Department of Geosciences

Mountain building processes in the northern Norwegian Caledonides

Examining Caledonian continental collision using a combination of structural mapping, phase equilibrium modelling and geochronology

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Fieldwork wildlife – Uløya, northern Norway.

Preface

This thesis is the outcome of a 4-year PhD-project that started in May 2013. The work was mainly funded by the Department of Geosciences, UiT The Arctic University of Norway, with additional support for analytical work and travel from the Norwegian Research School for Dynamics and Evolution of Earth and Planets (DEEP), University of Oslo. UiT The Arctic University of Norway is the degree-awarding institution. One year was assigned for duty work, which included practical teaching of field courses, and general geology, petrology and structural geology courses at BSc and MSc levels. I also assisted MSc students with their project work. During my PhD I attended a short course in P-T modelling at Charles University in Prague, and a presentation skills workshop run by the DEEP PhD school in Oslo, Norway. In my second year I spent 8 months at the University of Minnesota, USA, which included one semester of intensive coursework. This visit enabled me to participate in the STAMP (Structure, Tectonics and Metamorphic Petrology) group there, which was invaluable for my development as a researcher. Parts of the results in this thesis have been presented at two international conferences (EGU 2015 and EGU 2017). The thesis presented herein aims to discuss the evolution of Caledonian continental collision in northern Norway by examining the timing of metamorphism in two of the main nappe complexes exposed there. Fieldwork was carried out over four field seasons. This thesis consists of an introduction, three papers, and a brief synthesis. All three papers are as a result of collaboration between the co-authors.

The three papers are presented in the order they were written. They are:

Gasser, D., Jerabek, P., Faber, C., Stünitz, H., Menegon, L., Corfu, F., Erambert, M., and Whitehouse, M.J., 2015. **Behaviour of geochronometers and timing of metamorphic reactions during deformation at lower crustal conditions: Phase equilibrium modelling and U-Pb dating of zircon, monazite, rutile and titanite from the Kalak Nappe Complex, northern Norway**, Journal of Metamorphic Geology, 33, 513-534

Faber, C., Stünitz, H., Gasser, D., Jeřábek, P., Kraus, K., Corfu, F., Ravna, E.K., and Konopásek, J. **Dismembering of subducted continental crust by nappe stacking during continental collision: An example from the Reisa Nappe Complex in the Scandinavian Caledonides, northern Norway,** In preparation for submission to Journal of Metamorphic Geology

Faber, C., Stünitz, H., Gasser, D., Jeřábek, P., Kraus, K., and Konopásek, J. **Polyphase metamorphism in the Kalak Nappe Complex: Implications for the history of the Baltican margin prior to and during Caledonian continental collision**, In preparation for submission to Tectonics/Tectonophysics

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Abstract

Studying continental collision allows us to better understand the construction of continental crust and the lower crustal processes that occur in modern orogenic belts (e.g. the Himalaya). The Scandinavian Caledonides record continental collision between Laurentia and Baltica, and allow us to directly study processes associated with mid- to lower crustal metamorphism in a continental collision zone. In northern Norway, the Caledonian rocks comprise several allochthons. This work focuses on the Kalak and Reisa nappe complexes, which probably formed the outer margin of Baltica and margin metasediments. The Kalak Nappe Complex (KNC) is comprised of several nappes that display a pre-Caledonian Neoproterozoic evolution. Its origin has been strongly debated in recent years (e.g. Kirkland et al., 2006a, 2007b; Corfu et al., 2007, 2011; Gee et al., 2017). Most previous work has relied on geochronology, and this work aims to better constrain the timing and P-T conditions of pre-Caledonian and Caledonian metamorphism to improve our understanding of their tectonic context and evolution by using a combination of methods including: structural mapping, phase equilibrium modelling, and geochronology. This work also sheds light on the possible configuration of the pre-Caledonian Baltoscandian margin. The three papers focus in the same study area. Papers I and III examine the timing and conditions of metamorphism within the different units of the KNC, and Paper II describes the evolution of the Reisa Nappe Complex (RNC), attributing metamorphism to an early heating event followed by crustal thickening. In paper I we show that the KNC correlates with the Sørøy terrane, defined as part of the upper KNC in Finnmark. In Paper III we interpret that the KNC in the field area is comprised of an upper and lower nappe that record different pre-Caledonian evolutions and that Caledonian metamorphism may have followed an anticlockwise P-T path. In paper II we describe an anticlockwise P-T path for Caledonian metamorphism that occurred over ~10 Ma, with early Silurian heating, partial melting, and intrusion of tholeiitic gabbro (probably in a compressional setting) followed by higher pressure, lower temperature shearing associated with nappe stacking during crustal thickening. Nappe-stacking was in-sequence, and a block diagram representing the paleogeography of the Baltoscandian margin was created by unstacking the nappes. The anticlockwise P-T path for Caledonian metamorphism in northern Norway records either the subduction of a back-arc, or slab break-off at the onset of subduction of Baltica continental crust before ~440 Ma.

1 Introduction

It is useful to study the mechanisms by which continents collide with one another to gain a better understanding of processes that are involved in building continental crust, and in the generation of earthquakes and volcanism. The subduction of continental crust is an aspect of particular interest because it has traditionally been considered too buoyant to properly subduct, although the existence of ultra-high pressure rocks (UHP; rocks that have experienced depths greater than c. 90km) indicates that under some circumstances it is possible (e.g. Cloos, 1993; Chopin, 2003). From geophysical imaging in the Himalaya we know that the extent of subduction/underthrusting of continental crust can vary greatly along the collision zone (e.g. Schulte-Pelkum et al., 2005; Xu et al., 2015). Where continental crust does not subduct, it is thrust over the continental margin forming basement nappes (e.g. Escher et al., 1993; Escher and Beaumont, 1997). In some cases deeply buried continental crust can be exhumed, with its exhumation triggered or enhanced by partial melting (e.g. Hollister and Crawford, 1986; Gerya and Meilick, 2010; Labrousse et al., 2011). Understanding the specific timing and conditions of events that have affected rocks prior to and during orogenesis can therefore give important insight into controls and processes that facilitate crustal thickening. The Scandinavian Caledonides formed a mountain belt, on a similar scale to the modern Himalaya, during Silurian-Devonian continental collision of Baltica and Laurentia. What is left of this event in Scandinavia today forms a thick sequence of allochthonous nappes thrust eastward over Baltica (e.g. Corfu et al., 2014). The Caledonian nappes represent mid-to lower-crustal rocks and therefore give us an opportunity to study the lower- to mid-crustal processes that build mountains, and which we cannot directly observe.

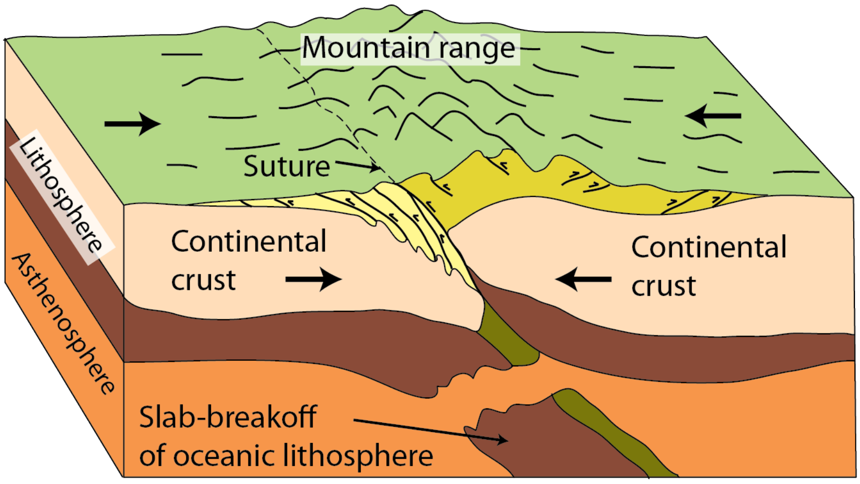


Figure 1 – Block cartoon depicting idealized continental collision and mountain building (modified after Lutgens and Tarbuck, p. 30).

1.1 Background

The Scandinavian Caledonides have traditionally been subdivided into a series of allochthons, based on their inferred origin at the Baltica margin, from the Iapetus realm, or as part of Laurentia/Laurentian margin. Most of the allochthons can be traced along the length of the Caledonides in Scandinavia, and are generally increasingly distal from the continental margin upwards (and westwards) in the nappe sequence (e.g. Fig. 2; Stephens and Gee, 1985, 1989).

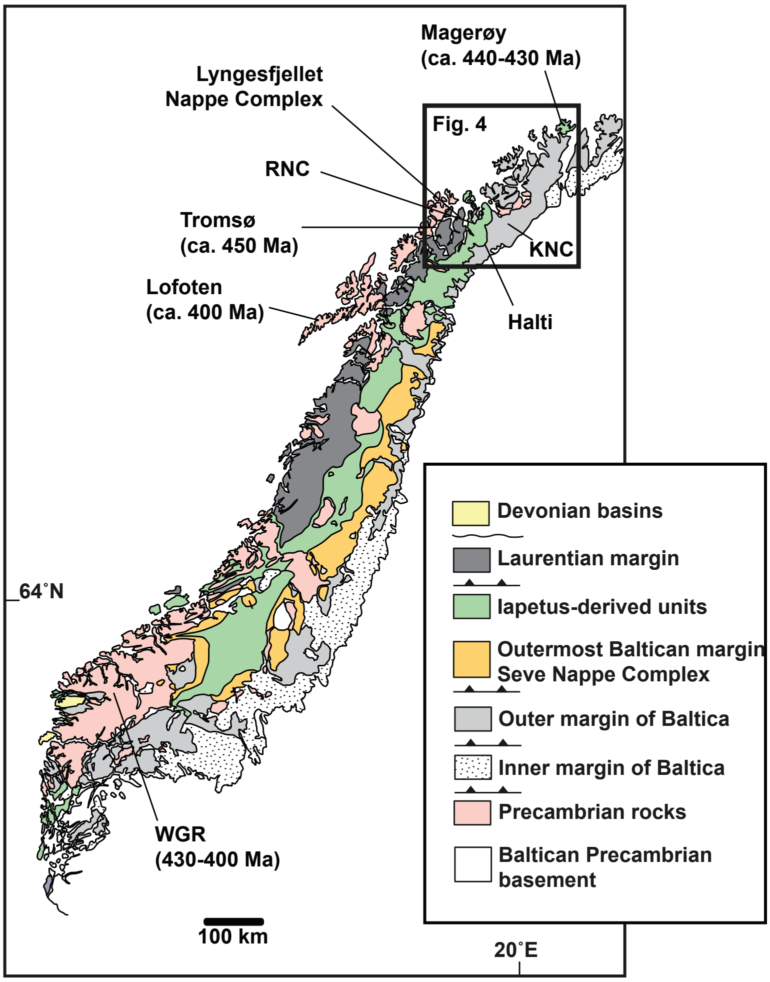


Figure 2 – Tectonostratigraphic map of Norway showing the paleogeographic origin of different Caledonian allochthonous units.

In northern Norway the origin of some of the nappes has recently been debated, and rocks previously interpreted as the re-worked Baltica margin have been instead interpreted as exotic (e.g. the Kalak Nappe Complex (KNC); Kirkland et al., 2006a, 2007b; Corfu et al., 2007, 2011). The lack of ocean floor rocks tectonostratigraphically below the KNC, in addition to the presence of oceanic rocks tectonostratigraphically above them (the Lyngsfjellet Nappe Complex - ophiolite and metasediments; Figs. 2, 3), indicates that an exotic interpretation for the KNC is problematic. In addition, detrital zircon ages, used to infer pre-Caledonian deposition of the rocks elsewhere, can be interpreted in different ways (e.g. Kirkland et al., 2007b; Gee et al., 2017). The origin of the Caledonian rocks and their role in continental collision in northern Norway is therefore still a matter of debate. A better understanding of the events that led to construction of the north Norwegian allochthons can therefore 1) improve our knowledge of the Baltoscandian margin and the various pre-Caledonian events that affected it prior to collision, and 2) give insight into the processes that accommodated Caledonian orogenesis. The allochtons in northern Norway include several nappes and nappe complexes, summarized in Figure 3. Most of the recent work (in the last 15 years) that examines the northern Norwegian Caledonides has focussed on the KNC in Finnmark (geochronological work), and on determining the nature and timing of UHP metamorphism in the uppermost Laurentia-derived nappes (Tromsø nappe; Figs. 2, 3) west of Lyngen (e.g. Corfu et al., 2003, 2007, 2011; Kirkland et al., 2005a, 2005b, 2006a; 2006b, 2007a, 2007b, 2008a, 2008b, 2016; Roberts et al., 2007; Ravna and Roux, 2006; Janák et al., 2013, Augland et al., 2014; Gee et al., 2017).

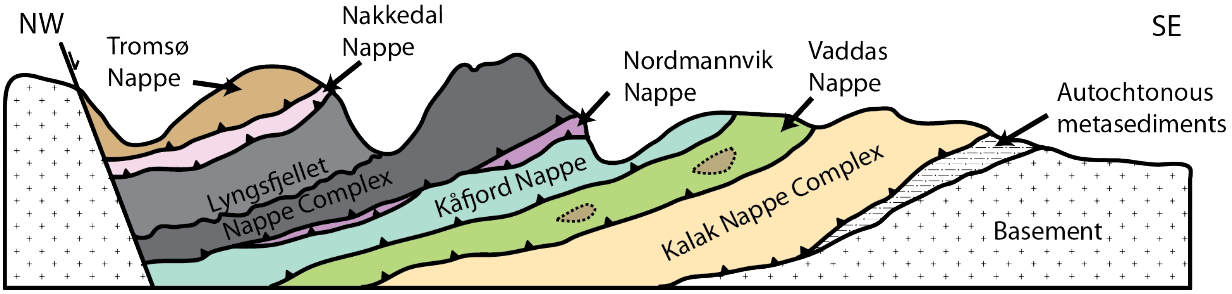


Figure 3 – Schematic cross section across the northern Norwegian Caledonides in Troms (after Augland et al., 2014).

The tectonostratigraphy and history of the southwestern extent of the Kalak Nappe Complex is less well constrained, and the timing and conditions of metamorphism in the overlying Reisa Nappe Complex (RNC) have not been studied in detail. In addition, the northern parts of the field area that fall on the Hammerfest 1:250 000 map sheet (Roberts, 1973) are not well correlated with the Nordreisa map sheet to the south (Zwaan, 1988), nor with current nappe classifications. And more recent maps from different publications assign varying nappe classifications, particularly on Arnøya (e.g. Andresen, 1988; Corfu et al., 2007; Augland et al., 2014). Defining the nappe-tectonostratigraphy is difficult because: 1) the Caledonian rocks are pervasively sheared, so that nappe boundaries are not obviously higher strain zones relative to nappe interiors, 2) the nappes comprise similar units of completely different age (e.g. Kirkland et al., 2006a; Corfu et al., 2011), and 3) units are probably tectonically repeated. Therefore, combining structural and lithological mapping with tectonostratigraphic correlation, and with modern P-T-t determination methods can help to better understand the structure of the northern Norwegian nappe complexes, and to contextualize events that affected the rocks. Because the Kalak and Reisa nappe complexes are both situated tectonostratigraphically below the only oceanic rocks in the area (Lyngsfjellet Nappe Complex; Figs. 2, 3), they probably represent different parts of the pre-Caledonian extended margin of Baltica, and studying their metamorphic evolution together can help us gain a better understanding of the entire Baltoscandian margin in northern Norway, and its role during Caledonian orogenesis.

1.2 The geology of northern Norway

In northern Norway a section across the Caledonides is exposed, from the autochtonous basement at the base to the Laurentia-derived Tromsø Nappe at the top (e.g. Ramsay et al., 1985; Augland et al., 2014; Figs. 3, 4). Structures through the allochtons record mainly east- and SE-directed emplacement of thrust nappes (e.g. Stephens & Gee, 1989). The Archean-Paleoproterozoic Baltica basement and Neoproterozoic-Ordovician para-authochtonous metasedimentary rocks comprise the lowermost rocks. They are overlain, from bottom to top, by the Gaissa and Laksefjord nappe complexes, the KNC, the RNC, the Lyngsfjellet Nappe Complex (LNC), the Nakkedal Nappe, and the Tromsø Nappe (Figs. 3, 4; e.g. Roberts, 1985; Andresen, 1988; Sundvoll and Roberts, 2003; Kirkland et al., 2005b, 2007a; Corfu et al., 2003, 2006, 2007, 2011; Augland et al., 2014). The KNC is comprised of Precambrian crustal rocks and unfossiliferous metapsammites with local mafic intrusive rocks (including the Seiland Igneous Province (SIP); Roberts et al., 2006; Kirkland et al., 2007a; Corfu et al., 2011) and the RNC is comprised of high-grade metasediments and mafic and felsic intrusives (Roberts and Sturt, 1980; Andresen, 1988; Andersen, 1984; Kirkland et al., 2005b; Corfu et al., 2006, 2007)

In northern Norway the metamorphic grade in the autochton and Laksefjord and Gaissa nappe complexes did not exceed subgreenschist to greenschist facies (Roberts, 1985). The KNC generally displays increasing Caledonian metamorphic grade upwards with greenschist facies metamorphism at its base and amphibolite facies metamorphism in the middle and upper units (Zwaan and Roberts, 1978; Rice, 1984, 1985,1987). Local granulite facies pre-Caledonian relicts also occur (e.g. Elvevold et al., 1994; Corfu et al., 2007; Menegon et al., 2011).

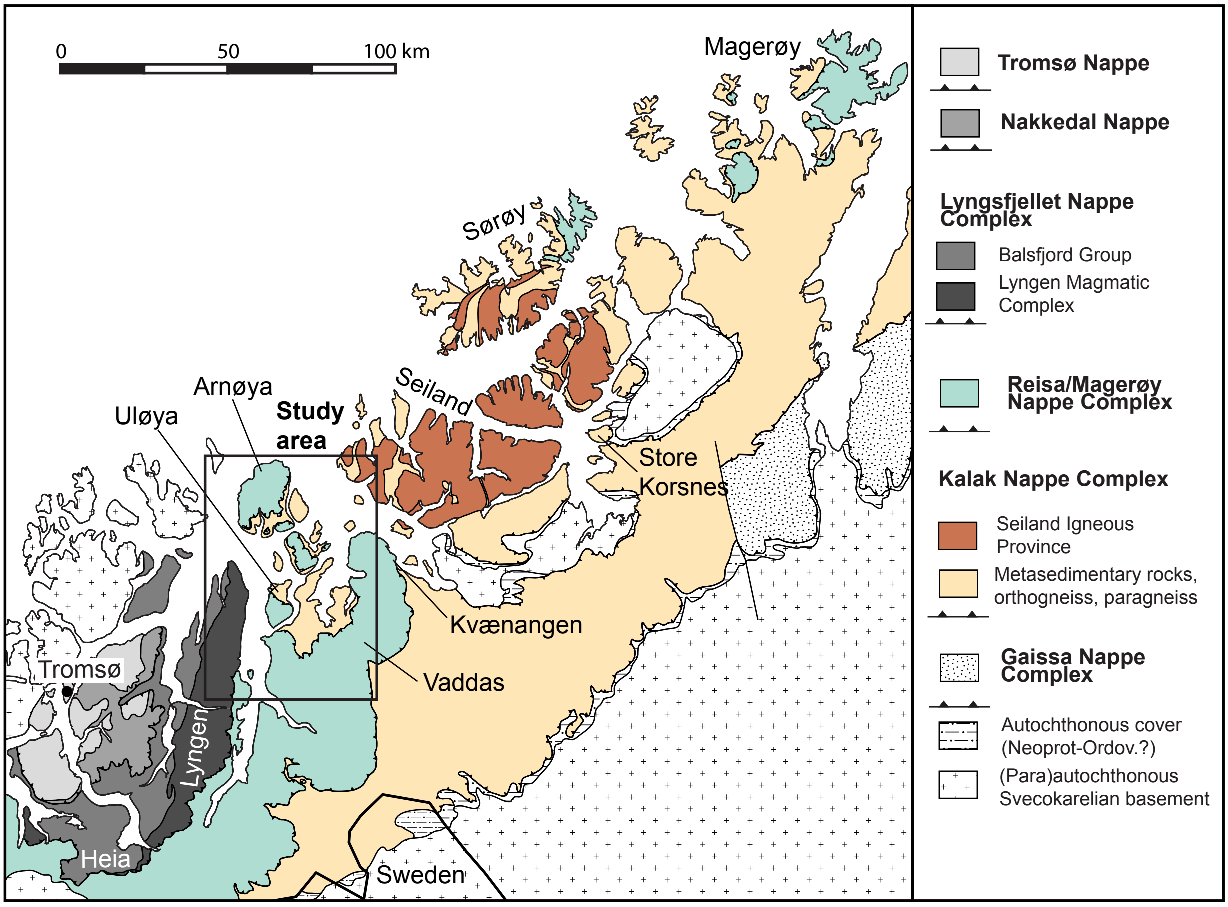


Figure 4 – Map of northern Norway showing the extent of the Kalak and Reisa Nappe complexes and the location of the study area.

The overlying RNC records amphibolite to granulite facies metamorphism, with increasing metamorphic grade upwards (Andresen, 1988). The metamorphic grade at the base of the LNC above decreases down to greenschist facies. There is evidence in the LNC for higher-grade metamorphism (up to amphibolite facies), however its age is unclear (Kvassnes et al., 2004). The overlying Nakkedal Nappe displays amphibolite to granulite facies conditions, and the Tromsø Nappe has a pervasive amphibolite facies foliation with eclogite facies relict lenses (Andresen and Steltenpohl, 1994; Corfu et al., 2003).

1.2.1 The Kalak and Reisa nappe complexes

Early work in northern Norway considered the KNC and RNC as a single sequence (e.g. Zwaan and Roberts, 1978), however the discovery of early Silurian fossils in the now recognized RNC led to a their consideration as two separate nappe complexes. Today the RNC is considered to be younger than the KNC (Andresen, 1988; Binns and Gayer, 1980). The KNC was also previously interpreted as several nappes that repeat the same sedimentary succession with slivers of its sedimentary basement (Baltica). Pre-Caledonian deformation (pre-dating the intrusion of the SIP) in the KNC was interpreted to be as a result of a local Precambrian "Finnmarkian" event (e.g. Zwaan and Roberts, 1978; Sturt et al., 1978). Improved dating of the SIP (580-560 Ma with late activity at 520 Ma; Roberts et al., 2006, 2010) and the discovery of several phases of Neoproterozoic intrusion and deformation led to the interpretation that the KNC containing at least two different sedimentary successions, re-worked within 5-10 nappes (e.g. Daly et al., 1991; Kirkland et al., 2005a).

The lower part of the KNC includes re-worked Baltica rocks (the Fagervik Complex) sheared together with Grenvillian/Sveconorwegian age metasediments of the Sværholt terrane. The upper KNC consists of paragneisses belonging to the Sørøy terrane, deposited before granitic magmatism at ~840 Ma, and affected by subsequent pre-Caledonian events at ~700 Ma and ~580-560 Ma (e.g. Daly et al., 1991; Kirkland et al., 2006a, 2007a, 2008b; Corfu et al., 2007). For a more detailed description of the lithologies, structures and ages in the KNC see papers I and III. The pre-Caledonian events recorded in the KNC are absent in current Baltica basement rocks in northern Norway, which led to the suggestions that the KNC may have formed as an exotic terrane that was later accreted to Baltica (e.g. Kirkland et al., 2006a, 2007b; Corfu et al., 2011). The origin of the KNC is therefore an ongoing debate, and other recent work argues for the origin of the KNC at the Baltica margin (e.g. Roberts, 2007; Zhang et al., 2016; Gee et al., 2017).

The Reisa Nappe Complex is comprised of three different nappes, from the bottom to top; the Vaddas, Kåfjord and Nordmannvik nappes (Fig. 3; Zwaan and Roberts, 1978; Andresen, 1988). The rocks are usually correlated with other Iapetus-derived allochtons, and are considered tectonically equivalent to the Magerøy and Køli nappe complexes to the north and south, respectively (Andersen, 1984; Lindahl et al., 2005; Corfu et al., 2006, 2007, 2011; Kirkland et al., 2005b, 2016). The RNC is considerably less well studied than the KNC. Of the three nappes, the Vaddas Nappe is the best described. The rocks were probably deposited as a sedimentary sequence in the late Ordovician to early Silurian (based on fossils; Binns and Gayer, 1980; Lindahl et al., 2005) and later intruded by mafic and felsic rocks. Age dates in the equivalent Magerøy nappe suggest nearly synchronous deposition and intrusion of mafic and felsic rocks in the early Silurian (Kirkland et al., 2005b; Corfu et al., 2006, 2007). Early Silurian intrusives are generally considered to be absent in the KNC, although the tectonostratigraphic position of the 434 ± 5 Ma Halti Igneous Complex is debated (e.g. Vaasjoki and Sipilä, 2001; Andréasson et al., 2003)

Early work on the Kåfjord Nappe suggested it may represent intensely deformed paragneiss related to the Nordmannvik Nappe (Lindstrøm and Andresen, 1992), although this is unconfirmed. The only age date reported from the Kåfjord Nappe is a Rb-Sr whole rock age interpreted to date anatexis and granite crystallization at ~440 Ma (Dangla et al., 1978). The Nordmannvik Nappe has been described as a polymetamorphic unit (Andersen, 1988; Zwaan, 1988). It contains granulite-facies relicts overprinted by an amphibolite facies foliation, however the age of the granulite facies metamorphism is not known (Elvevold, 1987; Andresen, 1988; Zwaan, 1988). The southernmost extent of the Nordmannvik nappe at Heia includes a lens of gabbro, interpreted as having been intrusive. The gabbro records an intrusive age of 435 ± 1 Ma (Elvevold, 1987; Augland et al., 2014). Generally, the geologic setting for the RNC is not well understood, and the origin of the Nordmannvik Nappe rocks is unknown. For a more detailed description of the lithologies and structures in the RNC see paper II.

2 Objectives of the project

The P-T history of many of these rocks have not been studied systemically since examination by Elvevold et al., (1987, 1993), and work using modern P-T methods (e.g. phase equilibrium modelling) is generally missing for both the KNC and RNC. The correlation of the western extent of the KNC with its eastern extent could be improved, and examining the KNC and RNC together will help to better understand their original relationship, and provide insight into the mid- to lower crustal mechanisms that facilitated construction of the northern Norwegian Caledonian mountain belt. This work set out to improve descriptions of the metamorphic and structural evolution of the Kalak and Reisa Nappe complexes in order to provide these insights, and to better understand the evolution of the pre-Caledonian margin. In order to do this the following questions were considered:

- What are the tectonostratigraphic relationships between and within the Kalak and Reisa nappe complexes?
- What are the timing and conditions of Caledonian metamorphism in the Kalak and Reisa Nappe Complexes?

- What are the timing and conditions of pre-Caledonian metamorphism in the Kalak Nappe Complex?
- Does the Reisa Nappe Complex (particularly the Nordmannvik Nappe) record pre-Caledonian metamorphism?
- What role did the Kalak and Reisa nappe complexes play in the pre-Caledonian margin?
- How and when were the Caledonian nappes constructed?
- How did a pre-existing history and evolving metamorphic conditions affect lower- to mid-crustal processes during continental collision in northern Norway?

3 Approach

A combination of structural and lithological mapping, microstructural observations, and phase equilibrium modelling together with age dating of microstructurally relevant minerals was used. These methods are useful for interpreting and discussing the metamorphic evolution and tectonic history of northern Norway, and complement the pre-existing database of ages and tectonostratigraphic correlations already in place. The field area (Fig. 4) was chosen because it includes almost an entire stratigraphic section through the KNC and RNC. Structural and lithological mapping were used to correlate previously uncorrelated units (on Skjervøy, northern Kågen and Arnøya) and to establish tectonostratigraphic relationships within the nappe complexes. Samples for phase equilibrium modelling and geochronology were selected so that they are representative of specific units and boundaries within the defined tectonostratigraphy.

Phase equilibrium modelling was chosen as a method for determining P-T conditions because it allows for more advanced understanding of the stable and metastable mineral assemblages in polymetamorphic rocks and can be used to construct P-T paths for complex rocks better than traditional thermobarometry. Analytical methods used for petrology and phase equilibrium modelling include X-ray fluorescence (XRF) for bulk rock chemical analysis, and electron microprobe (EMP) and semi-quantitative energy dispersive X-ray spectroscopy (EDS) on a scanning electron microscope (SEM; optimized using a cobalt standard) for mineral composition data, X-ray images and element maps. Careful consideration of microstructures was taken in choosing minerals and position of spots for mineral composition analyses. The consistency of mineral spot analyses between EMP (quantitative) and EDS-SEM (semi-quantitative) was checked using two common samples. Analyses for garnet compositions were consistent between the two methods.

For geochronology several analytical methods were used based on their usefulness for individual minerals and contexts: 1) Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was used to date detrital zircon because it is an in situ technique and offers the fastest method to analyse the large number of zircon grains required for detrital zircon analysis. 2) Secondary-ion mass spectrometry (SIMS) was used to date complex minerals (zircon and monazite) that may have undergone several phases of metamorphism, and therefore might display several phases of crystallization (e.g. zircons formed during migmatisation in the Nordmannvik Nappe – sample AR23a). SIMS was chosen because it is an in situ method that offers the high spatial resolution for dating complex mineral grains. Zircons were imaged using CL prior to SIMS analysis to best determine spot position. Monazites were imaged using CL and high-contrast back-scattered electrons (SEM). Trace elements were analysed in monazite (Ti, Zr, Si Fe, Nb, Cr) to establish whether the grains might display zoning resulting from one or more periods of mineral growth. 3) Isotope dilution thermal ionization mass spectrometry (ID-TIMS) was used to date metamorphic minerals (rutile and titanite) because it is more precise than other methods, and in most cases these minerals were expected to have formed in a single event, likely giving only a single age (e.g. metamorphic titanite formed during Caledonian shearing along the KNC-RNC boundary – sample UL248). For detailed descriptions of sample preparation and analytical procedures see the supplementary information for papers I and II.

4 Summary of papers

4.1 Paper I

Gasser, D., Jeřábek, P., Faber, C., Stünitz, H., Menegon, L., Corfu, F., Erambert, M., and Whitehouse, M.J., 2015. **Behaviour of geochronometers and timing of metamorphic reactions during deformation at lower crustal conditions: phase equilibrium modelling and U-Pb dating of zircon, monazite, rutile and titanite from the Kalak Nappe Complex, northern Norway**, Journal of Metamorphic Geology, 33, 513-534

The multifaceted aims of this paper are to: 1) gain an understanding of the behaviour of multiple geochronometers and gauge their effectiveness together to answer tectonic questions, and 2) to unravel the tectonometamorphic evolution of the Kalak Nappe Complex. The paper investigates one outcrop that preserves two foliations of different metamorphic grade; 1) a subvertical migmatitic foliation (S1) within a low-strain lens, and 2) a subhorizontal mylonitic foliation (S2) attributed to Caledonian shearing. The work establishes a maximum depositional age for the rocks and constructs a P-T path using phase equilibrium modelling combined with geochronometers zircon, monazite, rutile and titanite.

The main conclusions of the work with respect to tectonic history of northern Norway show that this particular part of the Kalak Nappe Complex records a complex and long-lived history, beginning in the Neoproterozoic. Detrital zircon dating indicates a maximum depositional age of 937 ± 14 Ma. Phase equilibrium modelling shows that the migmatitic S1 foliation formed at ~730-775 °C and ~6.3-9.8 kbar, above the wet solidus. Zircon crystallized in the leucosome associated with this event gives an age of 702 ± 5 Ma. Monazite ages in the S1 leucosome (concordia age of 698 ± 11 Ma) agree well with the zircon ages. A maximum depositional age around ~930 Ma and migmatisation at ~700 Ma indicate that the outcrop and rocks in the area are equivalent to the Sørøy succession, defined in the upper KNC in Finnmark (e.g. Kirkland et al., 2006a, 2007b). Monazite ages from the melanosome of the S1 sample give a ^{207}Pb/^{206}Pb age range between 786 ± 12 Ma and 594 ± 18 Ma, suggesting either protracted growth of monazite during long-lived metamorphism or partial resetting of monazite during high-T diffusion. Both scenarios indicate temperatures > 600 °C, suggesting that the rocks preserve evidence of long-lived residence at lower crustal levels. The S1 foliation is overprinted by the subhorizontal S2 foliation. The foliation preserves relicts of the S1 foliation, but the main assemblage represents S2-shearing. Phase equilibrium modelling indicates the conditions of S2 shearing were at ~600-660 °C and 10-12 kbar. Rutile in the S1 foliation records temperatures of 550 – 660 °C (Zr-in-rutile), indicating it underwent diffusional resetting during S2 shearing. This rutile gives a cooling age of 440 – 420 Ma. Phase equilibrium modelling suggests that titanite grew at the expense of rutile at ~550 °C during S2 shearing. U-Pb age dating of titanite indicate it grew between 440-430 Ma, giving a minimum estimate for the timing of Caledonian shearing, and suggesting that shearing might have been protracted over a 10 million year period.

The main conclusions of the work with respect to the effectiveness of the various geochronometers are that 1) despite having a mostly homogenous composition, monazite can show a large range in U-Pb dates, 2) that rutile can lose its Zr-in-rutile and U-Pb signtatures during an amphibolite facies overprint, and 3) that titanite is useful for recording the timing of shearing if the growth conditions are well constrained. Together the results were used to construct a P-T-t-d path and tectonic interpretation showing that the rocks were probably slowly heated between 800-700 Ma, reaching a peak above the solidus at c. 700 Ma and forming the S1 foliation in a likely collisional setting (based on P/T ratio). Subsequently the rocks were either slowly cooled between 700 – 600 Ma, or were kept at a high temperature relatively continuously until Caledonian shearing (440-430 Ma) and development of the S2 foliation at higher pressures and lower temperatures. The P-T conditions of S2 shearing indicate crustal thickening at the onset of the Caledonian Orogeny. Retrograde shearing is recorded from 440-420 Ma during top-to-SE nappe thrusting.

4.2 Paper II

Faber, C., Stünitz, H., Gasser, D., Jeřábek, P., Kraus, K., Corfu, F., Ravna, E.K., and Konopásek, J. **Dismembering of subducted continental crust by nappe stacking during continental collision: an example from the Reisa Nappe Complex in the Scandinavian Caledonides, northern Norway,** In preparation for submission to Journal of Metamorphic Geology

The aim of this paper is to establish an improved structural and tectonometamorphic history of the Reisa Nappe Complex in order to better constrain its role during the Caledonian Orogeny. The work describes the extent, tectonostratigraphy and structure of the RNC in northern Troms along the Norwegian coast. Field mapping correlates the various nappes across the study area and establishes a tectonostratigraphy on Arnøya. It also shows that the Vaddas Nappe rocks may have been deposited on a KNC basement. The paper describes two foliations in the RNC: 1) an S1 migmatitic foliation, indicating partial melting and 2) a crosscutting S2 foliation associated with Caledonian shearing. Phase equilibrium modelling is used to establish the conditions of metamorphism of S1 migmatisation and S2 shearing. Geochronology was used to establish the timing of: 1) migmatisation in the Nordmannvik nappe (U-Pb SIMS zircon), 2) metamorphism associated with S2 shearing in the Nordmannvik nappe (U-Pb TIMS titanite), 3) intrusion of gabbro into the Vaddas Nappe (U-Pb SIMS zircon), and 4) timing of shearing along the KNC-Vaddas boundary.

Combined geochronology and phase equilibrium modelling shows that the RNC records Caledonian metamorphism along an anticlockwise P-T path. An early phase of granulite facies high-temperature, moderate-pressure metamorphism (760 – 790 °C and 9.4 – 11.1 kbar) in the Nordmannvik nappe is concurrent with gabbro intrusion at 7-9 kbar into the Vaddas Nappe metasediments at c. 440 Ma. Melt in the axial planes of folds associated with Caledonian shearing indicates the rocks were deformed in a compressional setting while partially molten. Subsequent solid-state shearing (S2) is recorded at higher pressures and lower temperatures (640 – 720 °C and 9.5-13 kbar) between ~440 - 430 Ma. The structures and long-lived titanite growth (c. 10 Ma) indicate that this metamorphic path is associated with continuous Caledonian shearing between ~440 – 430 Ma during compression. The P-T conditions for S2 metamorphism show an increase in pressure downwards and an increase in temperature upwards within the KNC, suggesting the lower nappes underthrust the upper nappes during nappe stacking. The paper presents a simple paleogeographic block model reconstructed from the tectonostratigraphy of the nappes, indicating that the RNC probably formed at the Baltica margin, with the Vaddas and Kåfjord nappes deposited as metasediments on the Baltica basement or at the Baltica margin.

The paper discusses several tectonic models that offer explanations for the anticlockwise Caledonian evolution, lack of ocean floor rocks tectonostratigraphically below the RNC, late-Ordovician-early Silurian deposition of the Vaddas rocks on a KNC basement, and the metamorphic gradients displayed by S2 metamorphism. These models include: 1) subduction of a spreading ridge, 2) a back-arc basing setting with eastward subduction, and 3) slab break-off at the onset of Caledonian continental collision. The main conclusion of the work is that the metamorphism is best explained by slab break-off at the onset of Caledonian continental collision, and that the increase in pressure associated with amphibolite-facies S2 shearing records subsequent crustal thickening.

4.3 Paper III

Faber, C., Stünitz, H., Gasser, D., Jeřábek, P., Kraus, K., and Konopásek, J. **Polyphase metamorphism in the Kalak Nappe Complex: implications for the history of the Baltican margin prior to and during Caledonian continental collision**, In preparation for submission to Tectonics/Tectonophysics

The aim of this paper is to constrain the metamorphic evolution of the KNC to better describe the context of pre-Caledonian and Caledonian events. The work establishes an improved structural and tectonostratigraphic understanding of the KNC in northern Troms along the Norwegian coast and uses phase equilibrium modelling of structurally constrained samples to describe metamorphism through the tectonostratigraphy. Structural mapping and tectonostratigraphic correlation shows that the rocks comprise three different nappes. The lowermost nappe preserves greenschist facies conditions and was not investigated in detail. The two overlying nappes display amphibolite facies conditions, and preserve two different pre-Caledonian foliations in low strain lenses. The two foliations are preserved in different nappes and crosscut by a later S2 foliation associated with Caledonian shearing. Their relative timing is therefore unclear and they are differentiated using subscripts. In the lower nappe a low-grade foliation ($S1^S$) is preserved in low-strain lenses and in the hinges of 100 m-scale isoclinal folds. The $S1^S$ foliation is sometimes folded under low amphibolite facies conditions and crosscut by at least two phases of pre-Caledonian magmatism. Phase equilibrium modelling shows that the $S1^S$ foliation formed at epidote-amphibolite facies conditions (530 – 570 °C and 8.2 – 9.3 kbar). The upper nappe records a different high-grade pre-Caledonian foliation ($S1^E$) in low-strain lenses, described in paper I (Gasser et al., 2015) that formed at ~730-775 °C and ~6.3 - 9.8 kbar at 702 ± 5 Ma. This paper shows that this pre-Caledonian event is widespread in the upper nappe. The boundary between the upper and lower nappes also records low-pressure, high-temperature metamorphism at apparent conditions of 620 – 640 °C and 4.7 – 5.6 kbar, followed by cooling, prior to Caledonian metamorphism.

Peak Caledonian metamorphism is associated with an S2 foliation. In the lower nappe S2-synkinematic garnet records two phases of Caledonian metamorphism: 1) early Caledonian high-temperature, low-pressure conditions (675 – 690 °C and 8.3- 9 kbar) and 2) slightly lower temperature, peak pressure conditions typical of the Caledonian metamorphic overprint. This indicates an anticlockwise P-T path for Caledonian metamorphism, similar to that observed in the RNC (Paper II). The other samples only record the higher pressure Caledonian evolution, and rocks from the KNC-RNC boundary record low-eclogite facies conditions for S2 at ~700 °C; ~13.5 - 15 kbar. Major nappe boundaries generally show increasing P-T upwards along an inverted metamorphic gradient, and there is some variation between nappe cores and nappe boundaries. Temperatures between the upper and lower nappe are similar, and the lower nappe records slightly higher pressures (11-14 kbar) than the upper nappe (10-12.5 kbar).

The main conclusions of the work show that the two nappes in the area record different pre-Caledonian histories, and can probably be correlated with the Sværholt (lower) and Sørøy (upper) terranes previously defined in Finnmark (e.g. Kirkland et al., 2006a). This suggests that low-grade pre-Caledonian metamorphism in the lower nappe ($S1^S$) may be Grenvillian/Sveconorwegian in age, as this is the primary pre-Caledonian event affecting the Sværholt terrane in Finnmark. Pre-Caledonian metamorphism in the upper nappe was correlated with similar event in the Sørøy terrane in paper I (Gasser et al., 2015). The high pressure conditions for S2 shearing along the KNC-RNC boundary indicate that they were juxtaposed in the lower crust during crustal thickening. The inverted metamorphic gradient shown by the nappe boundaries is consistent with nappe stacking. The variation in metamorphic conditions between nappe cores and nappe boundaries is probably due to temporal variation, with nappe boundaries recording the most recent deformation and metamorphism. The higher pressures recorded in the core of the lower nappe relative to the upper nappe suggests that crustal thickening may have been facilitated by underthrusting of the upper nappe by the lower nappe during crustal subduction.

5 Synthesis

The three papers presented in this PhD thesis relate well as each attempts to answer a smaller piece of the larger northern Norwegian Caledonian puzzle, together answering the questions posed in section 2. Paper I examines the pre-Caledonian and Caledonian evolution of a single outcrop in the KNC, in an area where the KNC is previously poorly understood. It shows that the KNC in the field area records a Neoproterozoic history thereby relating the outcrop to the upper part of the KNC tectonostratigraphy in Finnmark (the Sørøy succession; Kirkland et al., 2006a). Paper II contributes a better understanding of the evolution of the overlying rocks in the RNC and its relationship with the KNC, allowing for an improved context for Caledonian deformation and metamorphism of both nappe complexes. Examining the RNC rocks is important for understanding the Caledonian deformation and metamorphic signature because some of the rocks (e.g. the Vaddas Nappe) are too young to preserve pre-Caledonian events. Pre-Caledonian events in the KNC can complicate interpretation of phase equilibrium modelling results and geochronological data related to the Caledonian event due to the presence of pre-existing foliations and mineral relicts. Paper II establishes that the timing and metamorphic conditions of pervasive S2 Caledonian shearing in the RNC are similar to those established for a part of the KNC in paper I. It confirms that some of the RNC rocks do not show a pre-Caledonian evolution, and also describes a two-phase Caledonian metamorphic evolution along an anticlockwise P-T path for the RNC. The new age and P-T data allow for large-scale tectonic interpretation of the Baltica margin and Caledonian continental collision. Paper III goes back to the KNC, armed with a better understanding of the evolution of the overlying RNC and the Baltoscandian margin, and gives a tectonostratigraphic, structural and metamorphic context for pre-Caledonian and Caledonian events in the KNC in northern Troms.

Considered together, the results of the three papers can be used to discuss the pre-Caledonian and Caledonian evolution of northern Norway more broadly. Figure 5 summarizes previous estimates for the timing of events in northern Norway together with the geochronology and metamorphic estimates from the three papers presented as part of this thesis (shown in orange boxes). Considered together these three papers confirm correlations of the KNC and the RNC with the KNC and Magerøy Nappe in Finnmark, contribute towards a better understanding of the pre-Caledonian Baltica margin, and show that the northern Norwegian Baltica margin (both nappe complexes) underwent metamorphism along an anticlockwise P-T path, associated with an early heating event and crustal thickening during continental collision.

5.1 The tectonometamorphic evolution of northern Norway

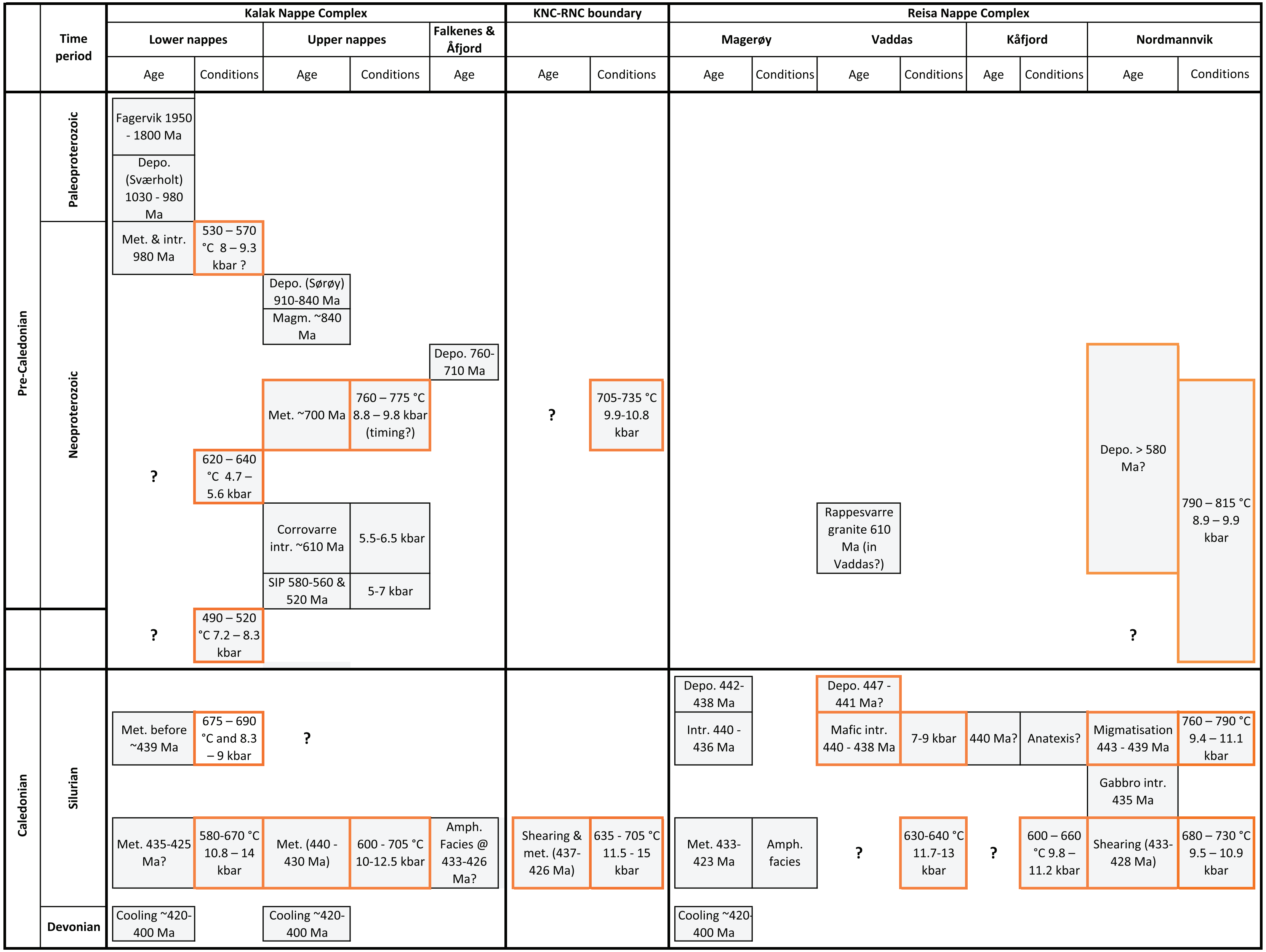
5.1.1 Pre-Caledonian signatures

Paper III agrees with previous work (e.g. Kirkland et al., 2006a, 2007a; Corfu et al., 2007, 2011) that the lower KNC displays a different pre-Caledonian evolution compared to the upper KNC, suggesting they were formed separately and accreted together later. Based on their current place in the tectonostratigraphy, the lower KNC units comprised the innermost rocks relative to Baltica prior to nappe stacking. These rocks are comprised of Baltica-type basement (the Fagervik Complex) and early Neoproterozoic sediments, and deformed prior to, and intruded by granitic rocks at 980 Ma. The metasediments of the Sværholt succession are not interpreted to have been deposited on the Fagervik (Baltica) rocks based on detrital zircon dating (Kirkland et al., 2007b), suggesting that a major tectonic boundary exists between a Baltica-derived basement sliver and the metasediments in the lower nappe.

Evidence for such a significant tectonic boundary in the study area is absent, although evidence for an unconformity is also absent. In the lower part of the KNC at Store Korsnes (Fig. 4) the Fagervik-type orthogenisses of the lower KNC are separated from the overlying migmatitic paragneisses of the upper KNC by a thrust sheet of metasediments. Shearing between them displays a strong S2 foliation consistent with Caledonian shearing. Ages of deposition, metamorphism and intrusion in the Sværholt rocks suggest a possible relationship with the Sveconorwegian/Grenvillian Orogen. This work suggests that metamorphic conditions related to this event ($S1^S$ foliation; Paper III – Fig. 10A) were low-amphibolite facies and give a geothermal gradient (~20 °C/km) consistent with regional metamorphism (Fig. 5). Since the $S1^S$ foliation affects both the orthogneisses (Fagervik-type) and overlying metasediments, it is possible that they were affected by the same pre-Caledonian regional metamorphic event.

The upper units of the KNC (including the Sørøy succession), deposited between 910-840 Ma (Kirkand et al., 2007b), display a more complex history, with ages of tectonic events decreasing upwards in the tectonostratigraphy (e.g. Kirkland et al., 2006a). The ~840 Ma granitic magmatism recognized in Finnmark has not been dated in the rocks of the study area. Papers I and III show that the rocks are, however, affected by a widespread granulite facies event at ~700 Ma (Paper I – Figs. 6A, 8), that so far has not been attributed to any known orogeny. The geothermal gradient related to this event (25 °C/km; Paper III - Fig. 10B) is consistent with normal regional metamorphism. The presence of ~600 Ma intrusives in the Corrovarre nappe and the ~580-560 Ma SIP in the Sørøy succession rocks just east of the study area suggests that these pre-Caledonian events should also be recorded in the upper KNC rocks of the field area, however the Caledonian overprint is so pervasive that the extent of their effect is unclear.

The high-temperature low-pressure pre-Caledonian metamorphism recorded on Skjervøy at the boundary between the upper and lower KNC (Paper III – Figs. 11B, C), may either record local elevated temperatures related to the intrusions, as the conditions record similar pressures to that of contact metamorphism related to both the Corrovarre intrusions and the SIP (e.g. Elvevold et al., 1994; Menegon et al., 2011; Fig. 5). Alternatively, it may record the widespread high-grade metamorphic event at ~700 Ma in the upper nappe, if the upper and lower parts of the KNC were juxtaposed at this time (consistent with observations by Kirkland et al., 2005a). Further work (geochronology) is required to resolve the age of this metamorphic signature.



		Kalak Nappe Complex					KNC-RNC boundary		Reisa Nappe Complex							
	Time period	Lower nappes		Upper nappes		Falkenes & Åfjord			Magerøy		Vaddas		Kåfjord		Nordmannvik	
		Age	Conditions	Age	Conditions	Age	Age	Conditions	Age	Conditions	Age	Conditions	Age	Conditions	Age	Conditions
Pre-Caledonian	Paleoproterozoic	Fagervik 1950 - 1800 Ma														
		Depo. (Sværholt) 1030 - 980 Ma														
	Neoproterozoic	Met. & intr. 980 Ma	530 – 570 °C 8 – 9.3 kbar ?													
				Depo. (Sørøy) 910-840 Ma												
				Magm. ~840 Ma												
						Depo. 760-710 Ma									Depo. > 580 Ma?	
				Met. ~700 Ma	760 – 775 °C 8.8 – 9.8 kbar (timing?)		?	705-735 °C 9.9-10.8 kbar								790 – 815 °C 8.9 – 9.9 kbar
		?	620 – 640 °C 4.7 – 5.6 kbar													
				Corrovarre intr. ~610 Ma	5.5-6.5 kbar						Rappesvarre granite 610 Ma (in Vaddas?)					
				SIP 580-560 & 520 Ma	5-7 kbar											
		?	490 – 520 °C 7.2 – 8.3 kbar												?	
Caledonian	Silurian								Depo. 442-438 Ma		Depo. 447 - 441 Ma?					
		Met. before ~439 Ma	675 – 690 °C and 8.3 – 9 kbar	?					Intr. 440 - 436 Ma		Mafic intr. 440 - 438 Ma	7-9 kbar	440 Ma?	Anatexis?	Migmatisation 443 - 439 Ma	760 – 790 °C 9.4 – 11.1 kbar
															Gabbro intr. 435 Ma	
		Met. 435-425 Ma?	580-670 °C 10.8 – 14 kbar	Met. (440 - 430 Ma)	600 - 705 °C 10-12.5 kbar	Amph. Facies @ 433-426 Ma?	Shearing & met. (437-426 Ma)	635 - 705 °C 11.5 - 15 kbar	Met. 433-423 Ma	Amph. facies	?	630-640 °C 11.7-13 kbar	?	600 – 660 °C 9.8 – 11.2 kbar	Shearing (433-428 Ma)	680 – 730 °C 9.5 – 10.9 kbar
	Devonian	Cooling ~420-400 Ma		Cooling ~420-400 Ma					Cooling ~420-400 Ma							

Figure 5 – Summary of timing and metamorphic conditions in northern Norway. Estimates from this work (orange boxes) are shown with estimated ages and metamorphic conditions from literature (Dangla et al., 1978; Binns and Gayer, 1980; Elvevold, 1987; Elvevold et al., 1994; Kirkland et al., 2005a, 2005b, 2006a, 2006b, 2007a, 2007b, 2008a, 2008b, 2016; Slagstad et al., 2006; Roberts et al., 2006, 2010; Corfu et al., 2007, 2011; Getsinger et al., 2013; Gee et al., 2017).

In the Reisa Nappe Complex the rocks are younger than those in the KNC, and pre-Caledonian events are only recorded in what is considered to be the lower Vaddas Nappe, and possibly in the Nordmannvik Nappe (based on sillimanite inclusions in garnet cores; Paper II – Fig. 10). The presence of the ~600-610 Ma Rappesvarre granitic gneiss within the lowest units suggests that the rocks traditionally considered to be part of the lower Vaddas Nappe around Kvænangen and Straumfjord may actually be an imbricate nappe containing both Silurian metasediments of the Vaddas Nappe and rocks more similar in age to the underlying Corrovarre nappe of the KNC (e.g. Corfu et al., 2007; Gee et al., 2017). The description of the tectonostratigraphy in paper II (Paper II – Fig. 4) confirms this, and shows that the marble layer containing late Ordovician-early Silurian fossils described by Binns and Gayer (1980) is tectonostratigraphically equivalent to a marble layer above the units containing the Rappesvarre granite. More work therefore needs to be done to establish the nature of this lower so-called Vaddas nappe unit.

It has been previously suggested that the Nordmannvik Nappe might preserve a polymetamorphic pre-Caledonian history (e.g. Andresen, 1988). Paper II provides pre-Caledonian zircon core ages and an estimate for possible pre-Caledonian metamorphism from garnet core compositions (Paper II – Figs. 10A, B, 11A, B). Considering the Late Paleoproterozoic zircon core ages, it is possible that the Transscandinavian Igneous Belt (1.86-1.66 Ga; e.g. Larson and Berglund, 1992) could have served as a detrital zircon source. The youngest zircon core age (~580 Ma) may be a maximum depositional age for the Nordmannvik Nappe, which is consistent with the chemostratigraphic depositional age for marbles in the possibly equivalent Narvik Nappe Complex (NNC; 610-590 Ma; Augland et al., 2014; Melezhik et al., 2014).

Sillimanite inclusions in garnet cores of Nordmannvik Nappe rocks (Paper II – Fig. 8) suggest either that migmatisation occurred near the kyanite-sillimanite reaction line, or that the garnets record some earlier history (Paper II – Fig. 10A). In the latter case, because the garnets were likely affected by diffusion during high-grade melting, the current composition of the garnet cores probably does not represent the original composition when sillimanite was included. The sillimanite could have formed during some pre-Caledonian partial melting event, but this would make subsequent early Caledonian higher pressure migmatisation more difficult due to removal of water. Alternatively, it could have formed early during the S1 Caledonian migmatisation, however this implies that the majority of melt would have been generated in the sillimanite field prior to pressure increase into the kyanite filed, which is not consistent with the microstructures. A third option is that the sillimanite formed at subsolidus conditions during a pre-Caledonian event or during prograde S1 Caledonian metamorphism and the associated garnet core compositions are no longer preserved. There is no evidence for pre-Caledonian metamorphism or deformation in the Nordmannvik Nappe based on structural or geochronological data. More work needs to be done to establish the significance of sillimanite inclusions in the garnet cores, which are common in the Nordmannvik Nappe not only on Arnøya, but in samples from Uløya and Lyngseidet.

5.1.2 Caledonian metamorphism

Figures 10, 11, 12 and 13 in paper II show that the RNC preserves an anticlockwise P-T path for Caledonian metamorphism, with an early high-temperature, low-pressure heating event (~440 Ma) followed by higher pressure, lower temperature Caledonian shearing during nappe thrusting (~440-430 Ma; Paper II – Figs. 11H, 12D). One sample in the lower KNC also records this anticlockwise Caledonian P-T evolution during S2 synkinematic garnet growth (Paper III – Fig. 10B). Anticlockwise P-T paths usually show either isobaric cooling or compression during the cooling history of a rock. In the case of the Nordmannvik nappe the rocks show more cooling and less compression, from S1 to S2 conditions, whereas the anticlockwise P-T path in the Vaddas and Kåfjord rocks and rocks in the KNC show a clear compression pathway. This indicates that the rocks from the Nordmannvik Nappe, Vaddas and Kåfjord Nappes and KNC probably experienced the same S2 Caledonian shearing event from two different starting points in the crust. The anticlockwise P-T path is therefore associated with an intial high-temperature event that affected rocks at various levels in the crust, followed by a later high-pressure event, associated with Caledonian shearing. This progression occurred over a 10 million year time span. Early Silurian magmatism is not isolated to northern Norway. Similar aged early Silurian intrusions are common at a similar tectonostratigraphic level in the Caledonian Orogen (e.g. Halti Igneous Complex; Sulitjelma gabbro; Honningsvåg igneous complex; Pedersen et al., 1992; Andréasson et al., 2003; Corfu et al., 2006). Therefore the early Silurian heating event is most likely due to widespread magma underplating. The tectonic implications for this are discussed further in section 5.3.

The second part to the anticlockwise evolution, the peak pressure Caledonian P-T conditions (S2), were estimated in multiple samples in Papers I, II and III and vary between 580 – 730 °C and 9.5 – 15 kbar through different parts of the KNC and RNC, indicating metamorphism at mid- to lower crustal conditions, associated with crustal thickening. The timing of this event is recorded between ~440 – 425 Ma in both the KNC and RNC. Figure 6 shows all peak (peak pressure) P-T estimates for the S2 foliation from Papers I, II and III.

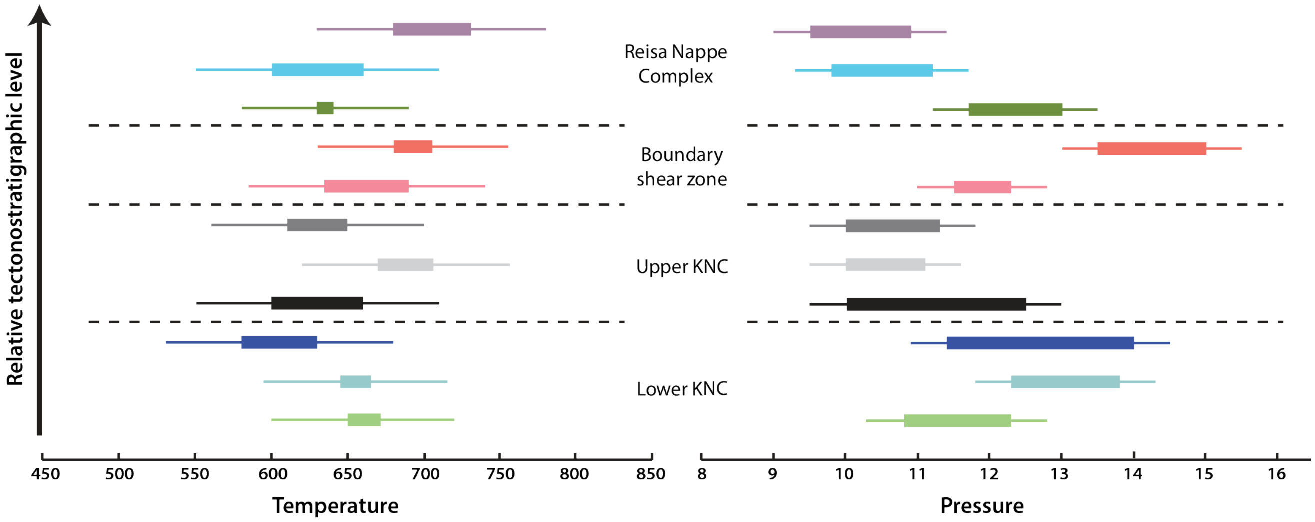


Figure 6 – Comparison of P-T estimates with respect to tectonostratigraphic level for the Kalak and Reisa Nappe Complexes. Temperature estimates (left) are shown with an error bar of ± 50 °C. Pressure estimates (right) are shown with an error bar ± 0.5 kbar.

Considering a ±50 °C maximum error on the P-T estimates, temperature does not vary significantly throughout the KNC and RNC (Fig. 6). Although, temperature conditions for shearing along major nappe boundaries generally show an increase in temperature upwards, indicative of an inverted metamorphic temperature gradient. The highest S2 temperature estimate is recorded at the top of the RNC. The pressure variation between the different nappes is more significant. In the KNC, pressures for S2 shearing along nappe boundaries generally increase upwards (basal KNC at low greenschist, lower KNC-upper KNC at ~11-14 kbar, and KNC-RNC boundary at 13-15 kbar), indicating a general inverted metamorphic pressure gradient for shearing along nappe boundaries. However, pressures in the RNC show a strongly decreasing pressure gradient upwards, from 11-13 kbar in the Vaddas nappe to ~9-11 kbar in the overlying Kåfjord and Nordmannvik Nappes (Fig. 6). Pressures in the cores of the KNC nappes are also more variable, and likely as a result of temporal variation in deformation between the nappe cores and nappe boundaries. The core of the lower KNC nappe records relatively higher pressures than the core of the upper KNC nappe and the upper parts of the

RNC (Kåfjord and Nordmannvik nappes). The tectonic implications for the temperature and pressure gradients are discussed more in section 5.3.

5.2 Implications for the paleogeography of the Baltoscandian margin

A better understanding of the context and distribution of pre-Caledonian events can allow us to speculate on the configuration of the pre-Caledonian Baltica margin. The timing of some pre-Caledonian events in the KNC not recorded elsewhere along the northern Norwegian Baltica margin does not necessarily preclude the formation of the KNC rocks near or at the Baltica margin, as previous authors have suggested (e.g. Kirkland et al., 2006a, 2007b, 2008b; Corfu et al., 2007; 2011). Though the lower KNC rocks record Sveconorwegian/Grenvillian intrusion and magmatism, the current northern Norwegian Baltica basement does not, and the northernmost Sveconorwegian rocks are currently found near Trondheim, with the majority in southern Norway (e.g. Bingen et al., 2008). Gee et al., (2017) argued that a northern Norwegian pre-Caledonian Baltica margin that did include Sveconorwegian elements may have been lost by subduction of continental crust during Caledonian continental collision. Roberts (2003) and Zhang et al., (2016) showed that the metasediments in the lower KNC were sourced from S-SE on the Fennoscandinan shield, based on paleocurrent data in low-grade metasedimentary rocks of the lower KNC and Laksefjord Complex in Finnmark. Considering current Rodinia re-constructions showing the configuration of Balitca-Laurentia-Rodinia (e.g. Li et al., 2008), it is not difficult to imagine that the Sveconorwegian Orogen extended further north into the Arctic, and was lost to Caledonian continental subduction. Therefore I favour the interpretation that the KNC rocks formed as part of the edge of pre-Caledonian Baltica margin. The age and context of tectonic event/s associated with juxtaposition of the upper KNC with the lower is still unclear and more work needs to be done to better constrain it. Kirkland et al., (2006a) discusses the possibility that the KNC formed by stepwise accretion, with the uppermost units representing the most recently accreted units. The age of the SIP and Corrovarre intrusives correspond with extension during the opening of the Iapetus ocean and probably the development of an extended Baltica margin (e.g. Andréasson, 1994; Andersen et al., 2012).

Based on the lack of ocean floor rocks in or below the KNC and RNC, and the likelihood that the upper parts of the KNC were juxtaposed with the lower Baltica-derived units (Fagervik Complex) prior to the Caledonian and reworked during the Caledonian, the KNC probably formed part of a wide Baltoscandian margin prior to collision and nappe stacking. Rice (2014) used branch-line reconstruction to show that the pre-Caledonian Baltoscandian margin was likely shortened by at least 250 km during Caledonian nappe-stacking. The inverted metamorphic gradient related to nappe boundaries in the KNC and RNC indicates in-sequence thrusting, so that deconstructing the nappes into their relative paleogeographic positions can be done using a simple block model unstacking the nappes (presented in Paper II – Fig. 14A). Based on mapping, the Vaddas (and lower Kåfjord) metasediments were deposited on a KNC basement, probably forming part of the outer Baltoscandian margin, just prior to collision. It is likely that the pre-Caledonian margin of Baltica was laterally extensive, with different units that form the different nappes relatively far apart, although evidence for hyperextension (as suggested for southern Norway; Andersen et al., 2012) is so far lacking in northern Norway.

5.3 Implications for Caledonian continental collision

Based on the configuration of the pre-Caledonian Baltoscandian margin and the timing and conditions of Caledonian deformation, magmatism, and metamorphism the tectonic processes associated with Caledonian continental collision can be discussed in more detail.

5.3.1 Metamorphism and tectonic setting

Changes in the type of metamorphism with time reflects different geodynamic processes. The anticlockwise P-T path for Caledonian metamorphism is particularly well recorded in the Nordmannvik Nappe. The recognition of an anticlockwise P-T path alone is not diagnostic of a particular tectonic setting, and continental collision can generate clockwise or anticlockwise P-T paths depending on rates of thickening and heat transfer (Wakabayashi, 2004). Normal collisional orogenesis generally follows a clockwise P-T path (e.g. Wakabayasi, 2004). Anticlockwise P-T paths are most common in granulite terranes, where rocks are heated immediately prior to or in conjunction with crustal thickening (e.g. magmatic underplating below an actively thickening region, involvement of a pre-existing arc or back arc in orogenesis; Abati et al., 2003; Johnson and Strachan, 2006). Paper II discusses the tectonic implications of early Caledonian event in the RNC. The most important elements related to this event that need explanation are 1) the deposition of Vaddas sediments on the KNC, rapid burial of sediments (Vaddas) to 7-9 kbar (33-30 km), and intrusion of tholeiitic gabbro at that depth in a compressional setting, 2) roughly contemporaneous migmatisation in the Nordmannvik nappe at ~30-35 km depth, and 3) initial compressional Caledonian deformation of the Nordmannvik rocks while partially molten followed by solid-state shearing.

Possible tectonic scenarios discussed in paper II include: 1) subduction of a spreading ridge (e.g. Northrup, 1997; Corfu et al., 2007), 2) an incipient back-arc basin, and 3) slab break-off at the onset of subduction. The first option is unlikely because the effect of ridge-subduction is usually very localized, and magma typically intrudes the overriding plate (e.g. Lomize and Luchitskaya, 2012). The second two options offer possible scenarios for the early Caledonian metamorphism and widespread magmatism. Magma underplating in either scenario is a good explanation for the tholeiitic mafic intrusives. A common explanation used to explain high-temperature conditions prior to high-pressure conditions is when a back arc forms and is subsequently closed and inverted during continental collision and crustal thickening (e.g. Johnson and Strachan, 2006). In the case of the RNC, the main problem with interpreting the rocks as having formed in an incipient continental back-arc is their tectonostratigraphic position within the northern Norwegian nappe stack. The lack of ocean floor rocks below them suggests that the suture is tectonostratigraphically above. Alternatively, if they formed as part of a back-arc on the Baltica margin, then subduction would have been eastward (e.g. Andréasson et al., 2003). Considering the back-arc hypothesis, the geochronology requires that a switch from extension to compression and closure of the back arc would have had to occur over only 10 million years. In addition, a hypothetical back-arc basin would have had to accommodate extremely rapid burial of Vaddas metasediments to at least ~20 km depth prior to intrusion of the Kågen gabbro, as the Kågen gabbro has an intrusion depth between 7-9 kbar (Getsinger et al., 2013).

As a solution, slab break-off then becomes more attractive because it better explains the rapid burial of the Vaddas metasediments and the deep intrusion of gabbro (Paper II – Fig. 14B). It also provides a heat source for migmatisation, an explanation for the compressional deformation of partially molten Nordmannvik Nappe rocks, and a source of the sagvandite slivers (metasomatised mantle rocks) that occur within this nappe. Interaction between crustal rocks and the mantle is not often recorded in the geologic record, however it is likely (e.g. Jahna et al., 1999). Slab break-off at or around ~445 Ma would also have facilitated widespread magmatism in both the upper and lower plates. In this case, the difference in the early Caledonian P-T in the KNC and Nordmannvik Nappe, and the presence of early Silurian mafic magmatism in the RNC and not the KNC, indicates that the Nordmannvik Nappe rocks were deeper and closer to the heat source (magma underplating) that drove early Caledonian high-temperature metamorphism. As discussed in paper II, in a slab break-off scenario migmatisation of the subducted Nordmannvik nappe rocks would have weakened them and made them more buoyant, possibly initiating nappe thrusting and exhumation of the down-going Baltica rocks. In the Nordmannvik nappe, thrusting is recorded mainly as a decrease in temperature during S2 shearing, indicating the rocks were not buried significantly after partial melting. Whereas the Kåfjord and Vaddas metasediments underwent a significant pressure increase during crustal thickening.

The conditions for S2 shearing record P-T conditions that could be classified on the lower-end of ecolgite-high pressure granulite (E-HPG) metamorphism, a regime considered to represent subduction or underthrusting of crustal rocks (e.g Brown, 2007). The ~440 – 430 Ma ages recorded for this metamorphism in Papers I and II (Paper I – Fig. 11; Paper II – Fig. 13) in the KNC and RNC suggest that continental collision and subduction of continental crust had begun during this time. The variation in P-T associated with S2 shearing throughout the nappes can be used to discuss mechanisms that facilitated crustal thickening.

5.3.2 Construction of northern Norwegian Caledonian Nappes

Crustal thickening generally occurs in continental collision zones. The crust can thicken by sedimentation, magmatic intrusion, and/or crustal shortening. Crustal shortening in continental collision zones is often accommodated by displacement of material in the lower crust. The increase in pressure recorded for amphibolite facies S2 shearing and nappe stacking in the northern Norwegian Caledonides indicates that crustal thickening was facilitated by the formation of ductile nappes, (displacement of material as laterally extensive thrust sheets) as Laurentia and Baltica collided. The inverted metamorphic gradient displayed for shearing along nappe boundaries indicates in-sequence nappe thrusting. However, the variation in pressure in the cores of the nappes is probably temporal and suggests underthrusting may have played an important role in the formation of the nappes (e.g. Fig. 6 the KNC, Paper III – Fig. 13B). Considering both the KNC and RNC together, pressure in the cores of the nappes generally increases downwards (i.e. the core of the lower KNC displays higher pressures than the core of the upper KNC or the Kåfjord and Nordmannvik Nappes. The higher pressures towards the bottom of the nappe stack can be explained by underthrusting of the RNC by the upper KNC, and underthrusting of the upper KNC by the lower KNC. This is consistent with the interpretation that the RNC (particularly the Nordmannvik Nappe) was weak and buoyant due to partial melting (Paper II), while the KNC comprised strong colder rocks. The lower KNC nappe, comprised mainly of quartz-feldpsar rocks (orthogneiss and meta-arkose) was probably strongest. Underthrusting is usually considered as a large-scale mechanism for the subduction of strong continental crust in collisional zones (e.g. Zhao et al., 1993). Ages in the lowermost rocks in the KNC that display lower-grade amphibolite and greenschist facies metamorphism indicate younger shearing (430-420 Ma; Kirkland et al., 2008a). These units record younger nappe stacking towards shallower crustal levels. Greenschist facies metamorphism associated with S2 therefore represents the final emplacement of the KNC over the para-autochtonous sediments and Baltica. Therefore the P-T pattern for S2 shearing in the KNC and RNC rocks records nappe stacking in the mid- to lower crust, probably mostly accommodated by underthrusting of colder units below warmer units, prior to final emplacement of the KNC to higher levels in the crust (recorded by younger greenschist facies metamorphism in the lower units).

6 Concluding remarks and recommendations for future research

The constraints we put on the timing and conditions of metamorphism and deformation in the Kalak and Reisa nappe complexes applies to current research by 1) constraining tectonic evolutions relating to the formation of supercontinents (e.g. Li et al., 2008), and 2) improved understanding of mid- to lower-crustal dynamics of continental collision. Establishment of the metamorphic conditions and timing of pre-Caledonian events allowed for the discussion of the paleogeography of the Baltoscandian margin. And constraining an anticlockwise P-T evolution for Caledonian metamorphism led to an alternative tectonic explanation (slab break-off) for early Silurian magmatism in the northern Caledonides. Establishing metamorphic conditions for S2 shearing provided constraints on the depth, conditions, and possible mechanisms of crustal thickening, and establishing the timing and conditions of lower crustal partial melting allowed for discussion about the strength of subducted crust during continental collision, and the role it might play in initiating nappe thrusting and exhumation.

In order to solve existing large-scale regional problems and answer process-based questions with respect to continental collision in the Caledonides, the timing of deposition, metamorphism and deformation in northern Norway needs to be further constrained and better correlated with the rest of the Scandinavian Caledonides. For example, the Seve Nappe Complex has previously been linked to the KNC (the Seve-Kalak superterrane; e.g.

Andréasson et al., 1998), but records similar early Caledonian high-grade metamorphism and magmatism to that which we observe in the RNC (Paper II – Fig. 13). However, the Seve Nappe Complex also records Ordovician UHP metamorphism (e.g. Klonowska et al., 2013) that we did not observe in any of the rocks in northern Norway. Therefore the relationship between the Seve Nappe Complex and northern Norwegian Caledonides, which are at similar tectonostratigraphic levels, needs to be better established.

To improve our understanding of the evolution of the nappes in northern Norway I recommend that further fieldwork and mapping be done on Laukøya and some of the smaller islands in the field area that were not visited for this work. I would also examine the Corrovarre Nappe to the south of the field area in more detail. Additionally, I think it would be interesting to perform some phase equilibrium modelling on KNC rocks in Finnmark, such as those on Sørøya and Magerøya, where several age dates already exist, to compare to the estimates from this work. In terms of age dating, I would recommend that detrital ages are determined for all three nappes in the RNC. The Kåfjord Nappe, in particular, could use more work (establishing the relationship and origin of the upper and lower parts, Paper II – Fig. 3). With respect to magmatism, I would recommend trying to date zircons from the granitic rocks that crosscut the $S1^S$ foliation on Skjervøy to better constrain its age of formation, and I would recommend trying to determine the age of $S1^S$ metamorphism directly using metamorphic minerals such as titanite. I would also recommend dating zircon from the orthogneiss unit in the lower KNC to confirm that it is part of the Fagervik Complex. In addition, it would be interesting to try dating the marble unit on northern Skjervøy to better understand its genetic history, as it is uncommon to find marbles in the lower KNC. To better understand the nature of the magmatism in the RNC I recommend more detailed geochemical work on the gabbros to better determine their petrogenetic context.

Since garnet in the study area often preserves several phases of metamorphism, I would also recommend trying Sm-Nd and Lu-Hf garnet dating (e.g. Smit et al., 2013) for some of the samples to better determine the timing of pre-Caledonian and Caledonian metamorphism. Because this age-dating method is a solution method and results are often difficult to interpret, I would recommend focussing on using it in the Reisa Nappe Complex first, to better understand the timing of garnet growth and better establish the anticlockwise P-T path. Care should be taken about using garnet dating in the KNC, as dating of polymetamorphic garnets is significantly more complicated (due to diffusion, and multiple growth episodes). On a more general and larger scale, I would recommend more work on understanding the relationship between the Lyngsfjellet Nappe and the Nordmannvik Nappe. A better understanding of the abrupt decrease in metamorphic conditions, and better constraints on the shear sense along the Nordmannvik-Lyngsfjellet boundary will lead to better tectonic interpretations of the entire region.

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Supplementary Material