicators such as folds, stretching lineations, boudins and duplexes yield an overall top-to-the WNW directed kinematic transport direction for the $S2^{GM}$-Tverrfjellet shear zone and $S1^{EG}$-shear zones in the Ersfjord Granite. In the latest stages of the deformation, coaxial out-of-sequence thrusts formed near the contacts, as the one observed at Buren.

4) A later $D3^{GM}$- /$D2^{EG}$-event comprised macro-scale folding (fig. 41c) due to crustal shortening in an approximately E-W-direction. This event refolded all the previously formed ductile structures, i.e. the Neoarchean TTG gneiss foliation, the Tverrfjellet shear zone in the Gråtind Migmatite, the Ersfjord Granite contact, the possible magmatic $S0^{EG}$-foliation, and $S1^{EG}$-shear zones in the Ersfjord Granite. Most important, the initial $D2^{GM}$- /$D1^{EG}$-thrust zones were all macrofolded, thus yielding contrasting thrust versus normal slip on either of the macrofolded limbs.

5) The final event involved WNW-ESE crustal shortening and formation of NE-SW to NNE-SSW striking, steep ductile shear zones (fig. 41d), that truncated all other structures in the study area, including $F3^{GM}$- /$F2^{EG}$-macrofolds. These shear zones seem to have formed along axial-surfaces of steeply-plunging folds in the Gråtind Migmatite. This event may also have rearranged the southernmost limb of the Tverrfjellet shear zone, and with it the nearby $S1^{EG}$-shear zones at the contact between the Ersfjord Granite and the Gråtind Migmatite at Middagstind.

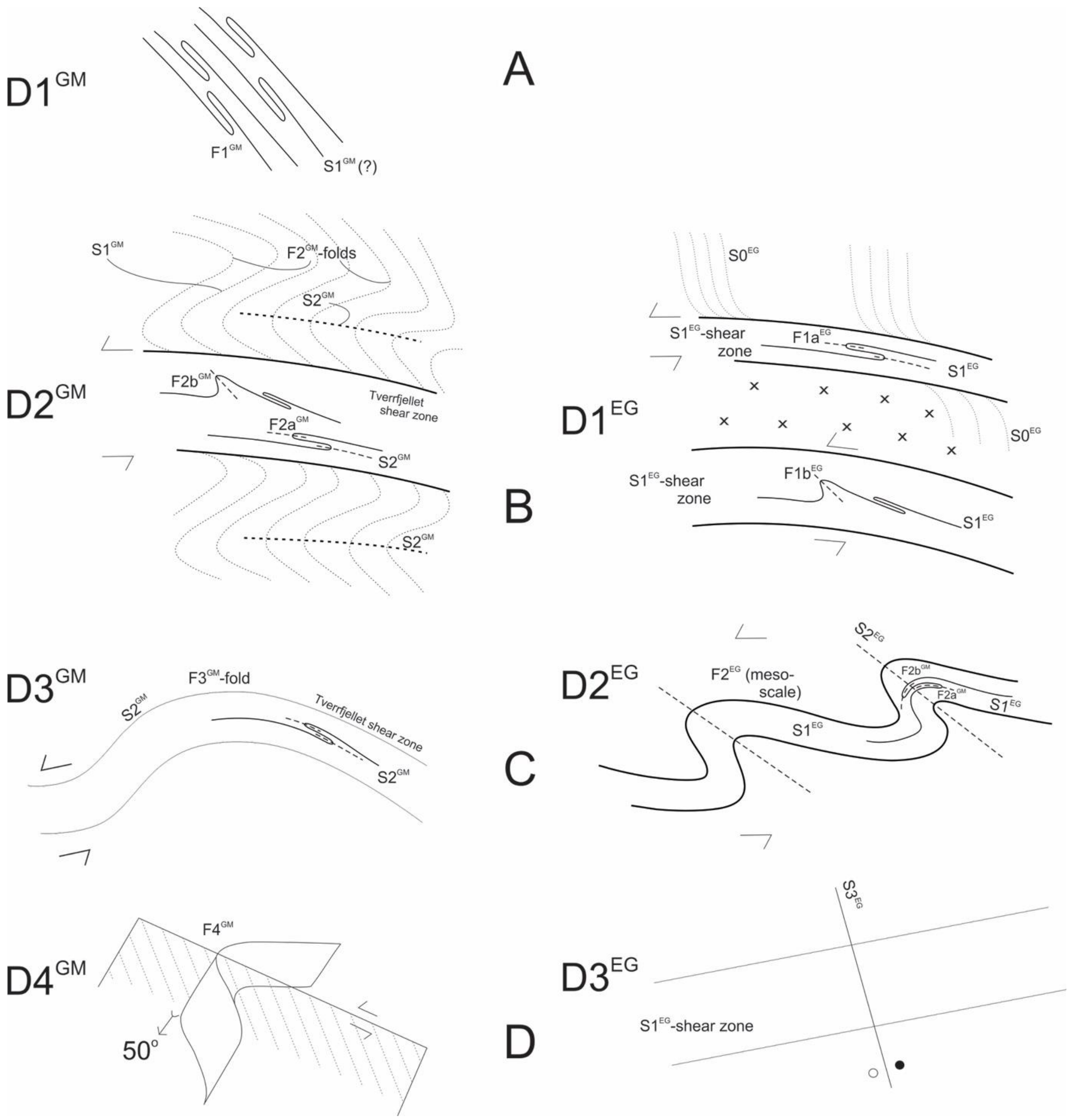

Figure 41. *Structural and tectonic model for the deformation structures in the Gråtind Migmatite and Ersfjord Granite. (A) The D1^GM^-event produced a well-foliated migmatitic texture in the Gråtind Migmatite. (B) During the D2^GM^-event asymmetric S2^GM^-folds formed. At Tverrfjellet, axial-planar slip took place in the low-angled Tverrfjellet shear zone. Internal structures like isoclinal- and asymmetric folds formed, as well as asymmetric clasts, boudins and local stretching lineations. The D1^EG^-event formed low-angled shear zones in the Ersfjord Granite, cross-cutting the magmatic S0^EG^-foliation. Intrafolial structures developed in the S1^EG^-shear zones, similar to those in the S2^GM^-shear zone at Tverrfjellet. (C) Large-scale, F3^GM^- /F2^EG^-folds refolded the shear zones into upright, open to tight folds in both the Ersfjord Granite and the Gråtind Migmatite. (D) Steeply plunging F4^GM^-folds formed with local slip parallel to axial planes. Parallel shear zones formed in the Ersfjord Granite.*

4.7 Regional Implications

This chapter compares and discusses similarities of the studied ductile shear zones in the Ersfjord Granite and surrounding Gråtind Migmatite (table 1) with previous results and tectonic models for the West Troms Basement Complex (chapter 2.3) and the Fennoscandian Shield (chapter 2.2), focusing on the Svecofennian orogeny (chapter 2.3.6).

4.7.1 Relation to West Troms Basement Complex

Previous structural and tectonic studies in the WTBC (e.g. Zwaan & Bergh, 1995; Bergh et al., 2010; Bergh et al., 2014; Bergh et al., 2015) have shown a complex tectono-magmatic history from the Neoarchean through the Paleoproterozoic to the early Mesoproterozoic.

The oldest mapped elements in the study area comprise the low-angled, migmatitic $S1^{GM}$-foliation in the Gråtind Migmatite. These fabrics commonly display a well-foliated, transposed migmatitic fabric assumed to have originated by Neoarchean crustal shortening. $S1^{GM}$-foliation is likely to be a part of the Neoarchean (2.7-2.6 Ga; Myhre et al., 2013), main migmatitic foliation in the TTG-gneisses of WTBC (Bergh et al., 2010). The deformation that formed it involved crustal thickening and underplating in an E-W direction, and possibly synchronous anatexis (fig. 6a).

The intrusion of the Ersfjord Granite occurred slightly before the peak of the Svecofennian deformation events in the WTBC (Bergh et al., 2015), as a part of the bimodal 1.8-1.7 Ga magma intrusions in the region (Andresen, 1980).

The first event recorded to have affected the Ersfjord Granite is the $D2^{GM}$- /$D1^{EG}$-deformation in the study area. This deformation produced a number of folds and low-angle migmatitic shear zones with an overall thrust character of top-to-the WNW. Within the shear zones, a main transposed foliation includes multiple internal, asymmetric tight to isoclinal folds, enclosed granite slivers, and extensive metatexite fabrics. In combination, this suggests that the shear zones formed as part of an imbricate fold-thrust belt system. This may have occurred in an island arc, subduction or underplating setting (cf. Cawood et al., 2009) as a consequence of regional accretionary tectonics during the Svecofennian orogeny (fig. 6c, d, 7a), the D1-event from Bergh et al. (2010). If so, the granite intruded in a partially melted crust, possibly mixing with melted crustal components as they were accreted and stacked in an imbricate thrust system. This might explain the melanosome origin in the low-angled Ersfjord Granite $S1^{EG}$-shear zones as melted inclusions from the nearby supracrustal units, and the leucosomes as injections from the granite.

During this D1-event in the WTBC, low-angle thrusts formed by NE-SW contraction and a main tectonic transport direction to the NE (Bergh et al., 2010). The results from this study, however, show that the movement on low-angle, SE and NW-dipping $S2^{GM}$- /$S1^{EG}$-shear zones recorded in the Ersfjord Granite and Tverrfjellet shear zone had a top-to-the WNW sense of shear. Since the dip direction is nearly opposite, and the shear-sense slightly oblique to the shortening direction for the Svecofennian D1-deformation in WTBC, a likely interpretation is that the $S2^{GM}$ and $S1^{EG}$-shear zones are antithetic thrusts in the regional geological setting (fig. 6). The reason for the oblique WNW sense-of-shear may be that the Svecofennian deformation was affected by the nearby, large Ersfjord Granite, causing local variations in movement directions. Thus, it is reasonable to conclude that the $S2^{GM}$- /$S1^{EG}$-migmatitic shear zones correspond with the D1-Svecofennian deformation event of the WTBC (Bergh et al., 2010; Bergh et al., 2015).

The large-scale, gentle to open $F3^{GM}$ and $F2^{EG}$-folding of the $S2^{GM}$ and $S1^{EG}$-foliations, corresponds well to the D2-event described by (Bergh et al., 2010). This event produced large-scale open to tight folds striking NW-SE, which is subparallel to the N-S strike recorded for the $F3^{GM}$ and $F2^{EG}$-folds (fig. 7b).

The youngest observed deformation features in the Gråtind Migmatite rocks are inferred macro-scale, steeply plunging to subvertical $F4^{GM}$-folds that refolded the axial trace of $F3^{GM}$-folds in the Gråtind Migmatite (fig. 19). This corresponds perfectly with observations further northwest at Mjelde-Skorelvvatn (fig. 7c), where such vertical folds are interpreted as Svecofennian F3-folds (Armitage & Bergh, 2005). This same event is interpreted to have formed the steeply dipping shear zones in the Ersfjord Granite and at Tverrfjellet, also in accordance with the steeply plunging axial-planar shear zones in the rest of WTBC (fig. 7c).

4.7.2 Relation to Fennoscandia

In the context of the Fennoscandian Shield, the Neoarchean deformation events started around 2.9-2.7 Ga (Holtta et al., 2008) and comprised E-W and NE-SW directed crustal shortening, involving subduction of oceanic crust (Lahtinen, 2012). This is older than the 2.8-2.6 Ga (Myhre et al., 2013) deformation structures in the WTBC, which involved E-W directed crustal thickening and underplating (Bergh et al., 2010).

The Svecofennian orogeny in Fennoscandia involved a complex and multiphase tectono-magmatic evolution dated at 1.92-1.79 Ga (Lahtinen et al., 2005). Also, this time span is older than in WTBC (chapter 2.3; Bergh et al., 2015), suggesting that a direct time link cannot be made. As there are clear similarities in the orogenic deformation, however, it is proposed that the same deformation took place, but at a later time in West Troms.

During the last stages of the Svecofennian orogeny in Fennoscandia, the Nordic orogen involved continent-continent collision and large-scale intrusions of granitic melts (cf. Condie, 2007), partially as the oldest intrusions of the Transscandinavian Igneous Belt (TIB) around 1.81-1.77 Ga. The age of the Ersfjord Granite is 1.79 Ga (Corfu et al., 2003) suggesting that it intruded in the very late stages of the Svecofennian orogeny, as it is defined in Finland and

Russia, possibly during the Nordic orogeny. This is the proposed origin of the Lofoten-Vesterålen regions and related tectonic windows (Griffin et al., 1978; Corfu, 2004; Steltenpohl et al., 2004; Corfu, 2007), which should also be considered a possibility for the Ersfjord Granite. It is, however, suggested that the intrusion of the Ersfjord Granite is linked to the formation of the rapakivi granites and related magmatic activity in eastern parts of today's Finland during the early stages of continental collision and underplating of magmatic arcs in the Svecofennian orogeny (Bergh et al., 2015). This suggestion also corresponds well with regional contacts and shear zone architecture in WTBC and the Archean to Proterozoic Fennoscandian basement, as NW-SE directed, regional lineaments are prominent in both domains (figs. 4, 5). Although time spans do not fully correlate, an explanation may be that progressive younging of the deformation has taken place northwestward in the Fennoscandian Shield (cf. Bergh et al. 2015).

5 Conclusions

The main objectives of this study have been to gain an understanding of the implications of internal deformation within the Ersfjord Granite, in particular ductile migmatitic shear zones. Structures in the surrounding Gråtind Migmatite have also been analyzed, in order to give a more complete understanding of the granite and its internal shear zones' relationship to the surrounding lithologies. A tectono-magmatic model for the Svecofennian deformation in the Ersfjord Granite has been proposed and compared to existing models of deformation in the surrounding TTG-gneisses of WTBC, as well as deformation in the Fennoscandian shield.

The tectono-magmatic evolution of the Ersfjord Granite and the Gråtind Migmatite can be summarized by the following five points:

1) Compressional tectonics and possible anatexis created a well-developed migmatitic $S1^{GM}$-foliation in the Gråtind Migmatite, prior to the intrusion of the Ersfjord Granite.
2) The Ersfjord Granite intruded into the lithosphere, possibly during compressional tectonics and crustal thickening. A magmatic $S0^{EG}$-foliation formed during the intrusion.
3) Compression resulted in low-angled thrust zones shortly after or during the late stages of the intrusion of the granite. These shear zones are migmatitic, top-to-the WNW-directed, ductile $S2^{GM}$- /$S1^{EG}$-shear zones.
4) Large-scale, N-S trending, open to tight, upright $F3^{GM}$- /$F2^{EG}$-folds formed during E-W directed crustal shortening and compression.
5) Steeply plunging $F4^{GM}$-folds refold the axial traces of the $F3^{GM}$-folds in the Gråtind Migmatite and the Kattfjord Complex directly west of the study area. Slip took place along steeply dipping, axial-planar $S4^{GM}$- /$S3^{EG}$-shear zones in both the Gråtind Migmatite and Ersfjord Granite.

Links can be made between the tectono-magmatic evolution of the Ersfjord Granite and the late-Svecofennian deformation in the rest of the WTBC, as summarized below:

1) Neoarchean (2.92-2.56 Ga) convergence accreted microcontinents in the WTBC, and formed a well-developed migmatitic foliation throughout the region, analogous to the $S0^{GM}$-foliation in the Gråtind Migmatite.
2) Neoarchean (2.85-2.83 Ga) and Paleoproterozoic (2.4-1.9 Ga) rifting was followed by a new stage of convergence and magmatism (1.9-1.8), likely intruding the Ersfjord Granite into the Neoarchean lithosphere.
3) Accretionary fold-thrust belt formation during the Svecofennian orogeny formed NE-directed, low-angled shear zones throughout the region. The shear zones in the Ersfjord Granite (as well as the Tverrfjellet shear zone in the Gråtind Migmatite) are WNW-directed, suggesting that they are obliquely antithetic to the regional transport direction in the crust. Anatexis caused partial mixing of crustal components.
4) W-E directed crustal shortening formed macro-scale folds with steep fold limbs and upright hinges in WTBC, similar to the N-S trending $F3^{GM}$- /$F2^{EG}$-folds in the Gråtind Migmatite and Ersfjord Granite.
5) The third and final stage of the Svecofennian deformation in WTBC formed large-scale, steeply plunging folds with axial-planar sinistral and dextral slip, oriented parallel to steeply plunging shear zones in the Ersfjord Granite and Gråtind Migmatite at Tverrfjellet.

A direct time link cannot be drawn between the presumed late-Svecofennian deformation of the Ersfjord Granite and WTBC, and the remaining Fennoscandian shield. A younging of the deformation to the northwest toward the margin of Fennoscandia is suggested (cf. Bergh et al., 2015). As a result, the Ersfjord Granite can be considered an intrusion from the continent-continent collision and underplating during the Svecofennian orogeny, associated with magmatic activity and island-arc accretionary tectonics similar to that of eastern and southern parts of today's Finland.

6 References

Åhäll, K.-I., & Connelly, J. N. (2008). Long-term convergence along SW Fennoscandia: 330 my of Proterozoic crustal growth. *Precambrian Research, 161*(3-4), 452-474.

Andresen, A. (1980). The age of the Precambrian basement in western Troms, Norway. *Geologiska Föreningen i Stockholm Förhandlingar, 101*(4), 291-298.

Armitage, P. (2004). Structural geological reconnaissance in the Svanfjellet Shear Zone, Senja, 6-9 Aug. 2004. *Unpublished report, University of Tromsø*.

Armitage, P. E. (1999). Kinematic analysis of a Precambrian metasupracrustal deformation zone between Mjelde and Skorelvvatn, Kvaløya, Troms. *Unpublished Cand. Scient. Thesis, University of Tromsø*.

Armitage, P. E., & Bergh, S. G. (2005). Structural development of the Mjelde-Skorelvvatn Zone on Kvaløya, Troms: a metasupracrustal shear belt in the Precambrian West Troms Basement Complex, North Norway. *Norwegian Journal of Geology, 85*.

Augland, L. E., Andresen, A., Gasser, D., & Steltenpohl, M. G. (2014). Early Ordovician to Silurian evolution of exotic terranes in the Scandinavian Caledonides of the Ofoten–Troms area – terrane characterization and correlation based on new U–Pb zircon ages and Lu–Hf isotopic data. *Geological Society, London, Special Publications, 390*(1), 655-678.

Barbey, P. J. G. B. (2009). Layering and schlieren in granitoids: A record of interactions between magma emplacement, crystallization and deformation in growing plutons (The André Dumont medallist lecture). *Geologica Belgica.*

Bell, T., Reinhardt, J., & Hammond, R. (1992). Multiple foliation development during thrusting and synchronous formation of vertical shear zones. *Journal of Structural Geology, 14*(7), 791-805.

Bergh, S., Corfu, F., Priyatkina, N., Kullerud, K., & Myhre, P. (2015). Multiple post-Svecofennian 1750–1560Ma pegmatite dykes in Archaean-Palaeoproterozoic rocks of the West Troms Basement Complex, North Norway: Geological significance and regional implications. *Precambrian Research, 266*, 425-439.

Bergh, S. G., Eig, K., Kløvjan, O. S., Henningsen, T., Olesen, O., & Hansen, J.-A. (2007a). The Lofoten-Vesterålen continental margin: a multiphase Mesozoic-Palaeogene rifted shelf as shown by offshore-onshore brittle fault-fracture analysis. *Norwegian Journal of Geology, 87*.

Bergh, S. G., Kullerud, K., Corfu, F., Armitage, P. E., Davidsen, B., Johansen, H. W., Pettersen, T., & Knudsen, S. (2007b). Low-grade sedimentary rocks on Vanna, North Norway: a new occurrence of a Palaeoproterozoic (2.4-2.2 Ga) cover succession in northern Fennoscandia. *Norwegian Journal of Geology, 87*(3).

Bergh, S. G. (2010). Svecofennian (c. 1.7 Ga) Shear Zones within the Neoarchaean Kattfjord Complex and its Contact Relationships to the Ersfjord Granite and Pegmatites, Grøtfjord, Kvaløya, Troms. 7.

Bergh, S. G., Kullerud, K., Armitage, P. E., Bouke Zwaan, K., Corfu, F., Ravna, E. J., & Inge Myhre, P. (2010). Neoarchaean to Svecofennian tectono-magmatic evolution of the West Troms Basement Complex, North Norway. *Norwegian Journal of Geology, 90*.

Bergh, S. G., Kullerud, K., Myhre, P. I., Corfu, F., Armitage, P., Zwaan, K., & Ravna, E. (2014). Archaean elements of the basement outliers west of the Scandinavian Caledonides in Northern Norway: architecture, evolution and possible correlation with Fennoscandia. In *Evolution of Archean Crust and Early Life* (pp. 103-126): Springer.

Binns, R. (1983). Rapport om berggrunnsgeologiske undersøkelser på Kvaløy og Ringvassøy, Troms, sommeren 1983. *Norges geologiske undersøkelse Rapport 046/83.016 D*.

Binns, R. (1984). Rapport om berggrunnsgeologiske undersøkelser i Ringvassøy/Kvaløy området, Troms, sommeren 1984. *62*(84.024).

Boyer, S. E., & Elliott, D. (1982). Thrust systems. *Aapg Bulletin, 66*(9), 1196-1230.

Brown, M. (1973). The definition of metatexis, diatexis and migmatite. *Proceedings of the Geologists' Association, 84*, 371-382.

Buchan, K. L., Mortensen, J. K., Card, K. D., & Percival, J. A. (1998). Paleomagnetism and U-Pb geochronology of diabase dyke swarms of Minto block, Superior Province, Quebec, Canada. *Canadian Journal of Earth Sciences, 35*(9), 1054-1069.

Butler, R. (1987). Thrust sequences. *Journal of the Geological Society, 144*(4), 619-634.

Butler, R. W. (1982). Hangingwall strain: a function of duplex shape and footwall topography. *Tectonophysics, 88*(3-4), 235-246.

Cawood, P. A., Kröner, A., Collins, W. J., Kusky, T. M., Mooney, W. D., & Windley, B. F. J. G. S., London, Special Publications. (2009). Accretionary orogens through Earth history. *318*(1), 1-36.

Condie, K. C. (2007). Accretionary orogens in space and time. *Memoirs - Geological Society of America, 200*, 145.

Corfu, F., & Easton, R. J. C. G. (2001). U–Pb evidence for polymetamorphic history of Huronian rocks within the Grenville front tectonic zone east of Sudbury, Ontario, Canada. *172*(1-2), 149-171.

Corfu, F., Armitage, P. E., Kullerud, K., & Bergh, S. G. (2003). Preliminary U-Pb geochronology in the West Troms Basement Complex, North Norway: Archaean and Palaeoproterozoic events and younger overprints. *Norges geologiske undersøkelse, 441*, 61-72.

Corfu, F. (2004). U-Pb Age, Setting and Tectonic Significance of the Anorthosite-Mangerite-Charnockite-Granite Suite, Lofoten-Vesteralen, Norway. *Journal of Petrology, 45*(9), 1799-1819.

Corfu, F. J. C. G. (2007). Multistage metamorphic evolution and nature of the amphibolite–granulite facies transition in Lofoten–Vesterålen, Norway, revealed by U–Pb in accessory minerals. *241*(1-2), 108-128.

Daly, J. S., Balagansky, V. V., Timmerman, M. J., & Whitehouse, M. J. (2006). The Lapland-Kola orogen: Palaeoproterozoic collision and accretion of the northern Fennoscandian lithosphere. *Geological Society, London, Memoirs, 32*(1), 579-598.

Faleide, J. I., Tsikalas, F., Breivik, A., Mjelde, R., Ritzmann, O., Engen, Ø., Wilson, J., & Eldholm, O. (2008). Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes, 31*(1), 82-91.

Forslund, T. (1988). Post-kaledonske forkastninger i Vest-Troms, med vekt på Straumsbukta-Kvaløysletta forkastningen. *Kvaløya [MS thesis]: Tromsø, Norway, University of Tromsø*.

Gaál, G., & Gorbatschev, R. (1987). An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research, 35*, 15-52.

Gee, D. G., Fossen, H., Henriksen, N., & Higgins, A. K. (2008). From the early Paleozoic platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland. *Episodes, 31*(1), 44-51.

Gorbatschev, R., & Bogdanova, S. (1993). Frontiers in the Baltic shield. *Precambrian Research, 64*(1), 3-21.

Gorbatschev, R. (2004). The Transscandinavian Igneous Belt-introduction and background. *Special paper - Geological survey of Finland, 37*, 9.

Grenne, T., Ihlen, P., & Vokes, F. (1999). Scandinavian Caledonide metallogeny in a plate tectonic perspective. *Mineralium Deposita, 34*(5-6), 422-471.

Griffin, W., Taylor, P., Hakkinen, J., Heier, K., Iden, I., Krogh, E., et al. (1978). Archaean and proterozoic crustal evolution in Lofoten–Vesterålen, N Norway. *Journal of the Geological Society, 135*(6), 629-647.

Henkel, H. (1987). *Tectonic studies in the Lansjärv region*. Retrieved from
Henkel, H. (1991). Magnetic crustal structures in northern Fennoscandia. *Tectonophysics, 192*(1), 57-79.
Högdahl, K., Andersson, U. B., & Eklund, O. (2004). *The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution* (Vol. 37): Geological survey of Finland Espoo.
Holtta, P., Balagansky, V., Garde, A. A., Mertanen, S., Peltonen, P., Slabunov, A., Sorjonen-Ward, P., & Whitehouse, M. (2008). Archean of Greenland and Fennoscandia. *Episodes, 31*(1), 13-19.
Indrevær, K., Bergh, S. G., Koehl, J.-B., Hansen, J.-A., Schermer, E. R., & Ingebrigtsen, A. (2013). Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture. *Norwegian Journal of Geology, 93*(3-4).
Kärki, A., Laajoki, K., & Luukas, J. (1993). Major Palaeoproterozoic shear zones of the central Fennoscandian Shield. *Precambrian Research, 64*(1-4), 207-223.
Koistinen, T. (2001). *Geological Map of the Fennoscandian Shield [(Scale 1: 2 000 000)*: Geological Survey of Finland.
Kontinen, A., Käpyaho, A., Huhma, H., Karhu, J., Matukov, D. I., Larionov, A., & Sergeev, S. A. J. P. R. (2007). Nurmes paragneisses in eastern Finland, Karelian craton: provenance, tectonic setting and implications for Neoarchaean craton correlation. *152*(3-4), 119-148.
Kullerud, K., Corfu, F., Bergh, S., Davidsen, B., & Ravna, E. (2006a). U-Pb constraints on the archaean and early proterozoic evolution of the west troms basement complex, North Norway. *Bulletin of the Geological Society of Finland Special Issue I, 79*.
Kullerud, K., Skjerlie, K. P., Corfu, F., & de La Rosa, J. D. (2006b). The 2.40 Ga Ringvassøy mafic dykes, West Troms Basement Complex, Norway: The concluding act of early Palaeoproterozoic continental breakup. *Precambrian Research, 150*(3), 183-200.
Lahtinen, R., Korja, A., & Nironen, M. (2005). Paleoproterozoic tectonic evolution. In Lehtinen, M., Nurmi, P. A., & Rämö, O. T. (Eds.), *Precambrian Geology of Finland - Key to Evolution of the Fennoscandian Shield* (pp. 481-532). Amsterdam: Elsevier B.V.
Lahtinen, R., Garde, A. A., & Melezhik, V. A. (2008). Paleoproterozoic evolution of Fennoscandia and Greenland. *Episodes, 31*(1), 20-28.
Lahtinen, R. (2012). Evolution of the bedrock of Finland: an overview. In *From the Earth's Core to Outer Space* (pp. 47-59): Springer.
Landmark, K. (1973). *Beskrivelse til de geologiske kart" Tromsø" og" Målselv": et snitt gjennom fjellkjeden i Midt Troms. Del II., Kaledonske bergarter*: Tromsø Museum.
Larson, S. Å., & Berglund, J. (1992). A chronological subdivision of the Transscandinavian Igneous Belt—three magmatic episodes? *Geologiska Föreningen i Stockholm Förhandlingar, 114*(4), 459-461.
Lister, G. S., & Snoke, A. W. (1984). S-C Mylonites.
MacKenzie, W. S., Donaldson, C. H., & Guilford, C. (1982). *Atlas of igneous rocks and their textures* (Vol. 12): Longman Harlow.
Mansfeld, J., Beunk, F. F., & Barling, J. (2005). 1.83-1.82 Ga formation of a juvenile volcanic arc-implications from U-Pb and Sm-Nd analyses of the Oskarshamn-Jönköping Belt, southeastern Sweden. *GFF, 127*(2), 149-157.
Melezhik, V. A. (2006). Multiple causes of Earth's earliest global glaciation. *Terra Nova*(18), 130-137.

Mertanen, S., Halls, H., Vuollo, J., Pesonen, L., & Stepanov, V. J. P. R. (1999). Paleomagnetism of 2.44 Ga mafic dykes in Russian Karelia, eastern Fennoscandian Shield—implications for continental reconstructions. *98*(3), 197-221.

Morley, C. J. T. (1988). Out-of-sequence thrusts. *7*(3), 539-561.

Motuza, G., Motuza, V., Beliatsky, B., & Savva, E. (2001). *Volcanic rocks of the Ringvassøya Greenstone Belt (North Norway): implication for the stratigraphy and tectonic setting.* Paper presented at the Journal of Conference.

Myhre, P. I., Corfu, F., & Bergh, S. (2011). Palaeoproterozoic (2.0–1.95 Ga) pre-orogenic supracrustal sequences in the West Troms Basement Complex, North Norway. *Precambrian Research, 186*(1-4), 89-100.

Myhre, P. I., Corfu, F., Bergh, S. G., & Kullerud, K. (2013). U-Pb geochronology along an Archaean geotransect in the West Troms Basement Complex, North Norway. *Norwegian Journal of Geology/Norsk Geologisk Forening, 93*(1).

Nironen, M. (1997). The Svecofennian Orogen: a tectonic model. *Precambrian Research, 86*(1-2), 21-44.

Nyheim, H., Bergh, S., Krogh, E., & Zwaan, K. (1994). *Torsnes-skjærsonen i det vestlige (nord-norske) gneisterreng, Kvaløya, Troms; evidenser for kompleks skorpeforkortning og orogen-parallell oblik strike-slip.* Paper presented at the Nordic Geological Winter Meeting, Luleå.

Olesen, O., Torsvik, T., Tveten, E., & Zwaan, K. (1993). The Lofoten-Lopphavet Project–an integrated approach to the study of a passive continental margin, Summary report. *Unpublished NGU report, Trondheim*.

Olesen, O., Torsvik, T. H., & Tveten, E. (1997). Basement structure of the continental margin in the Lofoten-Lopphavet area, northern Norway: constraints from potential field data, on-land structural mapping and palaeomagnetic data. *Oceanographic Literature Review, 12*(44), 1478.

Passchier, C., & Trouw, R. (2005). *Microtectonics*. Berlin, Heidelberg: Springer.

Pawley, M., Reid, A., Dutch, R., Preiss, W. (2013). *A User's Guide to Migmatites*. Adelaide: Geological Survey of South Australia, Resources and Energy Group.

Pedersen, B. (1997). Strukturell analyses av en prekambrisk, duktilt deformert metasuprakrustalsone (Astridal-skjærsonen?) på NØ-Senja, Troms. *Unpublished Cand. Scient. thesis, University of Tromsø.*

Ramberg, I. B., Bryhni, I., & Nøttvedt, A. (2013). *Landet blir til: Norges geologi* (2nd ed.). Trondheim: Norsk geologisk forening.

Ramsay, J. (1980). Shear zone geometry: a review. *Journal of Structural Geology, 2*(1-2), 83-99.

Roberts, D., & Gee, D. G. (1985). An introduction to the structure of the Scandinavian Caledonides. *The Caledonide orogen–Scandinavia and related areas, 1*, 55-68.

Roberts, D., Melezhik, V., & Heldal, T. (2002). Carbonate formations and early NW-directed thrusting in the highest allochthons of the Norwegian Caledonides: evidence of a Laurentian ancestry. *Journal of the Geological Society, 159*(2), 117-120.

Roberts, D. (2003). The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics, 365*(1), 283-299.

Samsonov, A., Berzin, R., Zamozhnyaya, N., Shchipansky, A., Bibikova, E., Kirnozova, T., & Konilov, A. (2001). Deep Structure Crustal Evolution of the Eastern Fennoscandian Shield: Kem'Kalevala Reflection Profile. *Karelian Research Center, Institute of Geology, Petrozavodsk*, 109-143.

Sawyer, E. W. (2008). *Atlas of migmatites* (Vol. 9): NRC Research Press.
Slabunov, A., Lobach-Zhuchenko, S., Bibikova, E., Sorjonen-Ward, P., Balagansky, V., Volodichev, O., et al. (2006). The Archean nucleus of the Baltic/Fennoscandian Shield. *European Lithosphere Dynamics: Geological Society of London, Memoir, 32*, 627-644.
Steltenpohl, M. G., Hames, W. E., & Andresen, A. (2004). The Silurian to Permian history of a metamorphic core complex in Lofoten, northern Scandinavian Caledonides. *Tectonics, 23*(1).
Stephens, M. B., & Gee, D. G. (1985). A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. In Gee, D. G. & Sturt, B. A. (Eds.), *The Caledonide Orogen—Scandinavia and Related Areas* (pp. 953–970). Chichester: Wiley.
Stephens, M. B., & Gee, D. G. (1989). Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America, Special Paper, 230*, 17-30.
Strachan, R., Holdsworth, R., & Prave, A. (2012). Proterozoic sedimentation, orogenesis and magmatism on the Laurentian craton (2500–750 Ma). In *Geological History of Britain and Ireland* (pp. 54-75).
Volodichev, O., Slabunov, A., Kuzenko, T., Bibikova, E., & Konilov, A. J. P. (2004). Archean eclogites in the Belomorian mobile belt, Baltic Shield. *12*(6), 540-560.
Williams, H., Hoffman, P. F., Lewry, J. F., Monger, J. W., & Rivers, T. (1991). Anatomy of North America: thematic geologic portrayals of the continent. *Tectonophysics, 187*(1-3), 117-134.
Zwaan, K. (1989). Berggrunnsgeologisk kartlegging av det prekambriske grønnsteinsbelte på Ringvassøy, Troms. *Norges geologiske undersøkelse Report, 89*, 101.
Zwaan, K. (1992a). Database for alle geologiske opplysninger om forkastninger og skjærsoner som opptrer på kartblade 1: 250 000. *92*, 24.
Zwaan, K. (1992b). Database for alle geologiske opplysninger om den prekambriske geologien på Kvaløya, Troms fylke. *92*.
Zwaan, K., & Bergh, S. (1995). Geology of the Precambrian West Troms Basement Complex, northern Norway, with special emphasis on the Senja Shear Belt: a preliminary account. *Norges geologiske undersøkelse Bulletin, 427*, 33-36.
Zwaan, K., & Tucker, R. (1996). *Absolute and relative age relationships in the Precambrian West Troms Basement Complex, northern Norway (Abstract).* Paper presented at the 22nd Nordic Geological Winter Meeting, Åbo, Finland.
Zwaan, K., Fareth, E., & Grogan, P. (1998). Geologisk kart over Norge, berggrunnskart Tromsø, M 1: 250.000. *Norges geologiske undersøkelse*.