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Post-Caledonian brittle faults along the SW Barents Sea Margin

Onshore-offshore margin architecture and fault rock-forming conditions

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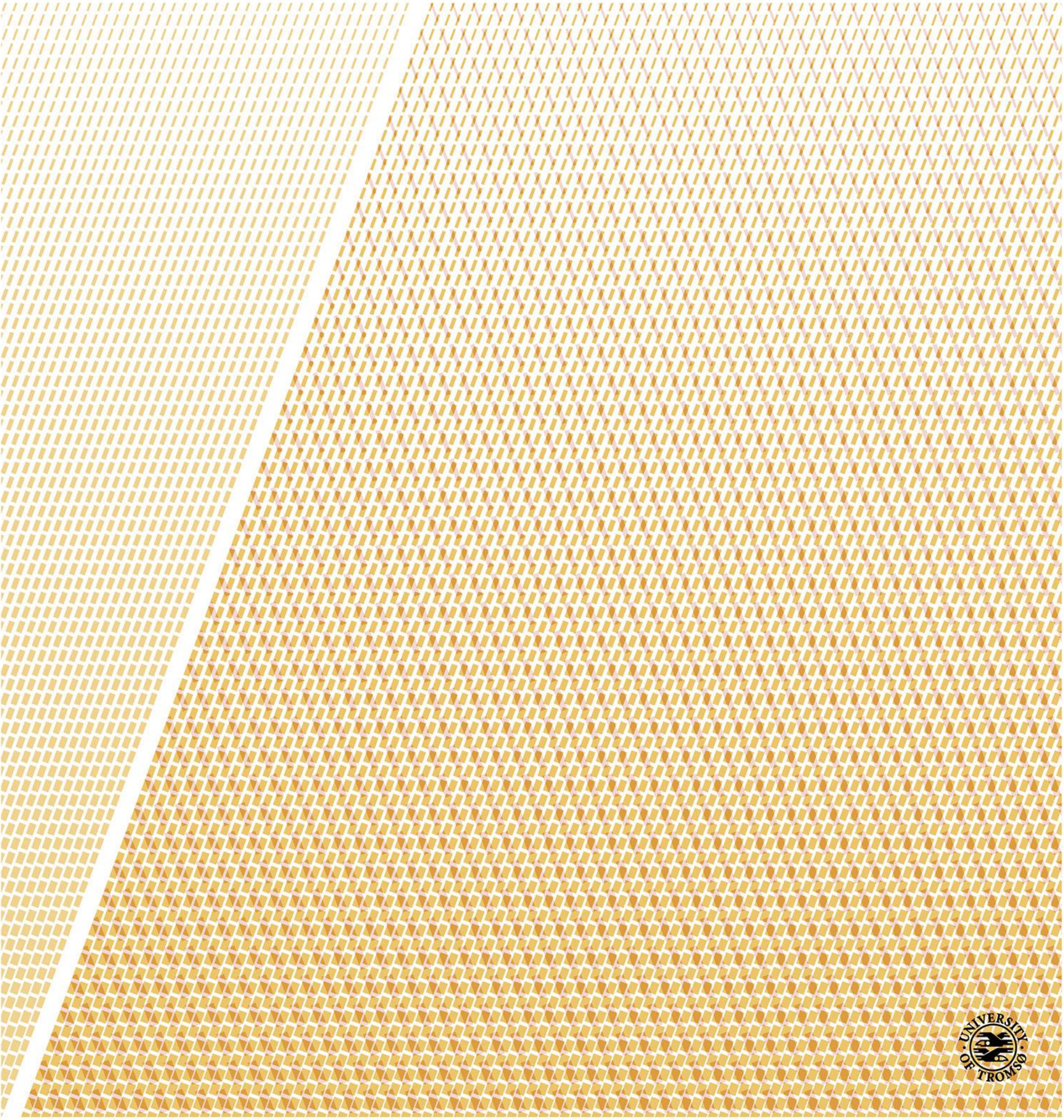

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Preface

This thesis is a result of a PhD-project that was carried out in accordance with the Industrial PhD-scheme as organized by the Norwegian Research Council. The project has been funded by the council and DONG E&P Norge. The University of Tromsø is the degree-awarding institution. Supervisors have been Professor Steffen G. Bergh (main) and Professor Holger Stunitz from the University of Tromsø and Arild Ingebrigtsen from DONG E&P Norge.

The thesis presented herein aims to unravel the evolution and finite stage architecture of the SW Barents Sea Margin, which formed as a part of the rifting of present day Greenland and Scandinavia and the opening of the North Atlantic Ocean (cf. Faleide et al., 2008). The SW Barents Sea Margin studied in this thesis starts just north of the Lofoten-Vesterålen archipelago, continues northward outboard northern Troms and into western Finnmark. This thesis focus on (i) *if* and *how* onshore Post-Caledonian brittle faults correlate with major offshore, basin-bounding fault complexes and (ii) under which conditions onshore faulting occurred.

As a part of the PhD, I have been employed at Front Exploration (August 2011-June 2012) and DONG E&P Norge (July 2012-present). The Industrial PhD-scheme has allowed me to move freely between offices at DONG E&P and the University of Tromsø as a fully integrated member of both institutions. As a part of my PhD, I have had a stay at NGU, Trondheim, a 6-weeks field course in the Mojave Desert, California, followed by 2 weeks of structural fieldwork in a similar tectonic setting as the western Barents Sea, mapping the San Andreas Fault and associated structures (These data are published elsewhere). The stays has given me a broadened view on the world's geology, expanded my contact network and led me into new, ongoing projects as co-author on related topics to those presented as part of my PhD (Bergh et al. 2014, unpublished; Schermer et al., unpublished). Further, I have attended several scientific cruises with the research vessel FF Helmer Hanssen in the Barents Sea and Greenland Sea and attended several scientific conferences presenting results from the PhD-project, including the "Onshore-Offshore relationships on the North-Atlantic margin" (Trondheim, Oct. 2012) and the EGU General Assembly 2014 in Vienna. Although I have not been obliged to do duty work, I have had the pleasure of teaching undergraduate students during exercises and excursions in structural geology at the University of Tromsø.

The PhD-project has resulted in three papers, which includes the tasks of (i) mapping basement structures and brittle fault zones onshore, on the shallow shelf and on the deep shelf using different techniques and (ii) unravelling details on the conditions under which these fault zones formed. The papers presented herein are:

Paper 1: Indrevær, K., Bergh, S.G., Koehl, J.-B., Hansen, J.-A., Schermer, E.R. & Ingebrigtsen, A., 2013: Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture. *Norwegian Journal of Geology, Vol 93 (3-4)*, pp. 167–188.

Paper 2: Indrevær, K., Stunitz, H., & Bergh, S. G., in press: On Palaeozoic-Mesozoic brittle normal faults along the SW Barents Sea margin: fault processes and implications for basement permeability and margin evolution. *Journal of the Geological Society, London*.

Paper 3: Indrevær, K. & Bergh, S. G., in press: Linking onshore-offshore basement rock architecture and brittle faults on the submerged strandflat along the SW Barents Sea Margin using high-resolution (5x5m) bathymetry data. *Norwegian Journal of Geology*.

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I would like to express my utmost gratitude to my main supervisor Professor Steffen G. Bergh for taking me under his wings and introducing me to his exiting research. His skills within- and enthusiasm for geology has been very inspiring to me.

I would also like to thank my co-supervisors Professor Holger Stunitz (UiT) and Arild Ingebrigtsen (DONG E&P Norway). Holger Stunitz's support and good advice has led to exciting discoveries on fault-rock forming processes during this project. I thank Arild Ingebrigtsen for guidance related to seismic data, for making sure that all administrative issues were sorted out and for being very supportive in every way during these three years.

I send my gratitude to Professor Elizabeth R. Schermer for enriching my PhD-experience by introducing me to the amazing geology of the US and for constructive collaboration, feedback and reviews during this project. I thank John-Are Hansen for help, especially within the start-up of the project and I thank Jean-Baptiste Koehl for exciting fieldwork.

I sincerely thank DONG E&P Norge (and Front Exploration) for taking on this project. I would like to thank all of my colleagues in DONG, especially Tom Arne Rydningen, Rikke Bruhn and Tanni Juul Abramovitz for project-related discussions and feedback.

This work has been a part of the Industrial PhD-scheme organized by the Norwegian Research Council. I would like to express my gratitude to all persons involved from this institution. I would also like to thank Odleiv Olesen and Laurent Gernigon at NGU for letting me visit and see the benefits of working with gravimetric and magnetic anomaly data.

I thank all of my colleagues at the Department of Geology, UiT. Especially Trine, Edel and others at the laboratory and Jan P. Holm for his help on finding long lost figures. Finally, I thank all of my fellow PhD-students at UiT for fun times during these three years.

Introduction

Background and scope of thesis

This work was initiated as a cooperation between Front Exploration (and later DONG E&P Norge) and the University of Tromsø as a part of the Industrial PhD-scheme organized by the Norwegian Research Council.

The work is the continuation of the project "Tectonic development of faults on the Lofoten-Vesterålen continental margin; comparisons with land" that was initiated in 2002 by Professor Steffen G. Bergh, as a collaboration between the University of Tromsø, the Geological Survey of Norway and the industry. This project led to an increase in the understanding of the Lofoten-Vesterålen margin and is summarized in the papers Bergh et al. (2007, 2008) and the PhD-theses of Karsten Eig and John-Are Hansen (Eig, 2008; Hansen, 2009).

The project presented herein has aimed to study the SW Barents Sea margin situated just north of Lofoten and Vesterålen (Figs. 1 & 2) in order to obtain knowledge on onshore-offshore structural relationships off northern Troms and western Finnmark. The work has included:

(1) Onshore fieldwork focussing on brittle fault structures, their kinematics and their relations to pre-existing basement structures on the outer islands of Troms, including Senja, Kvaløya, Ringvassøya and Vanna (Fig. 2).
(2) Detailed microstructural study of fault rocks with emphasis on fault-rock forming conditions, revealing details about P-T conditions, fluid flow characteristics and fault rock healing processes during and after faulting.
(3) Mapping of fault zones and fault complexes on the deep shelf based on the interpretation of seismic data, focusing on the Troms-Finnmark, Ringvassøy-Loppa, Nysleppen and Måsøy fault complexes, their associated basins (Harstad-, Tromsø- and Hammerfest basins) and the Finnmark Platform (Fig. 1).
(4) Using magnetic anomaly data and high-resolution bathymetry data from the shallow shelf (strandflat) along the margin in an effort to map ductile basement fabrics and link brittle fault complexes mapped onshore with fault complexes mapped offshore.

Geological setting

As a part of the breakup of the North Atlantic Ocean, the continental margin off mid-Norway (Fig. 1) was subjected to multiple rift events in the Palaeozoic through Early Cenozoic times (e.g. Doré 1991; Faleide et al. 1993; Blystad et al. 1995; Doré & Lundin 1996; Brekke et al. 2001; Osmundsen et al. 2002; Eig 2008; Faleide et al. 2008). The fault timing and evolution of different rift events are well constrained by seismic and potential field data offshore mid-Norway, but less constrained from the SW Barents Sea margin (e.g. Gudlaugsson et al. 1998; Dore et al. 1999; Brekke 2000; Faleide et al. 2008; Redfield & Osmundsen, 2013). On the mid- and north-Norwegian margin, the earliest events occurred in the mid-Carboniferous, Carboniferous-Permian and Permian-Early Triassic times (Doré 1991). On the Lofoten-Vesterålen margin (Fig. 1), rifting occurred during multiple tectonic events in the Permian-Early Triassic, Mid/Late Jurassic-Early Cretaceous and latest Cretaceous-Paleogene (Brekke 2000; Osmundsen et al. 2002; Bergh et al., 2007; Eig, 2008; Hansen et al., 2012). The Vestfjorden and northern Træna basins show large-scale fault activity in the Permian to Early Triassic (Brekke 2000; Osmundsen et al. 2002; Hansen et al. 2012), followed by Late Triassic regional subsidence (Faleide et al. 2008). The main fault array on the Lofoten-Vesterålen margin likely developed during the syn-rift, Late Jurassic and Early Cretaceous phase (Hansen et al. 2012) as the Atlantic rifting propagated northwards.

In the SW Barents Sea, north of Lofoten (Fig. 1), Carboniferous rift structures are widespread (Gudlaugsson et al. 1998) and led to the formation of early rift basins such as the Nordkapp and Tromsø basins (Faleide et al., 2008). The most prominent offshore fault complex in the region, the Troms-Finnmark Fault Complex, experienced long-term activity from the Carboniferous through the Eocene, with a main fault-related subsidence in Late Jurassic to Early Cretaceous times (Gabrielsen et al., 1990; Faleide et al., 2008) leading to the formation of the Harstad and Hammerfest basins and further deepening of the Tromsø Basin (Fig. 1). A Late Cretaceous to Paleocene rifting event was accomplished by dextral transform movement along the mega-shear system defined by the Senja Shear Zone (Fig. 1), which may be traced northwards from Senja to west of Spitsbergen, where it is known as the Hornsund-De Geer Fault Zone (Fig. 1; Gabrielsen et al., 1991; Faleide et al., 1993, 2008). The transform movement led to the formation of the Bjørnøya and Sørvestnaget basins and the further development of the Tromsø and Harstad basins as combined extensional and pull-apart basins (Gabrielsen et al. 1997; Knutsen & Larsen 1997; Faleide et al. 2008). Final lithospheric break-up along the margin occurred at c. 55-54Ma, leaving the SW Barents Sea as a passive continental margin since Oligocene time (Faleide et al. 2008).

Onshore Troms (Fig. 2), dating of fault rocks using 40Ar/39Ar and apatite fission track methods indicates that faulting in western Troms largely occurred during the Permian to Early Triassic rifting phase, thus corresponding with the initial large-scale fault activity on the Lofoten-Vesterålen margin, including the Vestfjorden and Træna basins, but with no major fault activity during the Mesozoic and Cenozoic (Hendriks et al. 2010; Davids et al., 2013). However, Mesozoic fault activity is suggested to have taken place onshore further north, in Finnmark (Roberts & Lippard 2005; Torgersen et al., 2013), and to the south in Lofoten-Vesterålen and Andøya (Dalland, 1981; Fursich & Thomsen, 2005; Hansen, 2009; Hendriks et al., 2010; Osmundsen et al., 2010; Davids et al., 2013). Paleomagnetic evidence for Permian as well as Cenozoic to recent phases of faulting and cataclasis has been obtained for the Kvaløysletta-Straumsbukta fault zone, which is a part of the Vestfjorden-Vanna Fault Complex (Olesen et al., 1997).

The margin off northern Troms and western Finnmark marks the transition between the spreading, normal passive margin off Lofoten-Vesterålen and the Barents Sea transform margin off the WTBC, marked by the Senja Shear Zone (Figs. 1 & 2), and is thus very important when discussing the evolution of the North-Norwegian margin as a whole. However, only a few onshore-offshore structural studies have previously been undertaken north of Lofoten, of which are mainly in northern Finnmark (Roberts & Lippard, 2005; Roberts et al., 2011).

The present thesis aims to fill this gap and focuses on the network of Palaeozoic-Mesozoic faults along the coast of Troms, and their genetic relationship with major structural elements in the deeper portions of the SW Barents Sea, such as the Troms-Finnmark Fault Complex (TFFC), the Ringvassøy-Loppa Fault Complex (RLFC) and the Måsøy and Nysleppen fault complexes, in addition to their relation with the Senja Shear Zone and the transition to a transform margin (Figs. 1 & 2; Ramberg et al. 2008; Smelror et al. 2009). Onshore western Troms, these brittle faults are manifested mainly as NNE-SSW and ENE-WSW trending normal faults (Fig. 2). They are constrained to the West Troms Basement Complex (WTBC, Zwaan, 1995), a major basement horst that extends from Lofoten in the south to island of Vanna in the north and comprises the islands of Senja, Kvaløya, Ringvassøy and Vanna, as well as several other smaller islands (Figs. 1 & 2; Olesen et al., 1997; Bergh et al., 2010). The WTBC horst can be traced southwestward to link up with the Lofoten Ridge, which is flanked by major normal faults (Blystad et al., 1995; Bergh et al., 2007; Hansen et al., 2012) that border the offshore Ribban and Vestfjorden basins. In Troms, corresponding fault zones can be divided into the Vestfjorden-Vanna Fault Complex (VVFC), which marks the southeastern boundary of the WTBC, down-dropping Caledonian nappes to the east in the order of 1-3 km (Forslund, 1988; Opheim & Andresen, 1989; Olesen et al., 1997) and a system of less prevalent, SE-dipping, faults situated along the outer rim of the islands of the WTBC (Fig. 2; Antonsdottir 2006; Thorstensen 2011).

Summary of papers

Paper 1: Indrevær, K., Bergh, S.G., Koehl, J.-B., Hansen, J.-A., Schermer, E.R. & Ingebrigtsen, A., 2014: Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture. *Norwegian Journal of Geology, Vol 93 (3-4)*, pp. 167–188.

The aim of this paper is to investigate the regional fault pattern and discuss how these faults are genetically linked across the SW Barents Sea Margin. It focus on the geometry and kinematics of selected previously described and undescribed fault zones onshore Troms, in an effort to elaborate all onshore fault data into a common frame of reference. Onshore brittle faults have been studied and compared with offshore fault complexes interpreted from seismic data, and correlated with offshore fault complexes by the use of bathymetry data and magnetic anomaly data. This is done in order to get a regional control on the behaviour of brittle structures and thus margin architecture.

The main conclusions of the paper are that the Palaeozoic-Mesozoic rift-related activity on the west Troms margin (Fig. 1 & 3) resulted in widespread NNE-SSW and ENE-WSW trending brittle normal faults that constitutes at least two major fault complexes, the Vestfjorden-Vanna and the Troms-Finnmark Fault Complexes and two subsidiary NW-SE trending transfer fracture systems, one present northwest of Senja and another near the island of Nord-Fugløya (Fig. 3). The onshore fault zones can be separated into (1) the major Vestfjorden-Vanna Fault Complex, which marks the southeastern boundary of the WTBC (Opheim & Andresen, 1989; Olesen et al. 1997) and continues offshore north of Vanna to link up with the offshore Måsøy and Nysleppen fault complexes, and (2) a less prevalent system of right-stepping fault segments that run along the outer rim of the islands of the WTBC, best exposed at Rekvika. This fault system is mainly SE-dipping with displacement in the order of 100's of meters or less (Fig. 2). Offshore, the Troms-Finnmark Fault Complex is the dominant basin-bounding fault complex and defines the northwestern boundary of the WTBC, that down-drops basement rocks from 4-5km depth on the Finnmark Platform to more than ~10km depth in the Harstad Basin (Fig. 1). The Troms-Finnmark Fault Complex can be traced from the Lofoten Ridge in the south to link up with the Ringvassøy-Loppa Fault Complex in the north. Thus, both the Troms-Finnmark and Vestfjorden-Vanna Fault Complexes can be traced for 100's of kilometers along strike along the North-Norwegian margin (Fig. 1; Olesen et al., 1997; Dore et al., 1997; 1999). The margin is segmented along strike by at least two major transfer zones, the Senja Shear Zone (e.g. Olesen et al., 1997) and the Fugløya transfer zone, the latter named after the nearby island of Nord-Fugløya. These two transfer zones mark a pronounced switch in fault polarity and/or amount of displacement of the Vestfjord-Vanna and the Troms-Finnmark Fault Complexes and spatially overlap with the ~NW trending, Proterozoic-Palaeozoic basement-seated Bothnian-Senja Fault Complex (and Senja Shear Belt) and the Bothnian-Kvænangen Fault Complex, respectively. The Bothnian-Kvænangen Fault Complex is suggested to be the controlling element for the location of the Fugløya transfer zone, the Ringvassøya-Loppa Fault Complex, and potentially also the transform Hornsund-De Geer Fault Zone that lie along strike of the Fugløya transfer zone farther north along the Barents Sea margin.

In the context of rifting along the SW Barents Sea margin, our results suggest a widespread initial distributed rifting event in the Carboniferous and Late Permian/Early Triassic along the NE-SW striking VVFC and TFFC. This early event was followed by a main, Late Jurassic/Early Cretaceous syn-rift extension in the Hammerfest Basin and a corresponding switch in localization of fault movements to the Troms-Finnmark and Ringvassøy-Loppa fault complexes. These major offshore, basin-bounding faults are characterized by a listric geometry and large-magnitude displacement, whereas a planar geometry is inferred for the onshore Vestfjorden-Vanna Fault Complex and related horst-internal faults. The contrast in fault geometry, where the dominant movement was localized to the Troms-Finnmark Fault Complex by Late Jurassic/Early Cretaceous, resulted in the formation of a short tapered, hyper-extended margin after final break-up in the Paleocene/Eocene (c. 55Ma). Later on, the West Troms Basement Complex was uplifted and exhumed as a short-tapered margin due to unloading and crustal flexure with continued uplift and erosion to the present stage level.

Paper 2: Indrevær, K., Stunitz, H., & Bergh, S. G., in press: On Palaeozoic-Mesozoic brittle normal faults along the SW Barents Sea margin: fault processes and implications for basement permeability and margin evolution. *Journal of the Geological Society*.

This paper focuses on the microstructural characteristics of onshore brittle fault rocks within the West Troms Basement Complex. It aims to estimate temperature and depth of faulting and to increase our understanding of processes that may have controlled margin-parallel faulting during the onshore Late Permian/Early Triassic rifting phase. The main conclusions from the study are that the minimum P-T conditions during early stages of brittle faulting is estimated to ~300°C and ~240MPa (~10km depth) based on the presence of greenschist facies mineral assemblages in the cataclasites. Later fault movement introduced pumpellyite, yielding minimum P-T condition of ~275°C and ~220MPa (~8.5km depth). Quartz-rich ultracataclasites occur within granitoid fault rocks and are interpreted as preserved fault rocks from early (deep) stages of faulting that formed due to the chemical breakdown of feldspar to epidote and chlorite with the release of quartz. Due to the lack of any subsequent formation of phyllosilicates within the process fault zone, which is common for cataclasis of granitoid rocks at shallower crustal levels (Wintsch et al., 1995; Janecke & Evans, 1998; Wibberley, 1999; Rutter et al., 2001; Holdsworth, 2004; Jefferies et al., 2006), the main fault activity is interpreted to have ceased during early stages of rifting.

Microstructural observations of the brittle fault rocks indicate that pore pressures locally reached lithostatic levels (240MPa) during faulting. Thus, the studied faults within the basement rocks acted as fluid conduits during rifting in the Late Permian/Early Triassic. Based on the presence of injected cataclasites, a minimum co-seismic fluid velocity is calculated to have been on the order of 10^{-1} m/s. However, evidence for grain growth and mineral precipitation suggest that the fault zones sealed of rapidely after faulting, thereby evolving from a fluid conduit to a fluid barrier through a fault cycle.

The occurrence of pumpellyite allowed for the estimation of a maximum geothermal gradient during faulting in the Late Permian/Early Triassic, which is calculated to ~30°C/km. This un-elevated geothermal gradient suggests either that faulting occurred during early stages of continental rifting or that the studied fault zones were located along the rift flanks where little or no subsidence took place. A minimum average exhumation rate of ~40m/Ma is estimated for the outer islands of the West Troms Basement Complex since Late Permian times. When considering normal erosion rates, the proposed late Cenozoic uplift, which has been discussed widely in the literature (c.f. Doré et al., 2002), may be explained by erosion alone, possibly as an effect of climate deterioration after the formation of the North-Atlantic Ocean, causing a faster rate of erosion along the margin, which led to a subsequent isostatic crustal re-calibration and greater isostatic uplift of the marginal crust, compared to inland.

Finally, a model is proposed, showing how fluid flow within a fault zone may be controlled by processes such as grain growth, mineral precipitation and hydrothermal alteration, which may alter fluid flow characteristics within a fault zone through a fault cycle. As the studied fault zones are the onshore portions of large fault complexes that continue offshore (Indrevær et al., paper 1), it is likely that the studied fault zones are analogue to basement-seated faults offshore. This implies that the conditions and nature of faulting observed onshore may be valid for offshore faults and that, at present, basement-seated fault zones offshore (e.g. on the Finnmark Platform and Loppa High) acted as fluid barriers and thus, have the potential to control hydrocarbon flow.

Paper 3: Indrevær, K. & Bergh, S. G., in press: Linking onshore-offshore basement rock architecture and brittle faults on the submerged strandflat using high-resolution (5x5m) bathymetry data in Troms, Northern Norway. *Norwegian Journal of Geology*.

Traditionally, the Norwegian Army has, within 12 nautical miles of the coast, considered a resolution finer than 50x50m of the MAREANO data as classified information, although it is collected with a resolution down to as much as 1x1m (depending on depth). An effort to get access to higher resolution MAREANO data for the correlation work in paper 1 was undertaken, but initially not successful. We were, however, later given access and permission to publish illustrations of high-resolution (5x5m) data. This has allowed us to identify and study astonishingly detailed morphological features visible on the strandflat outboard Troms, which shed light on the shallow shelf distribution of basement rocks, Caledonian thrust nappes and Post-Caledonian brittle faults. To our knowledge, high-resolution bathymetry data has never been used to this extent for the purpose of mapping offshore ductile and brittle fabrics visible on the seafloor.

The main results of the paper are that morphological features observed on the high-resolution bathymetry data in great detail mimic basement structures commonly observed onshore western Troms, i.e. Archaean-Palaeoproterozoic ductile fabrics (steep foliation, macrofolds, shear zones), gently dipping Caledonian nappe structures and post-Caledonian brittle faults. Our interpretations suggest firstly, that the basement lithologies of the WTBC continue onto the strandflat, secondly, that the contact between the WTBC units and the Caledonian thrust nappes crops out in the sound southwest of Nord-Fugløya, and thirdly, that post-Caledonian, rift-related and horst-bounding brittle normal faults are widespread on the shallow shelf. Importantly, the Caledonian nappe boundary correspond with the same strait that marks the location of the Mesozoic Fugløya transfer zone, the possible continuation of the Proterozoic-Palaeozoic Bothnian-Kvænangen Fault Complex (Indrevær et al., paper 1). The spatial overlap of these features suggests that the Precambrian and Caledonian structures both exerted an important role in controlling the rifting and passive margin deformation through the late Paleozoic, Mesozoic and Cenozoic time span.

The basement fabrics visible on the strandflat are transected by numerous NNE-SSW to ENE-WSW trending, mostly linear trenches that are interpreted as rift-related brittle normal faults, based on similar orientation with onshore and offshore faults and fault segments mapped on the continental shelf from seismic data (see paper 1). These faults overlap with scarps bounding asymmetric landscapes or rotated fault blocks (Osmundsen et al., 2009, 2010) that offset bedrock lithologies and structures across the trenches with estimated displacement in the order of kilometers. The structural relationship between strandflat escarpments and faults of different orientation suggests that the fault zones, independent of their orientations, formed during the same period. Our detailed investigation of the strandflat bathymetry and various strandflat aspects demonstrates a strong correlation with basement structures and brittle faults onshore and thus would support a strong tectonic influence on the present day coastal landscape and the SW Barents Sea margin architecture.

Synthesis

Onshore-offshore correlation studies on the Lofoten-Vesterålen margin have in the recent years significantly increased our understanding of the fault architectures and evolution of the North-Atlantic passive margin (e.g. Bergh et al., 2007, 2008; Eig, 2008; Faleide et al., 2008; Hansen, 2009; Hendriks et al., 2010; Osmundsen et al., 2010; Hansen et al., 2012). North of Lofoten, however, very few comparable margin studies have been undertaken. Roberts and

Lippard (2005) and Roberts et al. (2011) correlated onshore fault zones in Finnmark with offshore fault zones mapped from seismic data and bathymetry data. Previous work in western Troms, however, is mostly limited to the study of individual fault zones onshore (Andresen & Forslund 1987; Forslund 1988; Opheim & Andresen 1989; Gagama, 2005; Antonsdottir, 2006; Thorstensen, 2011) and large scale, basin-bounding fault complexes offshore (Gabrielsen 1984; Sund et al., 1986; Gabrielsen et al., 1990; Faleide et al., 1993; Waqas, 2012). Whilst the Vestfjorden-Vanna Fault Complex was previously identified and discussed in a regional context (Opheim & Andresen, 1989; Olesen et al., 1997), the continuation of this fault complex to north of Vanna, has not yet been considered in detail. Due to a vast amount of available seismic data from the offshore regions, the distribution and tectonic evolution of basin-bounding faults are relatively well known (cf. Gabrielsen et al., 1990; Smelror et al., 2001). However, an effort to correlate fault complexes onshore with those from offshore basins has not previously been done.

The present work is a first attempt to fully correlate major offshore and onshore brittle zones that bound the WTBC horst (Fig. 2). The present work also adresses other important unresolved issues concerning P-T conditions of margin faulting, timing of rifting events, extent of faulting, fault rock-forming processes, fluid flow, pore pressure and permeability.

Recent dating of brittle fault rocks in western Troms (Davids et al. 2013), supported by paleomagnetic dating of fault gouge from the VVFC (Olesen et al., 1997), has enabled us to infer onshore fault activities to a specific rifting event. Most important, the obtained ages suggest that only one phase of rifting (Late Permian/Early Triassic) is preserved onshore. By contrast, along other portions of the margin farther south and north, this early rifting phase was strongly overprinted by later Late Jurassic/Early Cretaceous and Late Cretaceous-Palaeocene fault activity. As a consequence, the study of brittle fault zones in western Troms gives a unique opportunity to obtain detailed information on the nature and significance of the earliest phases of the North-Atlantic rifting events.

Margin architecture

Our synthesis show that post-Caledonian brittle faults in western Troms on average display NNE-SSW and ENE-WSW trends and constitute two major NE-SW trending fault complexes, the TTFC and the VVFC, that bound the WTBC horst (Fig. 2 & 3). These boundary fault zones run partly onshore and offshore along the studied portion of the margin, linking up with the onshore Lofoten and offshore Nordland Ridges to the south, and with the

Ringvassøy-Loppa, Nysleppen and Måsøy fault complexes in the north (Indrevær et al. paper 1). The southeastern boundary of the WTBC horst is marked by the VVFC, which down-drops Caledonian thrust nappes to the east. Westward, the study of detailed bathymetry data reveal that the strandflat outboard the islands of Senja, Kvaløya and Ringvassøy and west of Vanna are made up of the same basement lithologies and structural fabrics (Fig. 2). This demonstrates that the WTBC horst extends offshore, at least to the western edge of the strandflat (Indrevær & Bergh, paper 3). Seismic sections that cover parts of the Finnmark Platform and the Harstad Basin are interpreted to suggest that the WTBC units are to a lesser extent down-faulted on the Finnmark Platform and that the TFFC defines the northwestern boundary of the WTBC horst down-dropping basement rocks more than 5 km into the Harstad Basin (Indrevær et al., paper 1). Remnants of Caledonian nappes on down-faulted basement units are thought to be present within large regions of the SW Barents Sea (Gernigon & Brönner, 2012) and may also be present on the Finnmark Platform offshore the WTBC. The planar geometry obtained for the VVFC (with displacement in the order of 1-3km) and the listric geometry of the TFFC (with estimated displacement of >5km) resulted in an overall asymmetric WTBC horst geometry (Indrevær et al., paper 1).

At least two transfer zones, the Senja Shear Zone and the Fugløya transfer zone seem to have segmented the margin along strike, allowing fault segments to step and change fault polarity across the transfer zones (Fig. 3) (Indrevær et al., paper 1), similar to the Lofoten Ridge (Tsikalas et al., 2005; Bergh et al., 2007). The dextral Senja Shear Zone is believed to mark the position of the initial, SW Barents Sea transform continent-continent boundary, which evolved to a continent-ocean transform boundary in the Eocene (Olesen et al., 1997; Faleide et al., 2008). The Fugløya transfer zone is considered by us to be genetically linked to the Senja Shear Zone and apparently displacing sinistrally both Mesozoic brittle normal faults (Indrevær et al. paper 1) and the contact between basement rocks and the Caledonian thrust nappes (Indrevær & Bergh, paper 3). The Fugløya transfer zone is suggested to be related to the Senja Shear Zone by accommodating for lateral differences in strain along the margin, due to the transition from a normal rift setting to a transform rift setting in Troms.

Fault timing

The derived ages of brittle fault-associated rocks onshore (Davids et al. 2013) are essential for the interpretation and implications of our results and conclusions. The obtained ages indicate that faulting onshore Troms occurred during Late Permian/Early Triassic, with few or no later significant fault movement. The only exception is a Late Cenozoic reactivation inferred from paleomagnetic dating of fault gouge from the VVFC (Olesen et al. 1997).

The present work contributes in a number of ways on the timing of faulting and possible later reactivation of faults both onshore as well as on the shallow shelf:

First, the presence of a widespread healed silica-rich cataclasite in the Rekvika fault zone suggests that faulting as observed onshore Troms, occurred in the deeper parts of the brittle deforming crust, with no later reactivation. This is supported by the estimates of P-T conditions during faulting, which indicate that faulting occurred at 8.5-10km depth. This implies that onshore fault activity came to a stop during *early and deep stages* of the continental rifting (Indrevær et al. paper 2). Thus, both the observed silica-rich cataclasite and the P-T conditions are consistent Late Permian/Early Triassic ages obtained for fault activity onshore Troms, with the general lack of evidence for any post-Triassic reactivation (Davids et al., 2013; Olesen et al., 1997).

Second, curved relationships of NNE-SSW and ENE-WSW trending faults and fractures are common in western Troms, suggesting that the two populations of faults formed contemporaneously (Indrevær & Bergh, paper 3). This is in contrast with the Lofoten-Vesterålen margin faults, where the NNE-SSW trending fault segments formed first due to WNW-ESE directed extension, and where later on replaced by ENE-WSW trending faults due to a switch to NNW-SSE directed extension (Bergh et al. 2007). Our work largely supports Hansen (2009) who suggested that the NNE-SSW striking fault segments in Lofoten formed as *en echelon*, right-stepping faults that were linked by NE-SW to E-W trending fault segments acting as transfer faults. In western Troms, our kinematic analysis of onshore fault zones has not enabled to solve the timing relationships between the two fault sets. Slickensided fault surfaces from the studied fault zones onshore as well indicate both normal dip-slip and oblique- normal senses of shear, independent of the fault trends.

Thirdly, the nature of displacement of fault zones and offset of the basement-Caledonian thrust nappe boundary across the Fugløya transfer zone indicate that this transfer zone was active during post Caledonian times (Indrevær & Bergh, paper 3). As this transfer zone displaces and/or accommodates a major shift in fault polarity across the zone for fault segments belonging to the Late Permian/Early Triassic Vestfjorden-Vanna Fault Complex

(Davids et al., 2013; Indrevær et al. paper 1), the activity may likely be tied to both the Late Permian/Early Triassic and the Late Jurassic/Early Cretaceous rifting phases.

Fourthly, the regionally sub-planar, Quaternary strandflat outboard of western Troms, is in several locations observed to be down-dropped by possible brittle normal faults (Indrevær & Bergh, paper 3). This observation suggests that certain post-Caledonian faults have modified the strandflat and thus been active during the Quaternary.

Basement control

Several indicators for basement control on post-Caledonian brittle structures have been observed through the present work. First, the studied onshore brittle fault zones, at least on a local scale, commonly formed close to, or along favourably oriented Precambrian or Caledonian structural trends such as lithological boundaries, foliation surfaces and/or ductile shear zones (Indrevær et al. paper 1). This suggests that brittle faulting utilized pre-existing zones of weakness in the basement to achieve brittle reactivation.

Second, on a larger scale, steep basement-seated Precambrian ductile shear zones, e.g. the NW-SE trending Bothnian-Senja Fault Complex (and Senja Shear Belt) and the Bothnian-Kvænangen Fault Complex, seem to have affected the NE-SW trending brittle fault complexes by allowing portions of these pre-existing structures to be reactivated as the Senja Shear Zone and the Fugløya transfer zone, respectively, which accommodated shifts in polarity and/or the stepping of fault segments to a new position along strike (Indrevær et al. paper 1; Indrevær & Bergh, paper 3). The conspicuous overlap of (i) the Fugløya transfer zone, (ii) the contact between the WTBC and Caledonian thrust nappes, (iii) a possible Svecofennian high-strain zone and (iv) the Proterozoic-Palaeozoic Bothnian Kvænangen Fault Complex (Indrevær & Bergh, paper 3) suggests that this zone has played a major role in accommodating margin-oblique crustal deformation through time. This zone may initially have formed as a ductile shear zone (or terrain boundary) in the Archean-Palaeoproterozic, possibly the Svecofennian, and later been covered by thrust nappes during the Caledonian orogeny. Post-Caledonian crustal rifting, which led to the opening of the North-Atlantic Ocean, have potentially reactivated this zone as a transfer zone, allowing Palaeozoic-Mesozoic brittle faults to step and change fault polarity across the transfer zone (Indrevær et al. paper 1), displacing the Caledonian thrust nappes sinistrally (Indrevær & Bergh, paper 3). It is suggested that the ~NW-trending Bothnian-Kvænangen Fault Complex also may be the controlling element for the Ringvassøya-Loppa Fault Complex and potentially also the transform Hornsund-De Geer Fault Zone further north on the Barents Sea margin, as they are located along strike of the Fugløya transfer zone (Indrevær et al. paper 1).

Thirdly, aspect analysis of the topography and bathymetry within the study area suggest that the coastal landscape and the strandflat are tectonically influenced (Indrevær & Bergh, paper 3). The analysis reveals that surface slopes and escarpments trending NNE-SSW and ENE-WSW, and subsidiary NW-SE trend, dominate the landscape and strandflat topography, thus reflecting the two populations of post-Caledonian brittle faults commonly observed in western Troms and the in general NW-SE trending ductile basement fabric, respectively.

Margin evolution

Based on the results and synthesis of the three papers, we propose a model for the evolution of the SW Barents Sea margin (Fig. 4). Initial NW-SE oriented extension occurred in the Carboniferous and Late Permian/Early Triassic along a distributed network of NE-SW trending, NW and SE dipping normal fault complexes (Fig. 4a). The onshore studies of fault rocks linked to the Late Permian/Early Triassic rift activity show that the present day surface was located in the deeper parts of the seismogenic zone (~8.5-10km depth) (Indrevær et al. paper 2). This is supported by the observation of preserved deep-forming silica-rich ultracastaclasites from granitoid fault rocks, and the lack of any subsequent formation of phyllosilicates within the core zones (Indrevær et al. paper 2). Faulting was characterized by high-pressure fluid infiltration of a mafic composition and processes such as mineral precipitation and grain growth influenced fault permeability through time (Indrevær et al. paper 2).

The termination of onshore fault activity after Early Triassic and the exhumation and preservation of the fault zones is believed to be due to a westward migration of fault activity to the offshore TFFC by the onset of the Late Jurassic/Early Cretaceous rifting phase. The reason(s) for such a westward migration of faulting to the TFFC is not known, but a reasonable explanation may be that the onset of the transform/strike-slip movement along the Senja Shear Zone and Fugløya transfer zone was involved. The hard-linkage of the Senja Shear Zone and the TFFC may have been the reason for the shutdown of faulting onshore in western Troms. If so, the effect of this onset came into place prior to the Late Jurassic/Early Cretaceous, in order to completely abandon the onshore fault zones by this time (Fig. 4b). It is therefore likely that the Senja Shear Zone and the Fugløya transfer zone initially only modestly influenced the nature and stepping of brittle normal faulting along the margin (during Late Permian/Early Triassic) and that any significant strike-slip motion along the transfer zones occurred later, during the Late Jurassic/Early Cretaceous rifting event.

The Late Jurassic/Early Cretaceous rifting event was accompanied by extension in the Hammerfest Basin and the activation of the adjoining Ringvassøy-Loppa and Troms-Finnmark fault complexes (Fig. 4b). The listric geometry and large amount of displacement along these few, along-strike basin-boundary faults offshore compared to the planar geometry and less amounts of displacement along the onshore VVFC, resulted in the formation of a short tapered, hyper-extended margin after final break-up in the Paleocene/Eocene (Fig. 4c). Offshore, further reactivation, listric faulting and sediment deposition in the offshore basins (e.g. Harstad and Tromsø Basins) continued in the Cenozoic, due to transform plate motion along the Senja Shear Zone. In onshore areas, the WTBC was uplifted and exhumed in the Early Cenozoic as a short-tapered margin due to unloading and crustal flexure of the crust (Indrevær et al. paper 1). Continued uplift, reactivation of faults and erosion followed in the Late Cenozoic due to climate deterioration linked to the formation of the North-Atlantic Ocean, which caused subsequent flexure and greater uplift of the marginal crust due to a faster rate of erosion along the margin than inland (Fig. 4d).

Implications for hydrocarbon exploration in basement rocks

The results from Indrevær et al. (paper 2) shows that the onshore Late Permian/Early Triassic fault zones likely became completely sealed shortly after faulting by the processes of mineral precipitation and grain growth. As the studied fault zones are shown to correlate with offshore basin-bounding faults and faults on the Finnmark Platform and possibly also the Loppa High (Indrevær et al., paper 1), the same processes may have been valid for offshore basement-involved fault zones as well. This implies that these faults at present will act as fluid barriers. As is evident from the evidence for fluid flow from the study, a reactivation of a fault zone after any potential entrapment of hydrocarbons, will temporary increase fault permeability significantly and allow for along- and across-fault migration of hydrocarbons.

Further, Olesen et al. (2013) discuss the presence of saprolites in northern Norway, in context with Triassic to Jurassic deep weathering of basement rocks. The saprolites commonly occur as chemically weathered, highly permeable grus deposits. It implies that within basement highs such as the Finnmark Platform and the Loppa High, highly permable weathered grus may be juxtaposed with impermeable Palaeozoic-Mesozoic fault zones due to normal faulting. Alternatively, highly fractured basement rocks may act as a reservoir. Important factors for the formation of hydrocarbon reservoirs may thus be present on basement highs in the Barents Sea.

Future research

The following suggestions on future research are given to further verify and/or evolve the results and models presented herein:

- The considerable gap between onshore fault outcrops and offshore seismic data has to some extent been made clearer by the study of high-resolution bathymetry and magnetic anomaly data. Still, large portions of the Finnmark Platform have a poor coverage of seismic data and are covered with glacigenic sediments, leaving the bathymetry data useless in these areas. Access to the new generation of magnetic anomaly data (BASAR, NGU) may increase the accuracy of fault correlation across the Finnmark Platform.
- Grav-mag modelling within the study area would further increase our understanding of the SW Barents Sea Margin, especially in relation to the structure of the deeper crust, including the depth to MOHO and the location of the taper break.
- The identification and existence of the Fugløya transfer zone may be verified by geological fieldwork on the islands of Nord-Fugløya and Spenna. These islands are difficult to access and have not been possible to visit as a part of this PhD.
- An XRF-analysis and pseudosection study of the metabasites used for determination of P-T conditions during faulting could further restrain the pressure and temperature stability fields for different stages of faulting during the Late Permian/Early Triassic rifting phase.
- The differences in derived ages on fault activity in Lofoten-Vesterålen, Troms and Finnmark needs further attention. The shut-off of onshore faulting in Troms has been tentatively explained by the hard-linkage of the Troms-Finnmark Fault Complex and the Senja Shear Zone prior to the Late Jurassic/Early Cretaceous rifting phase (this thesis) and would explain why rifting continued in the Lofoten Vesterålen, but not Troms. However, one would expect that such a hard-link would prevent Mesozoic fault activity in Finnmark as well, but evidence suggest otherwise (Roberts & Lippard, 2005; Torgersen et al., 2013).
- The genetic relationship between ductile shear zones, brittle-ductile shear zones and brittle faults within the West Troms Basement Complex is still uncertain. It is

important to settle if they represent distinct tectonic events, a progressive evolution by exhumation of the margin, or alternatively, both, with a progressive re-use of pre-existing structures from earlier events and the formation of new structures with the onset of a new tectonic event.

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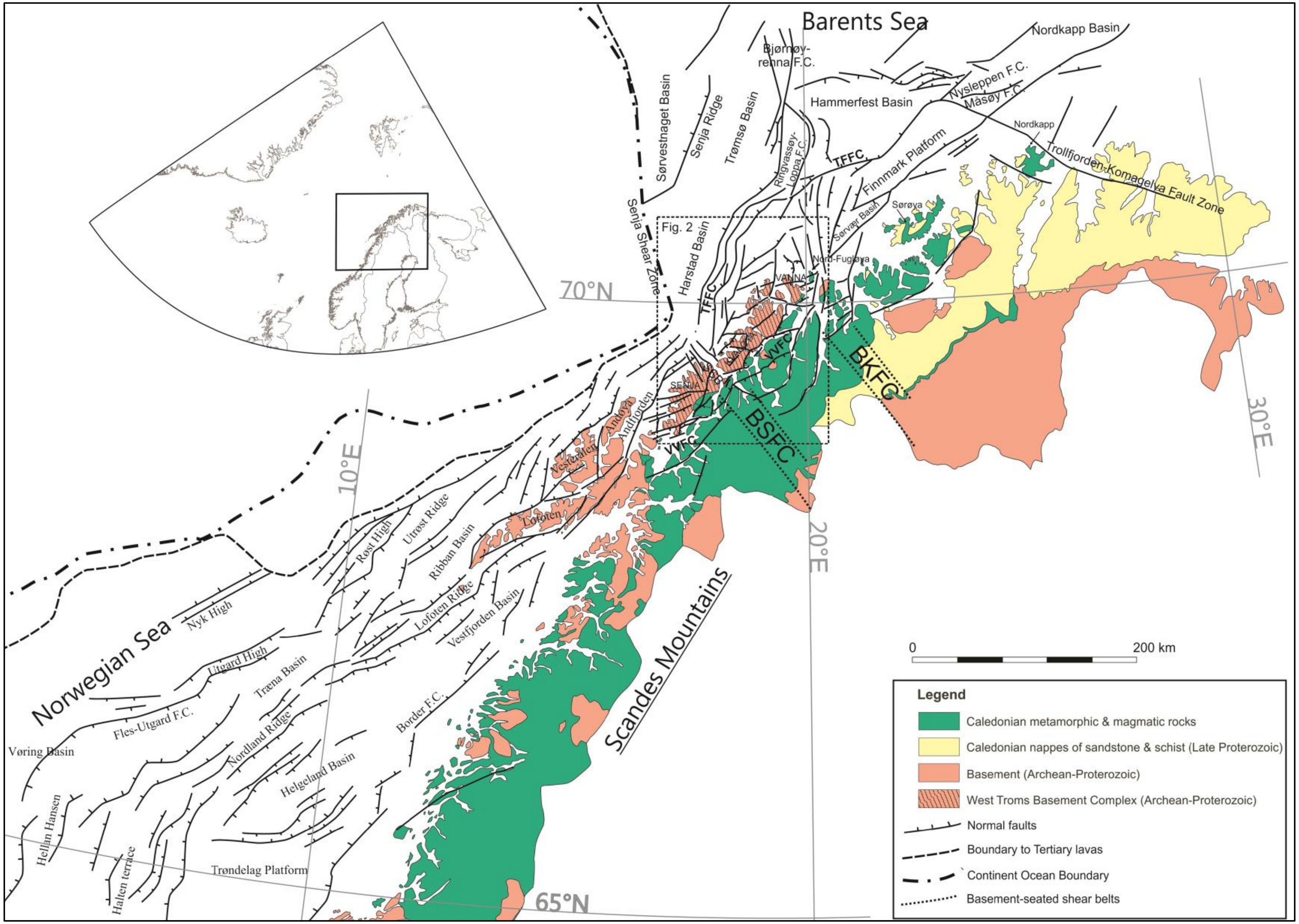

Figure 1: Regional onshore-offshore tectonic map and setting of the mid-Norwegian shelf, the West Troms Basement Complex and the SW Barents Sea margin (after Blystad et al., 1995; Mosar et al., 2002; Bergh et al., 2007; Faleide et al., 2008; Hansen et al., 2012; Indrevær et al., 2014). Onshore geology is from the Geological Survey of Norway. The yellow box outlines Fig. 2. Abbreviations: TFFC=Troms-Finnmark Fault Complex, VVFC=Vestfjorden-Vanna Fault Comple

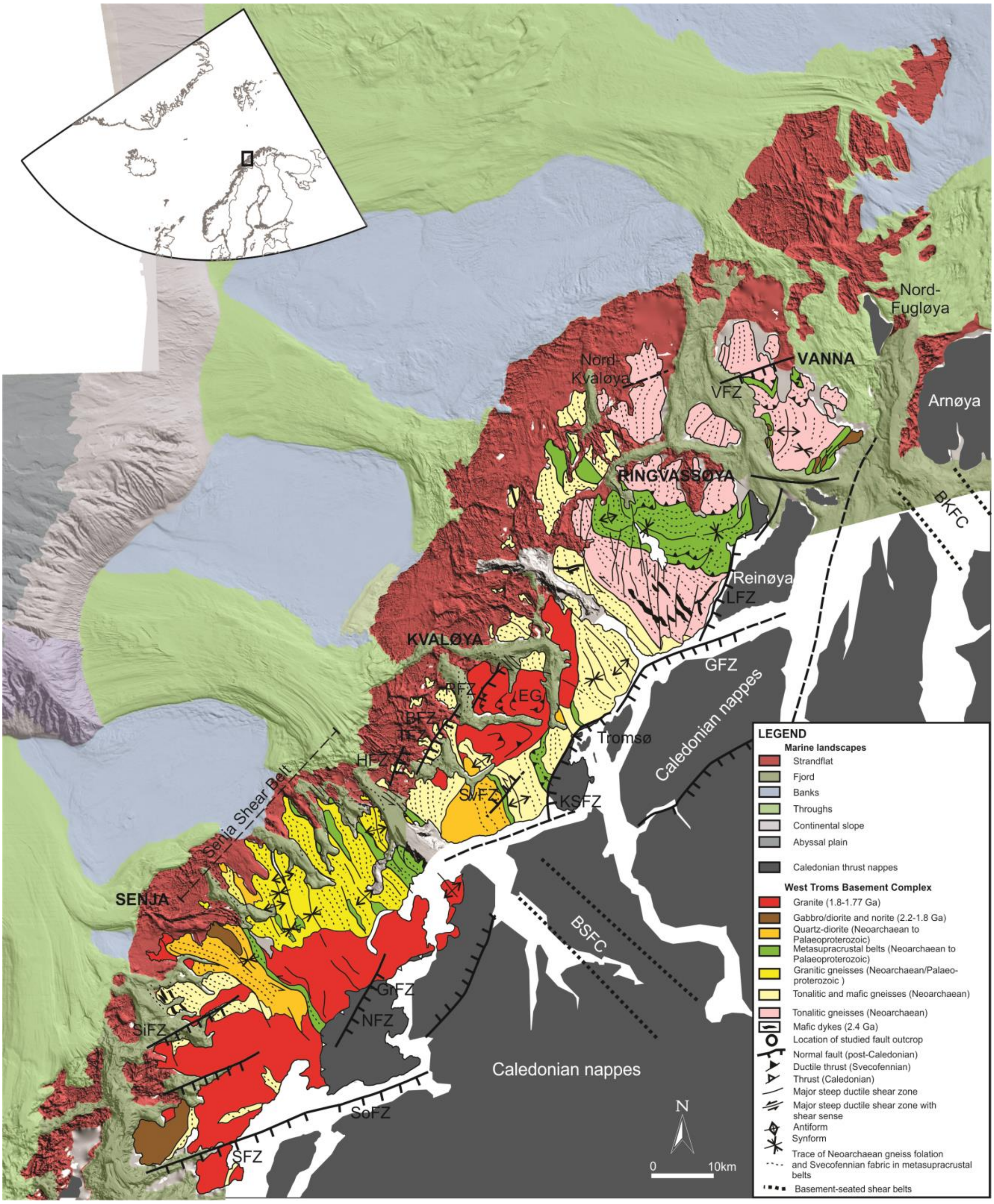

Figure 2: Detailed geological map of the West Troms Basement Complex showing main Archaean-Palaeoproterozoic fabrics and post-Caledonian brittle normal faults that separate the basement horst from down-dropped Caledonian nappes to the east (after Bergh et al., 2010). Offshore, marine landscape types are given, including the lateral distribution of the strandflat (mareano.no). Abbreviations: BFZ = Bremneset fault zone, BKFC=Bothnian-Kvænangen Fault Complex, BSFC=Bothnian-Senja Fault Complex, EG=Ersfjord Granite, GFZ=Grøtsundet fault zone, GrFZ=Grasmyrskogen fault zone, HFZ = Hillesøy fault zone, KSFC=Kvaløysletta-Straumsbukta fault zone, LFZ=Langsundet fault zone, NFZ=Nybygda fault zone, RFZ=Rekvika fault zone, SFZ=Stonglandseidet fault zone, SiFZ=Sifjorden fault zone, SoFZ=Solbergfjorden fault zone, SvFZ=Skorelvvatn fault zone, TFZ=Tussøya fault zone, VFZ=Vannareid-Brurøysund fault zone, VVFC=Vestfjorden-Vanna Fault Complex.

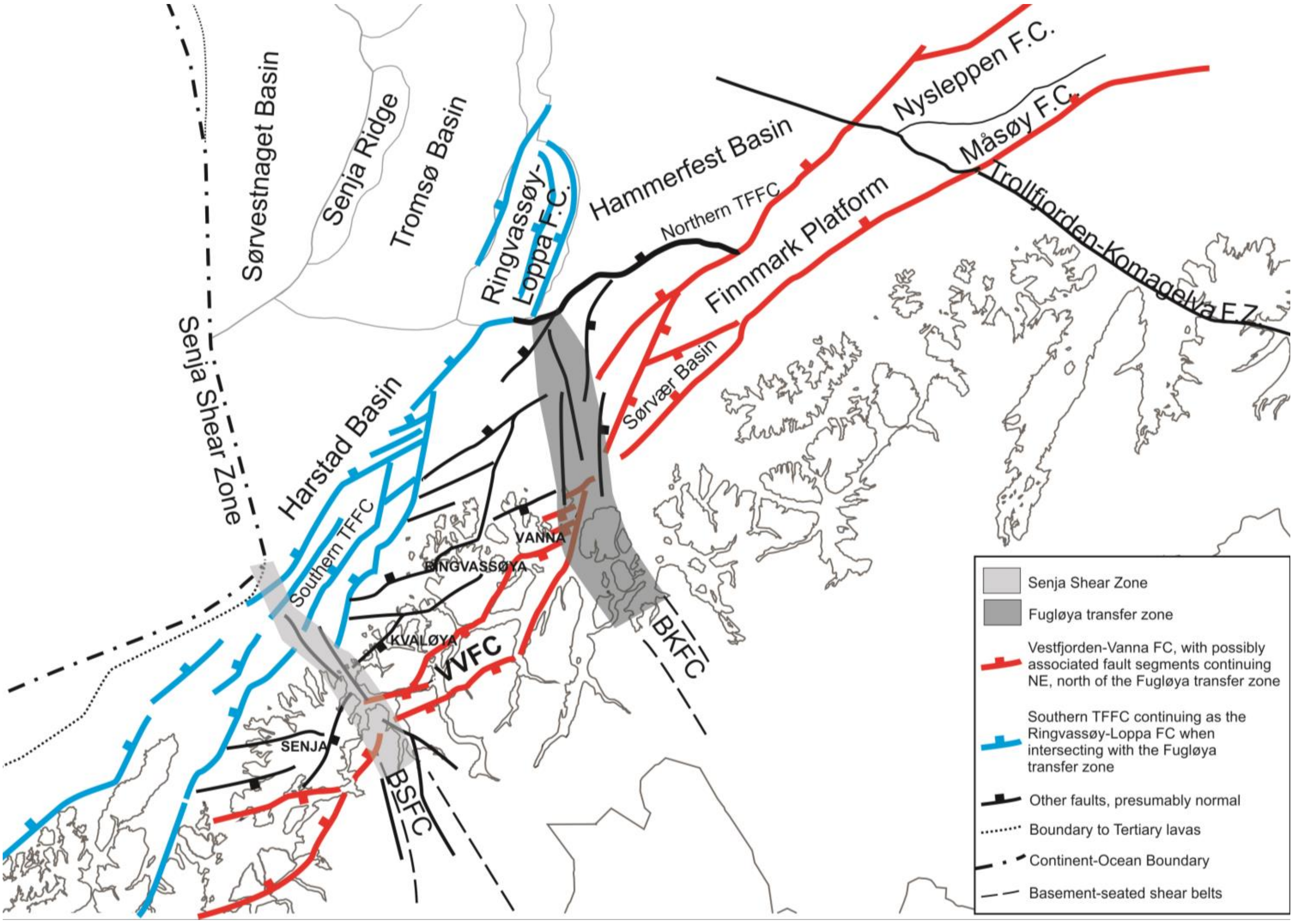

Figure 3: Simplified tectonic map of the SW Barents Sea region linking major NNE-SSW and ENE-WSW trending fault complexes onshore and offshore. At least two transfer zones, one located along the Precambrian Senja Shear Belt (BSFC = Bothnian-Senja Fault Complex) and the second, the Fugløya transfer zone, the continuation of the Bothnian-Kvænangen Fault Complex (BKFC), accommodate change in polarity and stepping of fault zones along the margin.

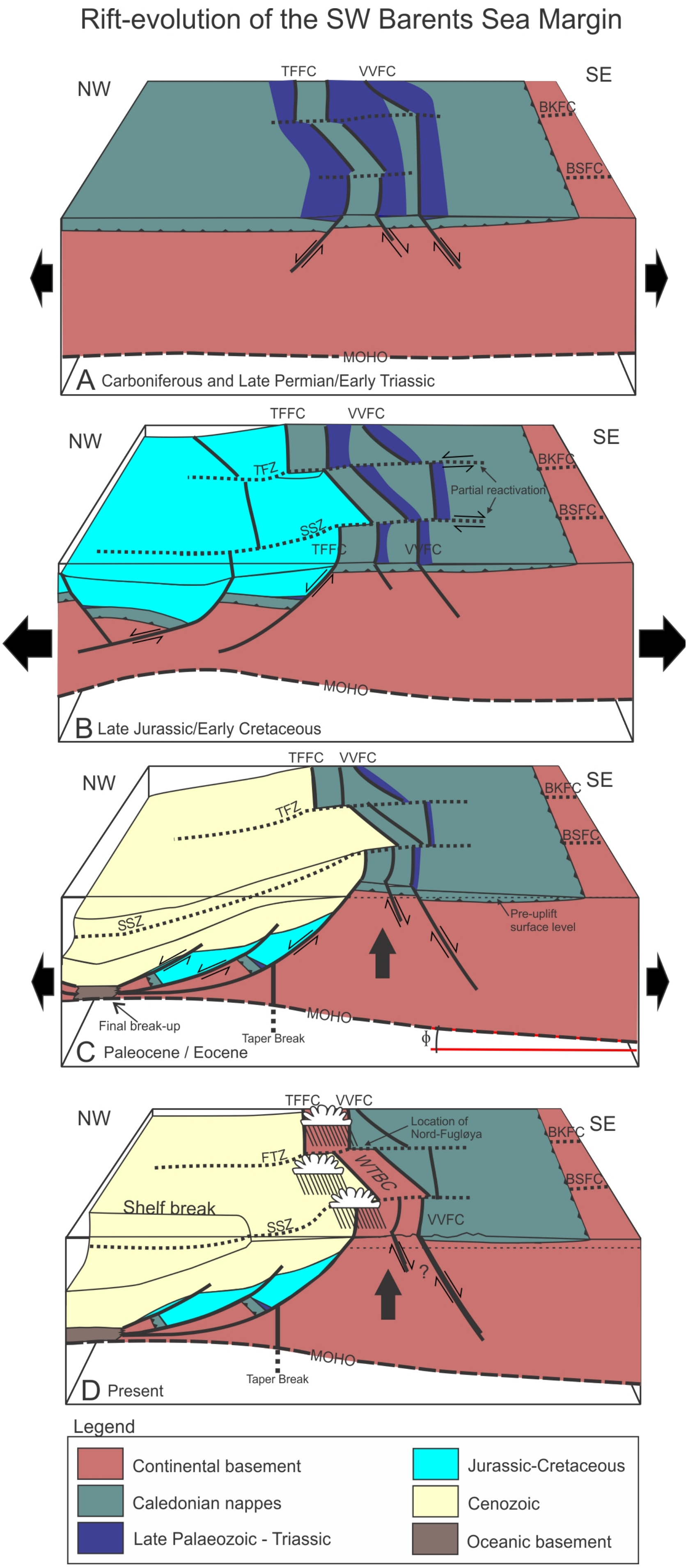

Figure 4: Schematic proposed tectonic evolution of the SW Barents Sea margin and the exhumation of the West Troms Basement Complex (WTBC). (a) Intial shallow and distributed NE-SW faulting in the Carboniferous and Late Permian/Early Triassic along the Troms-Finnmark and the Vestfjorden-Vanna fault complexes. Partial reactivation of the Bothnian-Kvænangen and Bothnian-Senja fault complexes as transfer zones allowed for changes in fault polarity along the margin. (b) Continued rifting in the Late Jurassic/Early Cretaceous was accompanied by the hard link of the Senja Shear Zone (SSZ) and the Troms-Finnmark FC and dextral and sinistral displacement along the SSZ and the Fugløya transfer zone, respectively (c) Paleocene/Eocene extension and transform movement along the SSZ caused final break-up, further listric faulting offshore and uplift of the short-tapered margin due to unloading and crustal flexure. (d) Continued uplift and exhumation of the WTBC due to climate detoriation and associated increase in coastal erosion rates. BKFC=Bothnian-Kvænangen Fault Complex, BSFC=Bothnian-Senja Fault Complex, TFFC=Troms-Finnmark Fault Complex, SSZ=Senja Shear Zone, FTZ=Fugløya transfer zone, VVFC= Vestfjorden-Vanna Fault Complex.

Paper 1

Paper 2

Paper 3