Assembly of the Caledonian Orogenic Wedge, Jämtland, Sweden

Hagen Bender
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Abstract

Collisional orogeny creates the largest mountain belts on Earth. The Caledonides of Scandinavia are a deeply eroded, ancient mountain belt, which today exposes a deep section through the former orogenic interior. The orogenic internides hold important geological information necessary to understand the geodynamic processes shaping collisional plate boundaries. This thesis explores the kinematics and timing of orogenic wedge formation in Jämtland, central Sweden. An integrated approach of structural field mapping, microstructural analysis, Rb–Sr radiogenic dating and rock magnetism yielded new and comprehensive tectonochronologic data. A regionally extensive network of kinematic field data demonstrated pervasive ductile top-to-the-ESE shearing across the entire tectonostratigraphy. Rb–Sr multi-mineral isochron ages constrained the absolute timing of ductile deformation to c. 430 Ma and c. 415 Ma. Local structural and magnetic data showed that final nappe emplacement and exhumation had occurred before extensional deformation initiated. The new data presented in this thesis contradicted a tectonic model previously proposed for Caledonian nappe stacking. These findings were used to develop an alternative tectonic model consistent with both the new and other available structural, petrological and chronological data. The new model for orogenic wedge assembly comprises three stages of foreland-directed, top-to-the-ESE thrusting. It reflects the complex interactions caused by the merging of two subduction zones accommodating Baltica–arc–Laurentia collisions during Ordovician to Devonian time.

Keywords: collisional orogeny, Scandinavian Caledonides, Seve Nappe Complex, Köli Nappe Complex, in-sequence thrusting, out-of-sequence thrusting, imbrication, nappe stacking, orogenic wedge assembly, Rb–Sr geochronology, rock magnetism, anisotropy of magnetic susceptibility.

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The painting depicts Hagen overlooking Edsåsdalen in Jämtland on one of his first days of fieldwork in 2014. Based on a photograph taken by Anna Semerow.

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Sammanfattning
När kontinenter kolliderar bildas världens största bergskedjor. Skandinaviska Kaledoniderna är en ursprunglig sådan bergskedja som formades genom kollisionen mellan kontinenterna Baltika, en vulkanisk terräng och Laurentia i Paleozoikum. Idag är Kaledoniderna djupt eroderade och därför syns på jordytan de delar av bergskedjan som tidigare befann sig djupt ner i jordkorn. De djupa inre delarna av bergskedjan absorberade stor del av konvergensen mellan de tektoniska platserna vilket ledde till hög deformation. Deformationen och metamorfosen som pågick på djupet under tiden bergskedjan växte, bevarades i berggrundens geometri såväl som kemiska och isotopiska sammansättning av mineral och kan studeras idag. Denna geologiska information kan användas för att rekonstruera bergskedjebildande processer som pågick i djupet, och de som förflyttade berggrunden upp till jordens yta. Den här avhandlingen utforskar kinematiken för bildandet och åldern av dessa bergskedjekärnor bevarade i Jämtland, Sverige.


En kombination av strukturgeologiskt fältarbete, mikrostrukturnalyser, radiometrisk åldersdatering och geomagnetiska mätningar ligger till grund för dessa nya och omfattande tektonokronologiska data. Storskalig kartering och insamling av strukturdatala visade att hela skollstapeln skjutades mot ostsydost. Åldersbestämning, med hjälp av Rb–Sr multimineralisochroner, daterar dessa strukturer till cirka 430 Ma och 415 Ma. Lokala strukturer och geomagnetiska data tyder på att slutskedet av exhumationen i Jämtländska skollstapeln skedde innan senorogenetisk extension inleds. Data presenterad i denna avhandling motsäger extrusionskilmodellen. Därför togs en ny tektonisk modell fram som tar hänsyn till alla nya samt redan tillgängliga data. Modellen innebär en
utveckling i tre steg bestående av olika ostsydost-riktade överskjutningsfaser. Två samtida men dynamiskt orelaterade faser skedde ca 430 Ma och den tredje fasen ca 415 Ma. Denna Modell återspeglar växelverkan mellan två subduktionszoner i kollisionerna mellan Baltika, den vulkaniska terrängen, och i slutänden Laurentia.
Zusammenfassung


Ein kombinierter Ansatz aus strukturgeologischer Kartierung, Mikrostrukturanalyse, radiometrischer Gesteinsdatierung und Gesteinsmagnetismus ergab einen neuen und umfangreichen tektonochronologischen Datensatz. Flächen-deckend kartierte strukturgeologische Geländedaten zeigten an, dass der
List of papers and author contributions

This doctoral thesis consists of a summary and three papers. The papers are referred to as Paper I–III in the text.


Field work for **Paper I** and **II** was carried out by Hagen Bender during two field seasons with assistance from Uwe Ring in both field campaigns, and from Bjarne Almqvist, Johannes Glodny, Bernhard Grasemann in one campaign. For **Paper I**, Hagen Bender conducted processing of field data and microstructural analysis, wrote the initial draft and created figures and tables. All authors contributed with interpretation of the results and editing of the manuscript. For Rb–Sr dating in **Paper II**, Hagen Bender and Johannes Glodny carried out TIMS analysis including mineral separation and chemistry, and interpreted the data. Hagen Bender wrote the initial draft and created figures and tables with help from Johannes Glodny. All authors contributed with interpretation of the results and editing of the manuscript. Field work for **Paper III** was carried out by Hagen Bender and Amanda Bergman. Hagen Bender and Bjarne Almqvist conducted the magnetic experiments, processed and interpreted the results. Hagen Bender created figures and tables and wrote the initial draft, which was edited by all co-authors.

The following paper on work carried out during this PhD is not included in this thesis:

Bender, H., Schneider, D.A., Ring, U. Limited success dating pseudotachylite from the Köli Nappe Complex, Jämtland, central Sweden, by in-situ $^{40}$Ar–$^{39}$Ar geochronology. Manuscript.
Glossary
Footwall versus hanging wall – A rock unit is called footwall beneath a dipping fault; hanging wall above it (cf. Figure 1).

Foreland versus hinterland – The foreland describes the frontal part of an orogen, which typically only involved deformation in the upper crust. The hinterland depicts the internal part of an orogen, where deformation has affected deeper parts of the crust and locally the lithospheric mantle. Exhumed high-grade metamorphic rocks are found in this zone.

In-sequence versus out-of-sequence thrusting – In-sequence propagation of thrusts means that future thrusts form in front of active thrusts with regard to their transport direction; out-of-sequence thrusts develop behind active thrusts. In-sequence thrusting progressively adds foreland-derived thrust sheets to a nappe stack from below. Out-of-sequence thrusts propagate hinterland-directed (backwards), and can therefore cut out previously assembled nappe stacks in their foreland (cf. Figure 6b).

Inverse metamorphic zonation – A change in metamorphic grade across different tectonic units is called inverse metamorphic zonation when metamorphic grade increases towards higher structural level. It indicates that high-grade metamorphic units have been emplaced on top of lower-grade units.

Lithosphere – The strong outer layer of the Earth comprising the crust and uppermost mantle. The lithosphere lies above the asthenosphere, a weak layer in the upper mantle.

Nappe – Tectonic unit bound by shear zones, typically formed by thrusting.

Normal fault versus thrust (fault) – Normal faults cause downward displacement of the hanging wall in respect to the footwall. Thrusts display upward displacement of the hanging wall, and most commonly refer to shallowly dipping ductile shear zones along which considerable movement of up to hundreds of km took place (cf. Figure 1).

Orogenic wedge – Lithospheric-scale tectonic unit containing thrust sheets accreted from the converging tectonic plates (Figure 6). Not to be confused with extrusion wedge (cf. section 1.2).

Orogeny – Geodynamic processes leading to the formation of mountain belts, caused by lithospheric thickening at convergent plate boundaries.
Pseudotachylyte – Quenched frictional melt formed in a fault zone during seismic slip.
1 Introduction

1.1 Collisional orogeny
When two continents collide at a convergent plate boundary, the lithosphere thickens and large mountains form in response. During mountain building, rocks are subjected to progressive deformation and metamorphism on their paths through the lithosphere. A rock exposed at the Earth’s surface represents the final state of such a path, which is recorded by the structures and compositions of minerals assembling the rock. Geometrical, geochemical and isotopic data collected from rocks can therefore be used to reconstruct their temperature–pressure–time–deformation paths, which in turn reveals insight to the orogenic processes involved.

Collisional orogens commonly have a similar architecture, characterized by several major tectonic elements observed in different orogens worldwide (Frisch et al., 2011). One of these elements is a high-grade metamorphic zone occupying the central parts of an orogen (Grasemann and Huet, 2016). This inner zone represents former sections of the orogenic middle and lower crust, which is thought to accommodate large amounts of shortening between the two colliding continents (Cottle et al., 2015). Exposed at the Earth’s surface today, the exhumed high-grade inner zone is typically found sandwiched between tectonic units recording significantly lower metamorphic grade (e.g., Trouw, 1973; Le Fort, 1975; Andréasson and Gorbatschew, 1980). Therefore, these orogenic internides are an excellent geological archive for studying both the processes that accreted them at depth and those that brought them up to the surface.

1.2 Exhumation in collisional orogens
The striking presence of a metamorphic sandwich zonation in both the Himalayas and the Scandinavian Caledonides has motivated comparisons of the geodynamic processes that shaped these orogens (Gee et al., 2010; Labrousse et al., 2010; Streule et al., 2010). In particular, exhumation of the Caledonian high-grade inner zone has been explained by the extrusion wedge model. This model envisions a tapered central unit that is exhumed between two synchronously active, opposite-sense shear zones (Figure 1). Pervasive ductile deformation is required within the extruding wedge (Grujic et al., 1996; Beaumont et al., 2001). Exhumation is accomplished by simultaneous movement of the central unit above a basal thrust and beneath a normal fault in its top during overall convergence (Ring and Glodny, 2010). The extrusion wedge model is consistent with structural,
petrological and geochronological data collected from the Himalayan orogenic wedge (e.g., Grujic et al., 1996; Beaumont et al., 2001; Godin et al., 2006), although recent work suggests a more complex tectonic evolution (Cottle et al., 2015). In any case, application of the extrusion wedge model in the Scandinavian Caledonides, yet locally supported (Grimmer et al., 2015), rests on sparse hard data and therefore demands thorough testing. Structural field data are critical for determining whether the shear zones bounding the Caledonian high-grade metamorphic zone display opposite kinematics. Geochronological data are necessary to constrain whether these shear zones were active contemporaneously. These data are crucial to either support or reject the proposed tectonic similarities between the Scandinavian Caledonides and the Himalayan orogen. Moreover, the Scandinavian Caledonides underwent substantial post-orogenic extension (Andersen, 1998; Fossen, 2000). At what time convergence switched to extension is debated, and how this switch affected nappe stacking in Jämtland remains controversial. One major question, framing the above issues, guided the work presented in this thesis:

How and when was the metamorphically zoned Jämtland nappe stack assembled?

2 Background

2.1 The Scandinavian Caledonides in central Sweden

The Caledonian orogen resulted from Paleozoic convergence between Baltica and Laurentia, which involved initial accretion of volcanic arc terranes to Baltica and final continental collision with Laurentia following closure of the intervening Iapetus Ocean (Gee, 1975; Stephens, 1988; Andréasson, 1994). In Jämtland, central Sweden, the Scandinavian Caledonides are composed of nappe complexes that contain Baltica- and Iapetus-derived rocks (Figure 2; Gee et al., 2010;
Bergman et al., 2012). The Iapetus-derived Köli Nappe Complex at the top of the nappe pile mainly consists of calcareous phyllites and mica schists metamorphosed at greenschist to amphibolite facies conditions (Figure 3; Sjöstrand, 1978; Beckholmen, 1984; Stephens and Gee, 1989). The underlying Seve Nappe Complex contains mica schists, paragneisses and amphibolites that originated from the outermost extended Baltica margin (Trouw, 1973; Sjöstrand, 1978; Svenningsen, 2001). It contains several thrust sheets that record up to eclogite or ultrahigh-pressure conditions, which indicates they have been subducted to mantle depths (van Roermund, 1985; Majka et al., 2014; Klonowska et al., 2016). During their exhumation, the deeply-subducted units were migmatized in the granulite facies (Majka et al., 2012; Ladenberger et al., 2014; Klonowska et al., 2017). Subsequently, the entire Seve Nappe Complex was affected by amphibolite-facies metamorphism (Bergman, 1992; Giuntoli et al., 2018). Beneath the Seve Nappe Complex, with decreasing structural position, lie the Särv Nappes, Offerdal Nappe and Lower Allochthon derived from progressively more proximal domains of the Baltica margin (Gee, 1975). All these units record not more than upper greenschist facies metamorphism (Andreasson and Lagerblad, 1980; Gilotti and Kumpulainen, 1986; Lindqvist, 1990). In summary, the Jämtland nappe stack is metamorphically zoned: peak metamorphic conditions are expressed in the central Seve Nappe Complex and decrease both structurally up- and downwards.

Figure 2. (a) Regional map of northern Europe showing the location of the Scandinavian Caledonides (shaded area). (b) Geological map of central Sweden and Norway.
Kinematic constraints and development of the extrusion wedge hypothesis in central Sweden

In central Sweden, structural evidence of nappe stacking is controversial. Thrust faulting with top-to-the-SE kinematics is well documented at the base of the Seve Nappe Complex (Trouw, 1973; Zwart, 1974; Sjöström, 1983; Bergman and Sjöström, 1997). However, contrasting field evidence is documented from the top of the complex and in its hanging-wall shear zone. In Jämtland, thrust-sense top-to-the-SE shearing is dominant, especially during amphibolite-facies nappe stacking (Figure 3a). Subordinate top-to-the-W shear sense criteria have been interpreted to postdate nappe stacking (Bergman and Sjöström, 1997). In Västerbotten (Figure 2b), normal-sense top-to-the-NW shearing is documented related to nappe emplacement (Trouw, 1973; Grimmer et al., 2015).

Naturally, the remarkable metamorphic sandwich zonation and conspicuous kinematic data prompted a number of authors to discuss the extrusion wedge model for the central Scandinavian Caledonides. Discussing a study by Greiling et al. (1998), Rice (1999) proposed to apply the channel flow model (Grujic et al., 1996) to the Seve Nappe Complex. Rice (1999) argued that ductile extrusion of
the Seve Nappe Complex between synchronous, opposite-sense shear zones was coeval with high-grade metamorphism in the Seve Nappe Complex and low-grade metamorphism in the Lower Allochthon below and Köli Nappe Complex above. This discussion was based on the documentation of top-to-the-NW shear sense indicators at the Seve–Köli contact by Greiling et al. (1998). These authors, however, argued that their top-to-the-NW shear sense criteria related to brittle, post-metamorphic deformation (Greiling et al., 1999). They interpreted these fabrics as back faulting caused by changes of the critical taper angle (Davis et al., 1983) in a brittlely deforming orogenic wedge. Gee et al. (2010) seized this discussion and stated that the extrusion wedge hypothesis requires testing in the central Scandinavian Caledonides. In 2015, Grimmer et al. (2015) presented structural and geochronological data locally favoring the extrusion wedge interpretation for the Västerbotten section across the Scandinavian Caledonides.

In the light of these data, the following aspects conflict with applying the extrusion wedge model to the central Scandinavian Caledonides:

- In Jämtland, no regionally extensive top-to-the-WNW shear zone above the Seve Nappe Complex has yet been documented (Figure 3a).
- The relation between metamorphism and deformation has been interpreted differently. It is therefore unclear at which depth in the orogen the nappes were assembled.

2.3 Chronologic constraints and paleotectonic evolution
The Jämtland nappe stack accreted prior to, during and immediately following final closure of the Iapetus Ocean during the Silurian to Devonian (Stephens and Gee, 1989). This episode is called the Scandian phase of Caledonian orogeny (Gee, 1975; Roberts, 2003). It encompasses processes leading up to and during the ultimate continent–continent collision between Baltica and Laurentia at c. 430 Ma (Figure 3b; Stephens and Gee, 1985; Soper et al., 1992; Torsvik et al., 1996). Prior to continental collision, two subduction zones were active: Iapetus subducted westward beneath Laurentia until c. 437 Ma (Nordgulen et al., 1993; Slagstad et al., 2011), while farther east the extended Baltica margin subducted beneath an island arc terrane (Stephens and Gee, 1989; Brueckner and van Roermund, 2004; Majka et al., 2014). Subduction–exhumation of the extended Baltica margin was recorded in the Seve Nappe Complex by ultrahigh-pressure metamorphism at c. 460 Ma (e.g., Brueckner and Van Roermund, 2007; Fassmer et al., 2017; Klonowska et al., 2017) followed by granulite-facies migmatization at c. 440 Ma (Majka et al., 2012; Ladenberger et al., 2014). While these processes
occurred at great depth, the volcano-sedimentary protoliths of the Köli Nappe Complex formed until c. 433 Ma in the Iapetus domain (Stephens et al., 1985; Dunning and Pedersen, 1988; Slagstad and Kirkland, 2017). Contemporaneously, the precursor of the Lower Allochthon was deposited until 433 Ma in the foreland (Gee, 1975). In summary, stratigraphic, petrologic and geochronologic data imply that the Seve Nappe Complex had already subducted into the mantle and exhumed back to the lower crust by the time the precursors of its future footwall and hanging wall were still depositing.

These chronologic constraints leave the following aspect unresolved:

• Timing of deformation in Jämtland can only be deduced relatively from other dated geological processes. Absolute age data are needed to understand the precise timing of nappe stacking beneath, within and above the Seve Nappe Complex.

2.4 Late-stage brittle deformation
Large-scale extension followed the contractional Scandian phase (Andersen, 1998; Fossen, 2000). Extensional deformation is remarkably expressed in crustal-scale shear zones that cut across the Caledonian nappe architecture (Norton, 1986; Fossen, 1992). An example is the Røragen Detachment in W Jämtland, where brittle top-to-the-WNW normal faults offset nappe boundaries (Figure 3a; Gee et al., 1994; Bergman and Sjöström, 1997). The overprinting relationship between these structures indicates that nappe assembly predated normal faulting in the upper crust. However, the Köli Nappe Complex, which is transected by the Røragen Detachment, holds evidence that the nappes within it also accreted in the upper crust. Ductile to brittle fault zones separating these nappes are associated with pseudotachylytes (Beckholmen, 1982), which generally form at the base of the upper crust (Sibson and Toy, 2006). Nevertheless, kinematics of the fault zones in the Köli Nappe Complex is unknown.

The role of brittle deformation in the Köli Nappe Complex is enigmatic:

• Pseudotachylyte-bearing faults are currently incompletely understood. Constraining their relation to earlier and later deformation stages is vital to explain final exhumation of the Köli Nappe Complex.
3 Thesis aims
The work presented in this thesis was carried out to answer three specific aims:

1. To create a regionally extensive tectonochronologic data set by collecting new kinematic field data and radiogenic ages for the Caledonian nappe stack in Jämtland.

2. To use the new data to test the extrusion wedge model for explaining the observed metamorphic zonation. If data and model are incompatible, an alternative tectonic model will be proposed.

3. To elucidate final nappe emplacement in the Jämtland nappe stack in relation to brittle extensional structures.

4 Overall approach and methods
This project focused on constraining the kinematics and timing of deformation in the Caledonian orogenic wedge in Jämtland to answer the aims set out above. Geological field data and microstructural analysis constitute the foundation of all studies involved in this project. Two additional approaches were taken to complement these results. Absolute timing of deformation was dated using Rb–Sr multi-mineral isochrons. Furthermore, magnetic properties of fault rocks were studied to identify deformation mechanisms during seismic faulting that caused final imbrication of the nappe pile.

4.1 Field work and microstructural analysis
Field work involved documenting and photographing structural and petrographic observations, measuring orientations of structures, collecting oriented samples for microstructural, geochronological and geophysical analysis and locating outcrops by GPS in order to later compile all data into a geological map (Figure 4). Accumulated ductile deformation causes preferred orientation of minerals in rocks. These orientations are generally expressed as foliations and lineations (Figure 4b). Together these fabric elements show the direction of movement during deformation. In a cross section perpendicular to the foliation and parallel to the lineation, structures with monoclinic symmetry indicate the sense of shearing. Common sense of shear indicators include minerals with wings or strain shadows, mica fish and foliation deflection (Figure 4c; Passchier and Trouw, 2005). Minerals in these fabrics allow to infer pressure–temperature conditions during their formation, which in turn indicates at what approximate depth in the crust the rocks were deforming (Stünitz, 1998). Both on outcrop and microscope scale,
kinematic analysis utilizes all this information for reconstructing the movement of particles in a rock during deformation (Figure 4b–c). The kinematic data are plotted in a geological map (Figure 4d) and are used together with other geological data for testing/developing tectonic models at the orogen scale.

Figure 4. Schematic work flow for structural field work and kinematic analysis. (a) Geological map containing geographical information, distribution of tectonic units in different colors and a marked sampling location. (b) Synoptic illustration of an oriented rock sample. Foliation is expressed as subhorizontal cleavage planes. Lineations are shown as aligned elongated minerals or mineral aggregates. Lineation L1 in the host rock is older than lineation L2 in the shear zone, as indicated by their cross-cutting relationship. (c) Thin sections A and B, marked as red squares on the hand sample in b, and interpretative sketches of the observed structures. Top-to-the-ESE sense of shear is indicated for both the host rock (L1) and crosscutting shear zone (L2). (d) Final structural map with kinematic data plotted on top of the geological map.
4.2 Geochronology

4.2.1 The $^{87}$Rb–$^{87}$Sr system

The underlying principle for determining absolute ages of geological processes is the decay of radioactive parent isotopes to their stable daughter isotopes. The Rb–Sr method is based on the decay of the radionuclide $^{87}$Rb to radiogenic $^{87}$Sr. In a Rb-bearing mineral, decay of $^{87}$Rb will therefore increase the amount of $^{87}$Sr over time, given that Rb and Sr cannot be transferred between the mineral and its surrounding phases. Due to distinct chemical affinity of Rb and Sr, different minerals incorporate these elements to a different degree. Rb commonly substitutes into K-bearing minerals such as white mica, biotite and K-feldspar. Sr commonly substitutes into Ca-rich minerals as plagioclase, apatite and calcium carbonate.

When multiple minerals containing different amounts of Rb and Sr crystallize simultaneously, they will consequently produce different amounts of $^{87}$Sr over time. This proportionality is shown by a straight line, called isochron, that connects different ratios of $^{87}$Rb/$^{86}$Sr and $^{87}$Sr/$^{86}$Sr. An isochron can only be obtained if the following conditions are met: (1) all minerals contained the same initial ratio of $^{87}$Sr/$^{86}$Sr ($S_{ri}$, Figure 5a) at $t=0$, and (2) no mineral exchanged Rb or Sr since that time. With time, the slope of the isochron increases (Figure 5b, c). The slope $m$ of the isochron is used to calculate the time $t$ using the equation

\[ t = \frac{1}{\lambda} \ln (m + 1) \]

where $\lambda$ is the decay constant of $^{87}$Rb in $y^{-1}$. The initial $^{87}$Sr/$^{86}$Sr ratio is marked by the intercept of the isochron with the y-axis (for a comprehensive overview, see Faure and Mensing, 2005).

4.2.2 Dating ductile deformation using Rb–Sr multi-mineral isochrons

Minerals in ductily deforming rocks are continuously recrystallizing, which causes isotopic resetting between the minerals composing them (Müller et al., 2000; Reddy et al., 2003). Such mineral assemblages, especially those containing white mica, are particularly useful to directly date ductile deformation because they also record geometrical and geochemical information to reconstruct kinematics and metamorphism of deformation (Müller et al., 2000). When ductile deformation ceases, recrystallization stops as well and the “Rb–Sr clock starts ticking”. Provided that no thermally induced diffusion resets the isotopic systems of a deformed rock, Rb–Sr multi-mineral ages date the waning stages of deformation (Freeman et al., 1997; Cliff and Meffan-Main, 2003). While some minerals stop recrystallizing earlier, for example, due to decreasing metamorphic
conditions or decreasing strain rate (minerals A, B, C; Figure 5b); others may continue to do so for longer or experience renewed recrystallization at later time (minerals X, Y, Z; Figure 5b). Cautious microstructural analysis and skillful sample preparation allow to separate the minerals belonging to these different processes, and to determine their ages (Figure 5c). For a more detailed description of this approach and for the applied analytical techniques, the reader is referred to section 4 in Paper II, as well as to Glodny et al. (2008).

4.3 Rock magnetic properties
All materials magnetize when subjected to an applied magnetic field. Magnetic susceptibility is the quantitative measure of magnetization in a material caused by a magnetic field. Three fundamental responses can be classified in pure materials: diamagnetic, paramagnetic or ferromagnetic (Butler, 1998). Additionally, minerals display anisotropy of magnetic susceptibility (AMS), which means that minerals show different magnitudes of magnetic susceptibility in different directions. AMS is described in terms of an ellipsoid defined by its principal axes, which correspond to the magnitudes of the maximum, intermediate and minimum susceptibility, respectively (Hrouda, 1982). Shape and crystallographic properties of minerals control their magnetic anisotropy. AMS in rocks simply sums all magnetic responses from the rock-forming minerals (Borradaile, 1987). Since different minerals show different types of magnetization, it is important to
understand the magnetic carriers when interpreting magnetic anisotropy of rocks. In structural geology, AMS is especially useful for determining preferred orientations of shape or crystallographic preferred orientations in deformed rocks. This information can be used to infer tectonic shortening or stretching directions, or even kinematics (Borradaile and Jackson, 2010). For descriptions of experimental setups and details about the kinematic interpretation of AMS, the reader is referred to paper III and references therein.

5 Key results and discussion

5.1 Paper I

Paper I, Metamorphic zonation by out-of-sequence thrusting at back-stepping subduction zones: Sequential accretion of the Caledonian internides, central Sweden, discusses the assembly of the Caledonian orogenic wedge in Jämtland supported by structural field data. Kinematic field data and structural analysis presented in Paper I expanded a local data set from central Jämtland and added new kinematic data for northern Jämtland. Available petrological and geochronological data were summarized to support the structural data.

In the Caledonian orogenic wedge in central Sweden, peak metamorphism is exhibited in units that are sandwiched between lower-grade units (Trouw, 1973; Andréasson and Gorbatschev, 1980). North of Jämtland, a wedge extrusion model has been proposed to explain this metamorphic zonation (Figure 1; Grimmer et al., 2015). While, north of Jämtland, the sense of shear reverses from lower to higher structural levels (Trouw, 1973; Grimmer et al., 2015), kinematic data from Jämtland are inconclusive (Figure 3a; Bergman and Sjöström, 1997). To test the extrusion wedge hypothesis in Jämtland, shear sense criteria were systematically mapped along two transects in northern and central Jämtland (Figure 2b).

Our new field data document abundant top-to-the-ESE shear fabrics on all structural levels in the Jämtland nappe stack, indicating pervasive foreland-directed thrusting across all nappes and their boundaries. These structural data are incompatible with wedge extrusion, which is one of the major outcomes of this study. Ductile deformation fabrics postdate the ultrahigh-pressure textures, and only developed during the waning stages of migmatization. The mylonitic fabrics generally occur in two groups: (1) higher-grade structures related to metamorphism typically occurring in the mid-crust and (2) lower-grade structures related to metamorphism that is typical at middle to upper crustal depth.
(a) Onset of continental collision: two subduction zones merged after 433 Ma

(b) Stages I & II: assembly of Jämtland nappe stack at c. 430 Ma

(c) Stage III: imbrication of Jämtland nappe stack at c. 415 Ma

Tectonic elements
- upper plate (Laurentia)
- oceanic plate and micro continent (Iapetus)
- lower plate (Baltica)
- accretionary/orogenic wedge
- fold- and thrust belt and foreland basin
- lithospheric mantle
- active/future shear zone

Jämtland nappe stack
- Köli Nappe Complex
- Seve Nappe Complex
- Offerdal and Särv Nappe Complex
- Lower Allochthon
- active thrust fault
- future thrust fault
Additionally, foliation-parallel boudinage and scattered top-to-the-WNW kinematic indicators imply general shear deformation, which means that overall top-to-the-ESE-directed shearing involved significant horizontal flattening. Overprinting of higher-grade by lower-grade fabrics suggests progressive exhumation during nappe transport. Concurrent thrusting and thinning exhumed the nappe stack through removing overburden by vertical thinning in its hanging wall and repeated accretion of units from below.

Summarizing available petrological and geochronological data showed that the exhumation of deeply-subducted parts of the Seve Nappe Complex to the lower crust pre-dated the onset of continental collision between Baltica and Laurentia (Figure 6a). This tectonic setting featuring two subduction systems served as input for developing an alternative tectonic model supported by our results and available data. We proposed a three-stage thrust model that generated the metamorphic zonation by combined in- and out-of-sequence thrusting. Two dynamically unrelated stages assembled the nappe stack in the mid-crust, and were followed by a third stage of imbrication at shallower crustal depth. In **Stage I**, the lower part of the Jämtland nappe pile beneath the Seve Nappe Complex assembled in-sequence related to subduction of the Baltica extended margin (Figure 6a–b). In **Stage II**, the upper part of the nappe pile thrust out-of-sequence atop the Seve Nappe Complex during final Baltica–Laurentia collision. This out-of-sequence thrusting was caused by back-stepping of Baltica subduction from beneath a volcanic arc to beneath Laurentia (Figure 6b). In **Stage III**, the Jämtland nappe stack imbricated due to protracted orogenic wedge propagation while Baltica continued to underthrust Laurentia (Figure 6c).
5.2 Paper II
Paper II, *Absolute timing of Caledonian orogenic wedge assembly, central Sweden, constrained by Rb–Sr multi-mineral isochron data*, further develops the tectonic model proposed in Paper I by directly dating deformation-related fabrics the model is based on. Rb–Sr multi-mineral isochrons provided the first absolute ages for mylonitic deformation that constructed the Jämtland nappe stack. The results supported the model proposed in Paper I.

Seventeen samples, collected during structural mapping presented in Paper I, yielded 16 deformation ages, four ages providing indirect deformation age constraints and one age indicating cooling at greenschist facies. Thirteen isotopic ages for mylonites showed that Stages I and II of nappe assembly occurred simultaneously at c. 430 Ma (Figure 6b). Three deformation ages revealed that certain rocks in the top, center and bottom of the nappe pile also deformed at c. 414 Ma. That is about 15 Myr after the nappe stack had been built in the mid-crust. Petrological observations suggest that the nappe pile cooled slowly within these approximately 15 Myr. We concluded that the composite nappe pile was being imbricated while it slowly exhumed to the upper crust. This represented Stage III of thrusting in Jämtland (Figure 6c).

The three-stage thrust model was discussed in a wider regional geological framework integrating studies from more internal parts of the Caledonian orogen in SW Norway. There, Baltica-derived tectonic units record subduction-related metamorphism with progressively younger ages at progressively lower structural depth. The youngest ages of subduction metamorphism in SW Norway are synchronous with Stage III ages in Jämtland. The compatibility of these age constraints supports a coherent model for Baltica–arc–Laurentia collision in central Scandinavia.

5.3 Paper III
Paper III, *Rock magnetic properties of pseudotachylytes, Jämtland, Sweden*, relates brittle faulting associated with assembly of nappes within the Köli Nappe Complex with earlier ductile and later deformation phases. We studied field relationships and structures of pseudotachylyte-bearing fault zones in the Köli Nappe Complex in W Jämtland. To constrain kinematics of these fault zones, microstructural and magnetic fabrics of pseudotachylyte in foliation-parallel fault veins and their host rock have been investigated. Oriented, around 5-mm long, cube-shaped specimens of the different rock types were prepared for magnetic experiments. Rock magnetism results revealed inverse proportionality between specimen size and AMS degree. Analysis of specimen dimensions showed that
this effect does not alter the implications drawn from AMS interpretations. This finding highlighted the necessity for cautious sample preparation when applying the AMS method for specimens much smaller than conventional samples. Magnetic anisotropy of pseudotachylyte indicated that flow direction in the seismic friction melts was parallel to the ductile stretching direction in the host rock. However, the magnetic fabric did not allow to deduce the seismic slip direction. Nevertheless, field and microstructural data demonstrated that E–W extensional deformation postdated movement along the studied fault zones. We concluded that the pseudotachylytes most probably formed late by out-of-sequence thrusting within the seismogenic zone during exhumation of the Jämtland nappe stack into the upper crust. Seismic faulting in the Köli Nappe Complex occurred during Stage III of thrusting in Jämtland (Figure 6c).

6 Summary and conclusion
The results presented and discussed in this thesis contributed to better understand the nappe structure and tectonic processes in the Scandinavian Caledonides. In Paper I, systematically mapped shear sense criteria demonstrated pervasive top-to-the-ESE general shear across the Caledonian tectonostratigraphy in Jämtland. In Paper II, Rb–Sr isotopic data provided absolute deformation ages for the kinematic field data. Although only partially successful, the magnetic and microstructural study presented in Paper III suggested final nappe stacking by seismic faulting. These new kinematic and geochronological data illustrated that the observed metamorphic sandwich zonation in Jämtland did not originate from an extrusion wedge. Instead, the results are compatible with a new tectonic model developed in Paper I, which explains Caledonian orogenic wedge assembly by a three-stage thrust model.

7 Unresolved questions, open problems and future work
This thesis proposes a new model for the Caledonian orogenic wedge assembly in central Sweden. Consequently, this model requires testing by different methodologies in future investigations. Several aspects of the Scandinavian Caledonides, which are vital for the suggested tectonic evolution, remain enigmatic and invite for future work:

(1) Nature and remnants of the volcanic arc. The existence of an intra-oceanic arc terrane within Iapetus has long been hypothesized (Stephens et al., 1985; Stephens and Gee, 1989) in the Köli Nappe Complex and plays an important role in previous (Stephens and Gee, 1989;
 Andréasson, 1994; Roberts, 2003; Brueckner and van Roermund, 2004) and recent (Majka et al., 2014; Paper I) models proposed for Caledonian orogen dynamics. However, geological evidence of this terrane only exists for the late Cambrian to Early Ordovician (c. 490–480 Ma) part of the tectonic evolution, probably influenced by the interference of continental collision and general low preservation potential of intra-oceanic arcs in collision zones (Draut and Clift, 2013).

(2) Detrital signatures of the Seve and Köli Nappe Complexes in foreland basins. Detrital sedimentary studies in sedimentary basins of the Himalaya have been successfully applied to better understand orogen dynamics (e.g., Najman, 2006). Only some sparse data exist in the Scandinavian Caledonides (Gee et al., 2014; Gee et al., 2015). Suitable sedimentary successions spanning the Llandovery–Wenlock boundary are preserved, for example, in Jämtland (Bassett, 1985) and farther south in the Siljan crater (Lehnert et al., 2012). Identifying Seve or Köli Nappe Complex-derived detritus could yield sedimentary constraints on whether these units were exposed and eroding at the time continental collision initiated.

(3) Weakening mechanisms explaining sequential decoupling of crustal units from the continuously subducting Baltica lithosphere. Progressively younger ages of (ultra)high-pressure metamorphism in successively more proximal domains of the former Baltica margin suggest a strong Baltica lithosphere that subducted continuously without slab break-off. Decoupling mechanisms that can facilitate successive detaching and exhumation of crustal units are, for example, partial melting as discussed for the Western Gneiss Region (Labrousse et al., 2015) or eclogitization as demonstrated for the Lindås nappe (Austrheim, 1987; Jolivet et al., 2005). Mechanisms that might have caused decoupling of the Seve Nappe Complex ultrahigh-pressure units from the subducting lithosphere are currently not known.

(4) Absolute timing of deformation in the basal décollement. Especially in the orogenic foreland (central Sweden), emplacement of the Allochthons on top of the Baltica craton has been explained by thin-skinned translation along a basal décollement exploiting Cambrian alum shales (Gee, 1978; Andersson et al., 1985). Deformation in the décollement
should be synchronous with, or slightly younger than, the c. 414 Ma deformation ages obtained in Paper II.

Post-orogenic extension in Jämtland. Correlation with the well-studied, post-collision extensional tectonics in Norway (Norton, 1986; Fossen, 1992; Milnes et al., 1997; Andersen, 1998), and relative timing constrained by structural overprinting relationships (Gee et al., 1994; Bergman and Sjöström, 1997; Paper III) imply that extensional structures in Jämtland developed after c. 410–405 Ma. However, the switch from contractual to extensional deformation in the Swedish part of the orogen is currently incompletely understood. Pseudotachylyte formation at 412.7 ± 11.0 Ma (2σ) in the Köli Nappe Complex provides a younger age limit for contractual deformation (Bender et al., in preparation), and is in accordance with findings from Paper II. U–Pb dating of fibrous calcite (cf. Hansman et al., 2018) associated with brittle faults such as the Røragen Detachment could provide direct age data for extensional faulting.
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