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Mid/Late Devonian-Carboniferous extensional faulting in Finnmark and the SW Barents Sea

A study of onshore and offshore brittle faults and fault-rocks, and their timing relationships

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Preface

The present Ph.D. thesis is the outcome of a Ph.D. project affiliated to Work Package 2 of the Research Centre for Arctic Petroleum Exploration (ARCEx), funded by the Research Council of Norway and the Norwegian authorities (grant 228107), in partnership with ten academic/research institutes and eight companies. During the Ph.D., I was employed by UiT-The Arctic University of Norway, the degree-awarding institution, and the ARCEx for a three-year period (March 2015-March 2018). Professor Steffen G. Bergh and Professor Jan-Inge Faleide were my primary and secondary supervisors.

This scientific project is the continuation of an initiative by Professor Steffen G. Bergh that started in Lofoten-Vesterålen and Western Troms with three earlier Ph.D. projects aiming at linking onshore and offshore brittle faults along the Norwegian continental shelf (Eig, 2008; Hansen, 2009; Indrevær, 2014). The thesis herein focuses on brittle faults in NW Finnmark and along the SW Barents Sea margin. More specifically, the thesis provides detailed mapping and structural analysis of brittle faults onshore NW Finnmark and in nearshore fjords and controlling fabrics (**Paper 1**). The thesis also addresses the early stages of formation of the margin in the late Paleozoic during late/post-orogenic extension related to the collapse of the Caledonides, with emphasis on offshore, sedimentary basin-bounding fault complexes (**Paper 2**). Finally, the thesis resolves absolute timing constraints on fault activity in NW Finnmark and pressure/temperature (p/T), and thus depth, estimates at time of faulting (**Paper 3**).

Paper 1: Koehl, J-B. P., Bergh, S. G., Osmundsen, P-T., Redfield, T. F., Indrevær, K., Lea, H. and Bergø, E.: Late Devonian-Carboniferous faulting in NW Finnmark and controlling fabrics, Norwegian Journal of Geology, submitted.

Paper 2: Koehl, J-B. P., Bergh, S. G., Henningsen, T., and Faleide, J. I.: Mid/Late Devonian-Carboniferous collapse basins on the Finnmark Platform and in the southwesternmost Nordkapp basin, SW Barents Sea, Solid Earth, 2018.

Paper 3: Koehl, J-B. P., Bergh, S. G. and Wemmer, K.: Neoproterozoic and post-Caledonian exhumation and shallow faulting in NW Finnmark from K/Ar dating and p/T analysis of fault-rocks, Solid Earth, submitted.

As part of my Ph.D., I attended a six-week course at the University Centre in Svalbard (UNIS) dealing with rift-basins reservoirs, which introduced me to the outstanding geology of Carboniferous rocks in Svalbard. Following this course, I led two field excursions to Bjørnøya and Spitsbergen, where I collected additional field data in early-mid Carboniferous sedimentary rocks, which will be published separately from this thesis.

I have also stayed at San Diego State University for three weeks mapping a portion of the San Andreas fault in Indio Hills as an analog to the Barents Sea sheared margin. Through this stay, I expanded my network, became aware of societal challenges Structural Geology and Tectonics face, thus broadening my horizons, and got to study a small piece of the world's most breathtaking geology. The results of this ongoing project with my primary supervisor, Professor Steffen G. Bergh, will be published elsewhere.

Acknowledgements

I express my most sincere gratitude to my primary supervisor Professor Steffen G. Bergh (UiT) for spending much time reviewing my writings and for initiating me to the amazing geology of Troms and Finnmark. Thank you very much Steffen for engaged scientific discussions and for your thorough guidance with scientific writing. In the future, I hope to get the chance to pass on the enthusiasm you gave me for Geology.

I also thank my secondary supervisor Professor Jan-Inge Faleide (UiO and UiT) for encouraging my initiatives and ideas and for introducing me with his research in the Barents Sea.

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Many thanks to Professor Arthur Sylvester from the University of Santa Barbara, California, and Jack Brown from the San Diego State University for fruitful field collaboration and scientific discussions when mapping a segment of the San Andreas fault in southern California.

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Thanks to my sisters, my parents and my grandparents for their love and encouragements through my Ph.D., and for the stability and joy they constantly provide me as a family.

Finally yet importantly, I express my deepest admiration and gratefulness to my wife for the inspiration she constantly provides me with in my research, for fieldwork collaboration, for critical advice on every scientific and popular presentations I give, and for her resilient patience and understanding throughout the incredible journey this Ph.D. was. Tu me encantas Hermosa.

Introduction

1.1 Background

This research is part of the ARCEx work-package two “Petroleum systems and play concepts”. The Ph.D. project is a continuation of the work initiated by Professor Steffen Bergh in 2002 with the project “Tectonic development of faults on the Lofoten-Vesterålen continental margin; comparison with land” and involving UiT-The Arctic University of Norway, the Geological Survey of Norway and industry partners. Earlier research include scientific articles (Bergh et al., 2007, 2008; Eig & Bergh, 2011; Hansen et al., 2012; Hansen & Bergh, 2012; Indrevær et al., 2013, 2014; Indrevær & Bergh, 2014), and Ph.D. theses in Lofoten-Vesterålen (Eig, 2008; Hansen, 2009) and Western Troms (Indrevær, 2014).

In the present Ph.D. thesis, we focus on brittle faults in coastal areas in NW Finnmark adjacent to the offshore Finnmark Platform in the SW Barents Sea (Figure 1). This Ph.D. project aimed at

(1) Establishing and resolving the architecture of Devonian-Carboniferous basins and basin-bounding faults on the Finnmark Platform and the southwesternmost Nordkapp basin using seismic data;

(2) Mapping and correlating onshore-nearshore fault complexes, such as Langfjord-Vargsund fault and Trollfjorden-Komagelva Fault Zone, and resolving their geometry, kinematic characters and interaction using structural fieldwork, high-resolution fjord bathymetry and aeromagnetic data;

(3) Providing constraints on pressure-temperature conditions (i.e. depth) during faulting through detailed analysis of onshore fault-rocks and, thus, resolving the exhumation history of NW Finnmark and the SW Barents Sea;

(4) Providing absolute ages and timing constraints on faulting in NW Finnmark using K/Ar radiochronology;

(5) Evaluating the influence of pre-existing, Caledonian and Proterozoic fabrics on late Paleozoic brittle faults.

1.2 Geological setting

Offshore geology

In the mid-late Paleozoic, Baltica and Laurentia collided to form the Caledonides (Corfu et al., 2014). Caledonian contraction was followed by a stage of late/post-orogenic collapse with widespread extension, resulting in the formation of spoon-shaped, Middle Devonian sedimentary basins in western- (Séranne et al., 1989; Chauvet & Séranne, 1994; Osmundsen & Andresen, 2001) and mid-Norway (Braathen et al., 2000), and of Carboniferous sedimentary rift-basins in the SW Barents Sea, e.g. the Nordkapp and Hammerfest basins (Gudlaugsson et al., 1998; Faleide et al., 2008; Indrevær et al., 2013). The study of exploration well-logs and shallow drill-cores on the Finnmark Platform shows that Carboniferous basins in the Barents Sea are filled with clastic and coal-bearing sedimentary rocks of the

Billefjorden Group and evaporite-bearing sedimentary strata of the Gipsdalen Group (Bugge et al., 1995; Larssen et al., 2002; Samuelsberg et al., 2003; Rafaelsen et al.,2008), analog to those found on Bjørnøya (Gjelberg, 1981, 1984; Gjelberg & Steel, 1983; Worsley et al., 2001) and Spitsbergen (Cutbill & Challinor, 1965; Cutbill et al., 1976; Gjelberg & Steel, 1981; Gjelberg, 1984; Braathen et al., 2011). Subsequent Mesozoic-Cenozoic extension related to the opening of the NE Atlantic Ocean is well-constrained (Faleide et al., 2008), but had little influence on the geometry of these basins in coastal areas of Finnmark.

Major offshore, basin-bounding fault complexes typically display zigzag geometries in map-view with alternating ENE-WSW and NNE-SSW trending fault-segments, northwestwards dips and listric attitudes in cross-section, e.g. Troms-Finnmark Fault Complex (TFFC; Figure 1; Gabrielsen et al., 1990; Gudlaugsson et al., 1998). Occasionally, these faults display abnormally linear map-view geometries, like the Måsøy Fault Complex (MFC; Figure 1; Gabrielsen et al., 1990; Gudlaugsson et al., 1998).

The SW Barents Sea margin is segmented by WNW-ESE to NNW-SSE trending transfer zones. The largest is the De Geer Zone, which proceeds northward to Svalbard off the coasts of Norway as the Senja Fracture Zone. In the south, the transform fault system merges with the Senja Shear Belt and Bothnian-Senja Fault Complex onshore Western Troms (Figure 1; Faleide et al., 2008). In western Finnmark, analog structure are present, e.g. the NNW-SSE trending Fugløya transfer zone (Figure 1; Indrevær et al., 2013; Indrevær & Bergh, 2014).

In the North Sea, recent seismic studies highlight the continuation of large Caledonian shear zones, e.g. the Hardanger and Karmøy shear zones, below sedimentary rift basins (Phillips et al., 2016; Fazlikhani et al., 2017). These define seismic packages of high reflectivity (Fountain et al., 1984) that are easily mapped in the footwall of merging brittle faults, e.g. the Åsta Fault that soles into the offshore prolongation of the Karmøy Shear Zone (Phillips et al., 2016).

Onshore geology

In NW Finnmark, analog zigzag-shaped, NW-dipping, listric normal faults, e.g. Langfjord-Vargsund fault (LVF; Zwaan & Roberts, 1978; Lippard & Roberts, 1987; Bergø, 2016; Lea, 2016), crosscut Caledonian nappes, e.g. the Kalak Nappe Complex and Magerøy Nappe (Roberts, 1973; Corfu et al., 2014), and Archean-Paleoproterozoic rocks of the Fennoscandian basement exposed in tectonic windows (Reitan, 1963; Roberts, 1973; Zwaan & Gautier, 1980; Gautier et al., 1987; Bergh & Torske, 1988; Jensen, 1996). An analog to the LVF in Western Troms is the SE-dipping Vestfjorden-Vanna fault complex, which is thought to proceed offshore onto the Finnmark Platform west and merge into the Nysleppen and Måsøy fault complexes (Indrevær et al., 2013).

In northern Finnmark, the LVF interacts with an older, WNW-ESE trending Neoproterozoic fault, the Trollfjorden-Komagelva Fault Zone (TKFZ; Siedlecka & Siedlecki, 1967; Siedlecki, 1980; Herrevold et al., 2009). This fault is believed to extend onto the Finnmark Platform and to merge with a similarly trending fault segment of the TFFC (Figure 1; Gabrielsen, 1984; Gabrielsen & Færseth, 1989; Roberts et al., 2011). East of the Varanger Peninsula, the TKFZ continues offshore where it bounds a NE-verging, Carboniferous half-graben (Figure 1) and merges with the Sredni-Rybachi Fault Zone in Russia (Roberts et al., 2011).

Absolute age dating

Existing K/Ar dating of fault gouge in the footwall of the LVF indicate that post-Caledonian faulting initiated in the early Carboniferous and persisted until the early Permian, while a subsidiary Early Cretaceous age suggests brittle faults in NW Finnmark experienced only mild Mesozoic reactivation (Torgersen et al., 2014). Along the TKFZ, faulting is constrained to the early Carboniferous, when transtension-related space opening enabled the emplacement of highly magnetic dolerite dykes that now seal the faults (Roberts et al., 1991; Lippard & Prestsvik, 1997; Nasuti et al., 2015). These ages are comparable to Late Devonian ages obtained on analog dykes intruded along NE-SW to N-S trending faults in eastern Finnmark (Guise & Roberts, 2002) and adjacent areas in Russia (Roberts & Onstott, 1995). Analogously in Western Troms, radiometric dating of onshore fault-rocks indicates that post-Caledonian faulting mostly took place in the Late Devonian-early Carboniferous (Davids et al., 2013).

Radiometric dating of inverted basement-seated shear zones in Lofoten-Vesterålen indicates that the collapse of the Caledonides and associated exhumation of basement ridges (e.g. the Lofoten Ridge; Figure 1) as core complexes may have initiated as early as the Early Devonian (Steltenpohl et al., 2011). Similarly, in western Norway, Eide et al., (1999) suggested an episode of intensive crustal thinning in the Late Devonian-early Carboniferous due to extensional inversion of low-angle Caledonian detachments combined with continental erosion. This is consistent with results from Northeast Greenland, where exhumation of basement rocks along basement-seated shear zones was constrained to the early Carboniferous (Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2016).

1.3 Summary of papers

Paper 1: Koehl, J-B. P., Bergh, S. G., Osmundsen, P-T., Redfield, T. F., Indrevær, K., Lea, H. and Bergø, E.: Late Devonian-Carboniferous faulting in NW Finnmark and controlling fabrics, Norwegian Journal of Geology, submitted.

The goal of this paper was to correlate onshore and offshore brittle faults in NW Finnmark using field data, satellite images and high-resolution bathymetry data on the strandflat in order to expand and compare our results with the work started by Indrevær & Bergh (2014) in Western Troms. We also used a set of new, onshore-nearshore, high-resolution aeromagnetic data from the Geological Survey of Norway (NGU) to supplement our interpretation and distinguish brittle faults from ductile fabrics and large-scale glacial lineations. We specifically focused on mapping a large zigzag-shaped, NW-dipping fault complex, the LVF (Figure 1; Zwaan & Roberts, 1978; Lippard & Roberts, 1987), which is composed of alternating ENE-WSW and NNE-SSW trending fault segments and minor, adjacent, synthetic and antithetic splays outcropping in coastal areas. Aeromagnetic data reveal potential km-scale, down-to-the-NW normal offset of NNW-SSE/NW-SE trending, 10-80 km wide aeromagnetic anomalies associated with Precambrian, basement granite-gneiss belts across the LVF.

Bathymetry and aeromagnetic data show that the LVF is laterally offset by subvertical, WNW-ESE trending faults such as the Neoproterozoic TKFZ (Siedlecka & Siedlecki, 1967; Siedlecki, 1980; Herrevold et al., 2009) and the Akkarfjord fault (Figure 1; Roberts, 1971), which may have acted as potentially conjugate, strike-slip transfer faults segmenting the margin. Further analysis of the map-view architecture of the TKFZ using aeromagnetic anomalies of dolerite dykes intruded along the fault (Roberts et al., 1991; Nasuti et al., 2015) suggests that the TKFZ broadens westwards onto the island of Magerøya, potentially representing the fault-tip process zone (Shipton & Cowie, 2003; Braathen et al., 2013) of the TKFZ, and dies out before reaching deep offshore portions of margin on the Finnmark Platform (Figure 1). However, km-scale lateral motions along margin-oblique faults appear to be responsible for the sigma-shaped (drag-folded?), map-view geometry of ENE-WSW to NNE-SSW trending fault segments and grabens along the LVF, e.g. the Ryggefjorden trough, which may represent small-scale analogs to offshore basins like the Nordkapp Basin.

This work also discusses several controlling basement fabrics mapped on high-resolution aeromagnetic data. These fabrics include (i) steep, NW-plunging folds in Proterozoic basement rocks of the Altenes (Jensen, 1996) and Alta-Kvænangen tectonic windows (Roberts, 1973; Zwaan & Gautier, 1980; Gautier et al., 1987; Bergh & Torske, 1988), (ii) NE-plunging folds in basement rocks of the Repparfjord-Komagfjord tectonic window (Reitan, 1963; Pharaoh et al., 1982, 1983), which fold limbs trend parallel to fault segments of the LVF and which hinge zones seem to coincide with major bends in the trace of the LVF, and (iii) inverted Caledonian, brittle-ductile thrusts, e.g. the Kvenklubben (Torgersen et al., 2014) and Talvik faults along which post-Caledonian normal faulting initiated (cf. Koehl et al., paper 3).

Post-Caledonian brittle faulting in NW Finnmark is constrained to the Late Devonian-Carboniferous by K/Ar dating along fault-segments of the LVF in Western Troms (Davids et al., 2013) and Finnmark (Torgersen et al., 2014; Koehl et al., paper 3) and by syn-tectonic, sedimentary growth strata along the northeastern prolongation of the LVF onto the Finnmark Platform (Koehl et al., paper 2), and by Ar/Ar ages obtained on dolerite dykes intruded along WNW-ESE trending fault segments of the TKFZ (Roberts et al., 1991; Lippard & Prestvik, 1997).

Paper 2: Koehl, J-B. P., Bergh, S. G., Henningsen, T. and Faleide, J. I.: Mid/Late Devonian-Carboniferous collapse basins on the Finnmark Platform and in the southwesternmost Nordkapp basin, SW Barents Sea, Solid Earth, 2018.

In this contribution, we mapped and analyzed three major fault complexes, the TFFC, MFC and LVF (Figure 1), which map-view and cross-section geometries are controlled by a large, km-thick, Caledonian thrust, the Sørøya-Ingøya shear zone (SISZ; Figure 1). Our data show that the SISZ curves up and down, defining a spoon-shaped topographic depression that may have accommodated the deposition of Mid/Upper Devonian sedimentary growth strata along inverted thrusts and normal faults on the Finnmark Platform west and in the southwesternmost Nordkapp basin, which possibly represent analogs to Middle Devonian collapse basins in western Norway (Séranne et al., 1989; Chauvet & Séranne, 1994; Osmundsen & Andersen, 2001).

The interaction of the SISZ and subsequent, post-Caledonian fault complexes formed NE-SW to ENE-WSW trending basement ridges (Figure 1) that may represent metamorphic core complexes exhumed through excisement-incisement processes (Lister & Davis, 1989) in the Mid/Late Devonian-early Carboniferous. We further argue for a regional, NE-SW/ENE-WSW trending core complex comprising from northeast to southwest, the Norsel High (Gabrielsen et al., 1990; Gudlaugsson et al., 1998), basement ridges in the footwall of the TFFC, the West Troms Basement Complex (Zwaan, 1995; Bergh et al., 2010) and the Lofoten Ridge (Blystad et al., 1995; Bergh et al., 2007; Figure 1). The end of core complex exhumation is constrained by a regional, mid-Carboniferous (Serpukhovian) erosional truncation of Devonian-lower Carboniferous sedimentary strata on the Finnmark Platform formed by the interplay of core complex exhumation and a major phase of eustatic sea-level fall (Saunders & Ramsbottom, 1986), which is further supported by analog observations in NE Greenland (Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2016).

Alternatively to previous models linking the TKFZ onshore northern Finnmark to the adjacent, subparallel, fault segment of the TFFC west of Magerøya (Gabrielsen, 1984; Gabrielsen & Færseth, 1989; Roberts et al., 2011) and to the “fault-tip process zone” model examined in Koehl et al. (paper 1), this contribution explores a potential truncation of the TKFZ during top-to-the-SE, Caledonian thrusting along the SISZ (Figure 1). We further discuss the formation of the WNW-ESE trending fault-segment of the TFFC as a hard-linked, accommodation cross-fault (Sengör, 1987) transferring displacement from the TFFC to the MFC during late/post-orogenic collapse along the SISZ. Importantly, this work differentiates margin-oblique, subvertical, Precambrian, strike-slip to oblique-slip fault fabrics like the TKFZ (Siedlecki, 1980; Herrevold et al., 2009; Koehl et al., paper 1) from post-Caledonian, listric, normal dip-slip faults such as the WNW-ESE striking segment of the TFFC.

Later on, in Carboniferous times, extension localized along new high-angle, normal fault complexes, e.g. the TFFC, MFC and LVF (Figure 1 & Figure 2), possibly formed as extensional brittle splays of inverted Caledonian thrusts like the SISZ. These high-angle normal faults now bound (half-) grabens filled with thickened, syn-tectonic, Carboniferous sedimentary deposits on the Finnmark Platform and (upper Carboniferous) evaporite-rich basins like the southwesternmost Nordkapp basin

(Figure 1), which may represent a shallow analog to the Nordkapp Basin. The Finnmark Platform and the southwesternmost Nordkapp basin were tectonically quiet after the end of the Carboniferous and experienced only minor extensional reactivation in Permian-Cenozoic times.

Paper 3: Koehl, J-B. P., Bergh, S. G. and Wemmer, K.: Neoproterozoic and post-Caledonian exhumation and shallow faulting in NW Finnmark from K/Ar dating and p/T analysis of fault-rocks, Solid Earth, submitted.

This paper uses K/Ar radiochronology of syn-kinematic illite in non-cohesive fault-rocks and p/T estimates from microtextural and mineralogical analyses of cohesive fault-rocks in Caledonian nappes and Precambrian basement rocks to resolve the absolute timing of formation of studied brittle faults and discuss the exhumation of Caledonian and Precambrian rocks in NW Finnmark.

On the one hand, three faulting events occurred from the latest Mesoproterozoic to mid Neoproterozoic (ca. 1050-810 Ma) in Paleoproterozoic basement rocks of the Alta-Kvænangen tectonic window. These included (i) latest Mesoproterozoic (ca. 1050 Ma.) and (ii) early Neoproterozoic (ca. 945 Ma) normal faulting characterized by quartz- and calcite-rich cataclasites formed at depth of ca. 5-10 km, possibly related to the opening of the Asgard Sea (Siedlecka et al., 2004; Nystuen et al., 2008; Cawood et al., 2010; Cawood & Pisarevsky, 2017), and (iii) a shallow depth (1-3.5 km), mid-Neoproterozoic (ca. 825-810 Ma) faulting episode with abundant authigenic smectite, most likely dating the initial phase of opening of the Iapetus Ocean-Ægir Sea and breakup of Rodinia between 825-740 Ma (Torsvik & Rehnström, 2001; Hartz & Torsvik, 2002; Li et al., 2008). Exhumation rates estimates in the order of 10-75 m per Ma between the opening of the Asgard Sea and Iapetus Ocean-Ægir Sea (ca. 945-825 Ma) suggest a period of tectonic quiescence through which exhumation may be explained by continental erosion alone. The preservation of abundant authigenic smectite in cohesive and non-cohesive fault-rocks suggests that brittle faults crosscutting Paleoproterozoic basement rocks of the Alta-Kvænangen tectonic window remained at shallow depth (< 3.5 km) since the mid-Neoproterozoic (ca. 825 Ma) and were not reactivated after mid-Neoproterozoic times, although oriented parallel to major Caledonian thrusts and post-Caledonian normal faults.

On the other hand, five faulting events defining three faulting periods were identified in Caledonian rocks. First, brittle faulting potentially initiated during late Caledonian thrusting in the Silurian at 10-16 km depth, and was possibly associated with epidote/chlorite-rich, stilpnomelane-bearing cataclasite. Second, widespread, Late Devonian-early Carboniferous (ca. 375-325 Ma) extensional faulting, possibly related to the collapse of the Caledonides, occurred at decreasing depth and was accompanied by quartz- (3-10 km depth), calcite- (5-7 km depth) and laumontite-rich cataclasites (2-8 km depth) formed through three discrete faulting events. Third, a final period of minor shallow faulting occurred in the late Carboniferous-mid Permian (ca. 315-265 Ma) and was characterized by smectite/chlorite-smectite rich fault-rocks formed at depth of 1-3.5 km, hence suggesting that Caledonian rocks were progressively exhumed to near-surface depth in late Paleozoic times. Decreasing exhumation rates, < 220 m per Ma in the Silurian-Late Devonian (425-375 Ma), < 160 m per Ma in Late Devonian-early Carboniferous (375-325 Ma) and < 115 m per Ma from mid-Carboniferous to mid-Permian times (325-265 Ma) support the inferred transition from widespread, extensive Caledonian thrusting and collapse-related normal faulting to minor, late Carboniferous-mid Permian normal faulting. Alternatively, late Carboniferous-mid Permian K/Ar ages may reflect an episode of weathering in NW Finnmark. Subsequent Mesozoic-Cenozoic extension migrated westwards and NW Finnmark remained tectonically quiet from the mid-Permian.

1.4 Synthesis

The SW Barents Sea margin experienced multiple stages of extension since the late Paleozoic. On the one hand, Mesozoic-Cenozoic rifting and subsequent break-up are well-constrained (Faleide et al., 1984, 1993, 2008). On the other hand, late Paleozoic, post-Caledonian extension is much less studied due to the great depth of Carboniferous faults and sedimentary units in the Barents Sea and due to the lack of late Paleozoic sediments onshore northern Norway. Although a few studies previously attempted to map brittle faults in northern and eastern Finnmark using bathymetry data and fieldwork (Roberts, 1971; Worthing, 1984; Lippard & Roberts, 1987; Roberts & Lippard, 2005; Roberts et al., 2011), regional fault complexes in this part of the margin remain poorly studied. For example, the presence of the LVF was, so far, solely based on the juxtaposition of different Caledonian nappe units across Langfjorden and Vargsundet (Zwaan & Roberts, 1978), and most brittle faults were presumed post-Caledonian.

The present Ph.D. thesis provides a detailed and comprehensive geometric and kinematic analysis of these faults at both regional and local scale, as well as a thorough correlation of onshore and offshore faults like the LVF, TKFZ, TFFC and MFC (Koehl et al., papers 1 & 2). In addition, the thesis discusses potential pre-existing Precambrian-Caledonian fabrics and their controlling effects on post-Caledonian brittle faulting. Paper 3 presents new K/Ar ages obtained from authigenic illite clays in fault gouge and combine them with mineral assemblages in brittle fault-rocks to infer the evolution of p/T conditions during exhumation of Precambrian and Caledonian rocks in NW Finnmark. In combination, data from the three papers can be used to better constrain the late Paleozoic evolution of the SW Barents Sea margin (Figure 2).

In northern Norway, late/post-orogenic extension initiated as early as the Early Devonian (Steltenpohl et al., 2011) along inverted, spoon-shaped, brittle-ductile thrusts and shear zones, e.g. SISZ (Koehl et al., paper 2) and Talvik fault (Koehl et al., paper 1; Figure 2a), which truncated existing, margin-oblique (e.g. TKFZ; Koehl et al., paper 2) and margin-parallel, latest Mesoproterozoic-mid Neoproterozoic brittle faults related to the opening of the Asgard Sea and Iapetus Ocean (Koehl et al., paper 3). These thrusts remained active through the Devonian and early Carboniferous (Davids et al., 2013; Koehl et al., paper 3) and accommodated the deposition of thick, Mid/Upper Devonian growth strata, analog to those in Middle Devonian collapse basins in western Norway (Séranne et al., 1989; Chauvet & Séranne, 1994; Osmundsen & Andersen, 2001) and delineated by gravimetric lows (Johansen et al., 1994), and of subsequent, syn-tectonic, lower Carboniferous sedimentary rocks in spoon-shaped troughs on the Finnmark Platform and in the southwesternmost Nordkapp basin (Figure 2a-b; Koehl et al., paper 2).

Coeval, NE-SW trending basement ridges delineated by aeromagnetic highs exhumed as part of a regional metamorphic core complex along bowed portions of the SISZ and in the footwall of high-angle normal fault complexes, such as the TFFC and Rolvøya fault, which formed as extensional brittle splay-faults (Wilks & Cuthbert, 1994) following attitude changes of pre-existing basement fabrics (Figure 1 & Figure 2a-b; Koehl et al., paper 2). Extensive, late/post-Caledonian exhumation is also documented onshore adjacent areas in NW Finnmark by retrograde fault-rock mineral assemblages and K/Ar faulting ages along the LVF indicating rapid exhumation from > 10 km to 2-8 km depth in the Late Devonian-early Carboniferous (Koehl et al., paper 3). Exhumation had ceased by the mid-Serpukhovian when a major episode of eustatic sea-level fall (Saunders & Ramsbottom, 1986) contributed to expose and (partially) erode Upper Devonian (?) - lower Carboniferous sedimentary rocks.

In addition, inherited, margin-oblique brittle faults such as the TKFZ (Siedlecka & Siedlecki, 1967; Siedlecki, 1980) and Akkarfjord (Roberts, 1971) fault acted as (conjugate?) strike-slip transfer faults segmenting the margin and offsetting major fault complexes like the LVF (Koehl et al., paper 1; Figure 2a-b). The truncation of the TKFZ by inverted Caledonian thrusts (e.g. SISZ) and the alternative fault-tip process zone model imply that the TKFZ had only a limited impact on the structuration of offshore sedimentary basins along the SW Barents Sea margin. By contrast, the WNW-ESE trending, margin-oblique fault segment of the TFFC formed as a hard-linked, accommodation cross-fault (Sengör, 1987) due to incremental extension and displacement transfer between the TFFC and MFC, decoupling the Finnmark Platform west from the southwesternmost Nordkapp basin and allowing preservation of thick Mid/Upper Devonian-lower Carboniferous sedimentary succession in the latter (Figure 2a-c; Koehl et al., paper 2).

Further, late Carboniferous normal faulting localized along fewer, major, high-angle fault complexes, marking the decline of faulting activity. High-angle faults included the LVF, TFFC, MFC and Rolvsøya fault (Figure 2c; Koehl et al., papers 1 & 2) and these formed as extensional brittle splays of inverted thrusts (Wilks & Cuthbert, 1994; Koehl et al., paper 2), which zigzag-shaped map-view geometry is controlled by NW- and NE-plunging macrofolds and steep fold limbs in Paleoproterozoic basement rocks (Koehl et al., paper 1). In places, normal faulting led to the truncation of inverted Caledonian thrusts (Koehl et al., paper 1), slow exhumation of Caledonian rocks to < 3.5 km depth

(Koehl et al., paper 3) and deposition of thick, upper Carboniferous evaporites in the southwesternmost Nordkapp basin (Figure 2c; Koehl et al., paper 2). Bathymetry data further show that zigzag-shaped fault complexes bound sigma-shaped mini-basinswith dense, internal, fault-fracture networks (e.g. Ryggefjorden trough). These nearshore mini-basins potentially represent small-scale analogs to major offshore basins such as the Nordkapp Basin (Koehl et al., paper 1) and a detailed analysis of these mini-basins may yield valid input in the geometry of deep brittle faults and sedimentary strata below late Paleozoic evaporites.

Most offshore brittle faults die out within Carboniferous sedimentary successions and the resulting, constant thickness of Permian sedimentary rocks throughout the entire study area suggests that the margin was tectonically quiet by the end of the Carboniferous and was only subjected to minor, Permian-Cenozoic tectonic adjustments (Figure 2d; Koehl et al., paper 2). Alternatively, the large number of late Carboniferous-mid Permian K/Ar ages obtained in NW Finnmark reflect an episode of weathering (Koehl et al., paper 3), possibly consistent with weathering surfaces in Magerøya, with the tropical climate inferred for Baltica in Carboniferous-Permian times (Stemmerik, 2000; Larssen et al., 2002; Samuelsberg et al., 2003), with the regional erosional truncation of Mid/Upper Devonian-lower Carboniferous sedimentary deposits on the Finnmark Platform (Koehl et al., paper 2) and with the minimum Early Mesozoic age inferred for weathering surfaces in coastal areas of Norway (Olesen et al., 2012, 2013).

1.5 Future research

The results presented the present PhD thesis raise new questions and exciting challenges related to the Devonian-Carboniferous tectonic history of Arctic basins and faults in general. The following aspects and topics are considered important follow-ups of the project. First, extend the correlation of onshore and offshore faults to the Nordkinn-Varanger peninsulas in eastern Finnmark. Although analogous studies already exist offshore, east of the Varanger Peninsula (Roberts et al., 2011), poor seismic coverage and data quality north/northeast of the peninsulas make it difficult to distinguish faults from glacial troughs, e.g. the Djuprenna trough (Ottesen et al., 2008; Rise et al., 2015) erroneously interpreted as a WNW-ESE striking brittle fault on shallow seismic data (the Austhavet fault zone; cf. Townsend, 1987; Lippard & Roberts, 1987; Roberts et al., 2011).

Second, examine deep seismic images in the Hammerfest Basin in conjunction with seismic survey BSS-01 used in Koehl et al. (paper 2). NNW-SSE trending seismic 2D lines of this 2D survey show that the SISZ may extend below late Paleozoic-Cenozoic sedimentary strata of the Hammerfest Basin and possibly bound Devonian (?) – Carboniferous collapse-related, sedimentary deposits analog to those in the southwesternmost Nordkapp basin, minor (half-) grabens on the Finnmark Platform (Samuelsberg et al., 2003; Koehl et al., paper 2) and Middle Devonian basins in western Norway (Séranne et al., 1989; Osmundsen & Andersen, 2001). As well, extending the interpretation of the SISZ along the eastern flank of the Norkapp Basin, adjacent to the Finnmark Platform east is of great importance to resolve the early phases of formation of late Paleozoic basins like the Nordkapp Basin. Preliminary results suggest that the SISZ bends from a NE-SW to a NNW-SSE trend at the intersection of the southwestern and central segment of the Nordkapp Basin (Gernigon et al., 2014; Figure 1). In addition, low-angle normal faults bounding wedges of thickened pre-Permian (growth) strata appear to sole into the SISZ, displaying similar cross-section geometries as the MFC and the TFFC farther southwest (Koehl et al., paper 2).

Third, the potential exhumation of NE-SW to ENE-WSW trending basement ridges along inverted, bowed portions of the SISZ in Devonian-early Carboniferous times suggests widespread, regional extension during the deposition of clastic and coal-bearing sedimentary deposits of the Billefjorden Group in the SW Barents Sea, e.g. in the southwesternmost Nordkapp basin and on the Finnmark Platform (Koehl et al., paper 1, paper 2, paper 3). Analogously, onshore Bjørnøya, Late Devonian-early/mid Carboniferous sedimentary strata bear marks of extensive, syn-sedimentary normal faulting, while late Carboniferous-mid Permian are relatively undeformed (Worsley et al., 2001; Koehl, in prep.). Future research may explore brittle faults in lower Carboniferous deposits in Spitsbergen where sedimentary strata of the Billefjorden Group are considered as “pre-rift” deposits (Braathen et al., 2011). Preliminary results of fieldwork in newly exposed outcrops of Billefjorden Group sedimentary units in Odellfjellet, north of Billefjorden, show extensive fracturing and growth strata in lower/mid Carboniferous deposits, while most brittle faults die out before reaching overlying, upper Carboniferous sedimentary units, particularly most WNW-ESE trending faults (Koehl et al., in prep.). This discrepancy is rather curious considering the strong influence of NW-SE trending faults in shaping the margin in Cenozoic times, e.g. offset of the NE Atlantic Mid-Ocean Ridge west of Spitsbergen (Cianfarra & Salvini, 2015). Furthermore, recent field studies in Ellesmere Island in Arctic Canada suggest that lower Carboniferous sedimentary strata of the Borup Fiord Formation in the Sverdrup Basin represent syn-tectonic sedimentary units deposited in the hanging-wall of active normal faults (Beauchamp et al., submitted). This accounts for further structural fieldwork in lower Carboniferous sedimentary rocks in Spitsbergen and Arctic Canada in order to resolve the magnitude and extent of early Carboniferous extension.

Fourth, salt diapirism in the southwesternmost Nordkapp basin may have initiated in the late Carboniferous (Koehl et al., 2017), i.e. earlier than in the Nordkapp Basin where salt diapirism started in the Early Triassic (Nilsen et al., 1995; Rojo Moraleda et al., 2017). Further study of upper Carboniferous evaporite deposits in the southwesternmost Nordkapp basin may provide additional insights into the mechanisms that triggered and drove salt diapirism. Preliminary results suggest that high extension rate may have initiated salt diapirism in this basin (Koehl et al., 2017), while on the contrary extension had little to no impact on Early Triassic salt diapirism in the Nordkapp Basin (Rowan & Lindsø, 2017).

Fifth, the possible decapitation of the TKFZ during top-to-the-SE, Caledonian thrusting along the SISZ (Koehl et al., paper 2) suggests that segments of the TKFZ might be preserved in basement highs to the west. Preliminary results of ongoing work suggest this might be the case in basement rocks on the Veslemøy High (Kairanov et al., 2016), but much more work is needed to verify a correlation of these faults with the TKFZ. In addition, gravimetric anomalies on the Senja Ridge and the Veslemøy High seem to be left-laterally segmented along a WNW-ESE trending axis (Riis et al., 1986; Gabrielsen et al., 1990), which aligns with the imaginary prolongation of the onshore-nearshore Akkarfjord fault (Roberts, 1971), an inherited, WNW-ESE to ENE-WSW trending brittle fault in NW Finnmark that possibly formed as a conjugate to the TKFZ in Neoproterozoic times (Koehl et al., paper 1). Further interpretation of NNE-SSW/NE-SW oriented seismic sections on the Veslemøy High, Senja Ridge and on the southern edge of the Loppa High might help to explore and resolve the influence of WNW-ESE trending faults on the architecture of the SW Barents Sea margin.

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Figures

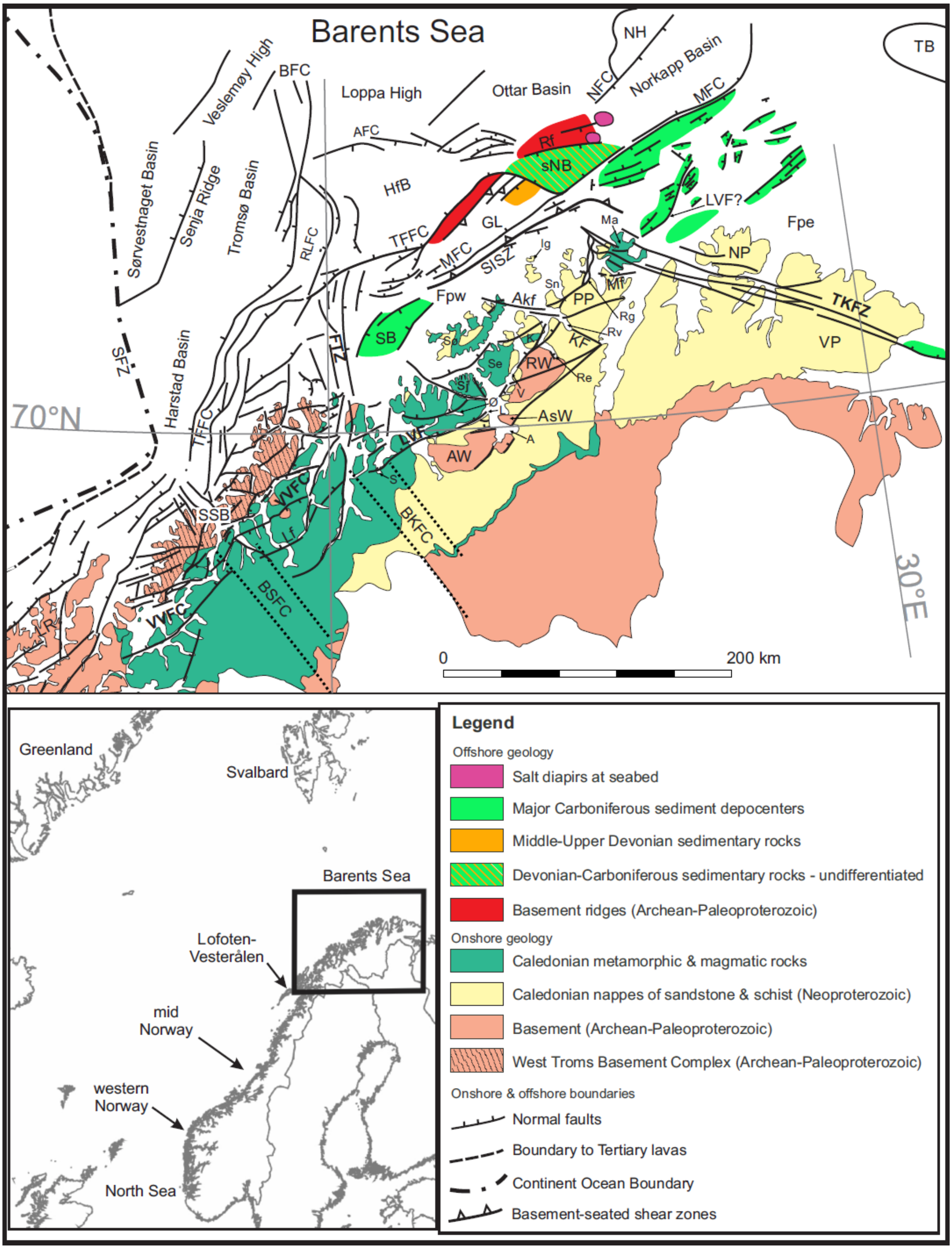

Figure 1: Regional tectonic map showing compiled architecture of brittle faults along the SW Barents Sea margin and onshore areas of NW Finnmark (based on Faleide et al., 2008; Hansen et al., 2012; Indreværet al., 2013). The onshore geology is partly from Ramberg et al. (2008). The black frame in the lower left inset locates the Barents Sea along the Norwegian continental shelf. Abbreviations: A = Altafjorden; AFC =

Asterias Fault Complex; Akf = Akkarfjord fault; AsW = Altenes tectonic window; AW = Alta-Kvænangen tectonic window; BFC = Bjørnøyrenna Fault Complex; BKFC = Bothnian-Kvænangen Fault Complex; BSFC = Bothnian-Senja Fault Complex; FTZ = Fugløya transfer zone; GL = Gjesvær Low; He = Helnes; HfB = Hammerfest Basin; KF = Kokelv Fault; Kv = Kvaløya; L = Langfjorden; Lf = Laksvatn fault; LR = Lofoten Ridge; LVF = Langfjord-Vargsund fault; Ma = Magerøya; Mf = Magerøysundet fault; MFC = Måsøy Fault Complex; NFC = Nysleppen Fault Complex; NP = Nordkinn Peninsula; PP = Porsanger Peninsula; Re = Repparfjorden; Rf = Rolvsøya fault; Rg=Ryggefjorden; RLFC = Ringvassøya-Loppa Fault Complex; Rv = Revsbotn; RW = Repparfjord-Komagfjord tectonic window; S = Sørkjosen; SB = Sørvær Basin; Se = Seiland; SFZ = Senja Fracture Zone; SISZ = Sørøya-Ingøya shear zone; Sj = Sjernøya; Sn = Snøfjorden; sNB = southwesternmost Nordkapp basin; SSB = Senja Shear Belt; Sø = Sørøya; TFFC = Troms-Finnmark Fault Complex; TKFZ = Trollfjord-Komagelv Fault Zone; Tu = Tufjorden; V = Vargsund; VP = Varanger Peninsula; VVFC = Vestfjorden-Vanna fault complex.

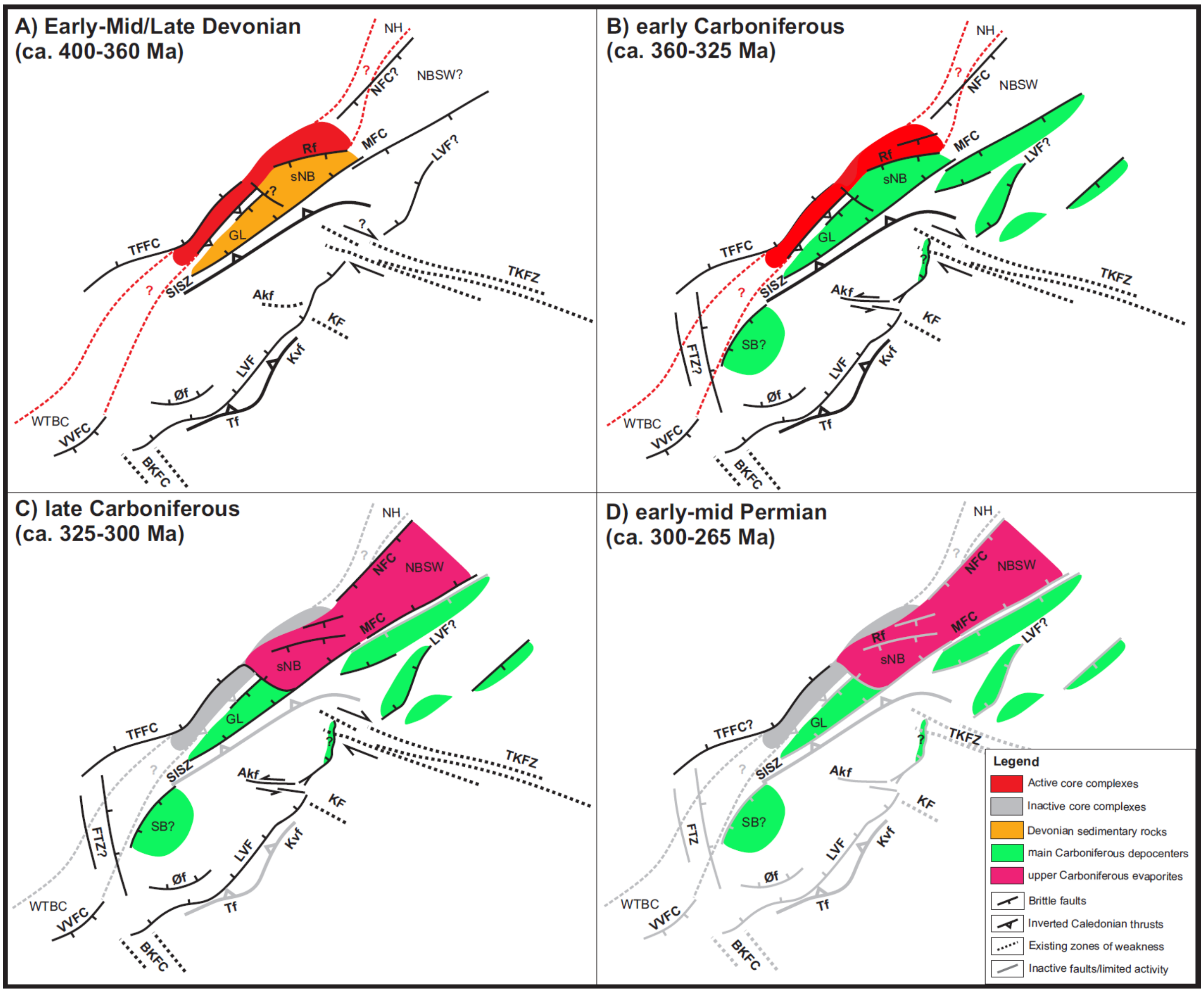

Figure 2: Map-view model showing the late Paleozoic evolution of the Finnmark Platform, southwesternmost Nordkapp basin (sNB) and NW Finnmark. Abbreviations as in Figure 1; a) In the Early to Mid/Late Devonian, major Caledonian thrusts such as the SISZ were inverted and exhumed core complexes in the footwall of the TFFC and of the Rolvsøya fault. Thick Devonian sedimentary growth strata deposited within the spoon-shaped depression created by the SISZ; b) Core complex exhumation continued through the early Carboniferous and was accommodated by high-angle normal faults (e.g. MFC, TFFC, Rolvsøya fault and potentially LVF) formed as extensional brittle splays along inverted Caledonian thrusts/shear zones. Core complex exhumation ceased by the end of the Serpukhovian, and the WNW-ESE trending fault segment of the TFFC formed as an accommodation cross-fault decoupling the Finnmark Platform west from the southwesternmost Nordkapp basin, thus contributing to preserve thick Devonian and lower Carboniferous sedimentary successions in the southwesternmost Nordkapp basin, whereas analog sedimentary rocks were almost completely eroded on the Finnmark Platform west during a major phase of eustatic sea-level fall. In addition, minor graben and half-graben structures formed on the Finnmark Platform east. Precambrian, WNW-ESE to NNW-SSE trending fault zones such as the TKFZ acted as strike-slip transfer faults, segmenting the margin. Lateral movements along these faults ceased in the early (-late?) Carboniferous; c) In the late Carboniferous, inverted Caledonian thrusts and shear zones became inactive and, in places, were truncated by high-angle splay-faults that accommodated the deposition of syn-tectonic sedimentary wedges on the Finnmark Platform, and of thick, partly evaporitic deposits in the southwesternmost Nordkapp basin; d) By the end of the Carboniferous, brittle faulting came to a halt and the margin is believed to have remained tectonically quiet.

Paper 1

Paper 2

Paper 3