Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture

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Indrevær, K., Bergh, S.G., Koehl, J.-B., Hansen, J.-A., Schermer, E.R. & Ingebrigtsen, A.: 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, pp. 167–188. Trondheim 2013, ISSN 029-196X.

Onshore-offshore correlation of brittle faults and tectonic lineaments has been undertaken along the SW Barents Sea margin off northern Norway. The study has focused on onshore mapping of fault zones, the mapping of offshore fault complexes and associated basins from seismic interpretation, and the linkage of fault complexes onshore and offshore by integrating a high-resolution DEM, covering both onshore and offshore portions of the study area, and processed magnetic anomaly data. This study shows that both onshore and offshore brittle faults manifest themselves mainly as alternating NNE–SSW- and ENE–WSW-trending, steeply to moderately dipping, normal fault zones constituting at least two major NE-SW-trending fault complexes, the Troms-Finnmark and Vestfjorden-Vanna fault complexes. These fault complexes in western Troms bound a major basement horst (the West Troms Basement Complex), run partly onshore and offshore and link up with the offshore Nysleppen and Måsøy fault complexes. Pre-existing structures in the basement, such as foliation, lithological boundaries and ductile shear zones are shown, at least on a local scale, to have exerted a controlling effect on faulting. On a larger scale, at least two major transfer fault zone systems, one along the reactivated Precambrian Senja Shear Belt and the other, the Fugløya transfer zone, accommodate changes in brittle fault polarity along the margin. Our results suggest that distributed rifting during Carboniferous and Late Permian/Early Triassic time was followed by a northwestward localisation of displacement to the Troms–Finnmark and Ringvassøy–Loppa fault complexes during the Late Jurassic/Early Cretaceous, resulting in the formation of a short-tapered, hyperextended margin with final break-up at ~55 Ma. An uplift of the margin and preservation of the West Troms Basement Complex as a basement outlier is suggested to be due to unloading and crustal flexure of the short-tapered margin in the region.

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Introduction

The continental margin off Central/Mid Norway was subjected to multiple rift events in the Palaeozoic through to Early Cenozoic times as a part of the break-up of the North Atlantic Ocean (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 these rifting events and the resulting margin architecture are well constrained by seismic and potential field data offshore Mid Norway (e.g., Dore et al., 1999; Brekke, 2000; Redfield & Osmundsen, 2013). On the Lofoten–Vesterålen margin (Fig. 1), recent work on the linking of onshore and offshore fault systems and morphotectonic elements has established a very complex rift evolution (Olesen et al., 1997, 2007; Tsikalas et al., 2001, 2005, 2008; Wilson et al., 2006; Bergh et al., 2007; Eig, 2008; Hansen, 2009; Hansen et al., 2012). However, north of Lofoten, on the West Troms margin, few onshore-offshore structural studies have been undertaken (Gabrielsen et al., 1990; Roberts & Lippard, 2005). This region marks the transition between the spreading, normal passive margin and the Barents Sea transform margin (Fig. 1). Along the West Troms margin, onshore brittle faults manifest themselves mainly as NNE–SSW- and ENE–WSW-trending normal faults, as in the Lofoten–Vesterålen archipelago. They are constrained to a major basement horst that extends from Lofoten in the south to Vanna in the north (Fig. 1) 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 basement horst is named the West Troms Basement Complex (WTBC) (Zwaan, 1995) and is flanked in the south by major normal faults (Blystad et al., 1995; Bergh et al., 2007; Hansen et al., 2012) that border the offshore Ribban and Vestfjorden basins. Northwards it is bound to the east by

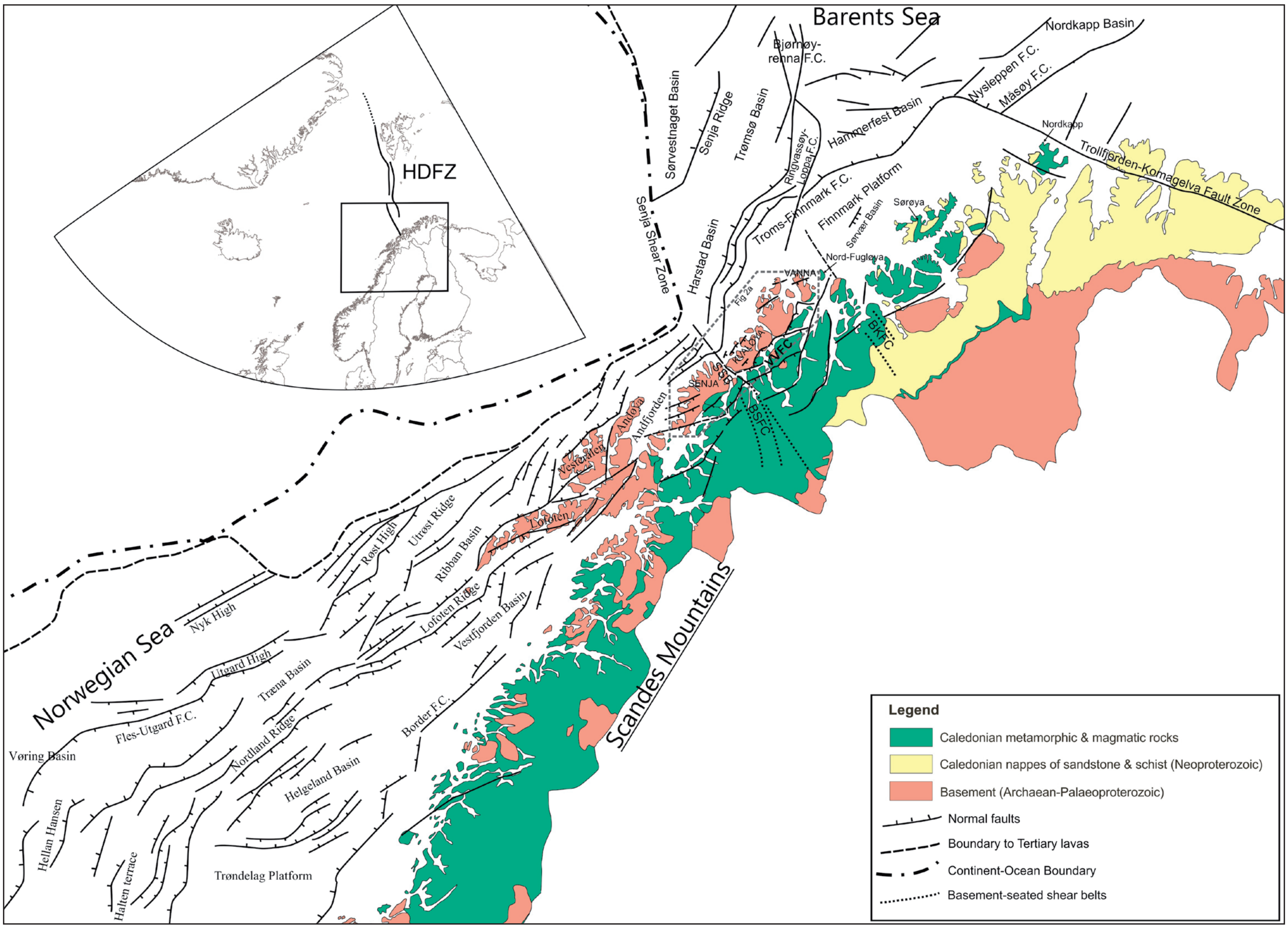


***Figure 1.** Regional onshore-offshore tectonic map and setting of the Mid-Norwegian shelf, the Lofoten–Vesterålen archipelago and the SW Barents Sea margin (after Blystad et al., 1995; Mosar et al., 2002; Bergh et al., 2007; Faleide et al., 2008; Hansen et al., 2012). Onshore geology is from the Geological Survey of Norway. The boxed area in the inset map outlines Fig. 2A. Abbreviations: BKFC – Bothnian–Kvænangen Fault Complex, BSFC – Bothnian–Senja Fault Complex, HDFZ – Hornsund–De Geer Fault Zone, SSB – Senja Shear Belt, VVFC – Vestfjorden–Vanna Fault Complex.*

the SE-dipping Vestfjorden–Vanna Fault Complex that down-drops Caledonian nappes (Andresen & Forslund, 1987; Forslund, 1988; Opheim & Andresen, 1989; Olesen et al., 1997; Roberts & Lippard, 2005).To the west of the WTBC, no specific major faults or fault zones have yet been observed that may correspond to horst-bounding faults offshore.

The present work focuses on the network of Palaeozoic–Mesozoic faults in the West Troms Basement Complex and their relationship to major structural elements in 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 (Figs. 1, 2; Ramberg et al., 2008; Smelror et al., 2009). We aim to identify and characterise rift-related fault zones exposed onshore, and to discuss the possible controls of inherited basement fabrics as a framework for regional correlation. Particular emphasis will be given to proposed boundary faults of the onshore basement horst, e.g., the Rekvika fault zone in the west, suggested to be a possible onshore portion of the Troms–Finnmark Fault Complex (Antonsdottir, 2006; Thorstensen, 2011; Hansen et al., 2012), and the Kvaløysletta–Straumsbukta fault zone (and others) on the landward side of the WTBC (Andresen & Forslund, 1987; Forslund, 1988; Olesen et al., 1997). Comparisons with offshore fault zones will be made based on seismic data. We have performed detailed mapping in regions where major structural elements converge, diverge or change orientation, in order to understand their origin and relationships. We have used a digital elevation model (DEM) and magnetic anomaly data to link up and/or extend fault traces between and beyond exposures of onshore faults and to map tectonic lineaments in offshore regions where seismic data coverage is insufficient. The compiled data on fault behaviour in the region will be evaluated in the context of a hyperextended Norwegian margin, as proposed by Redfield & Osmundsen (2013).

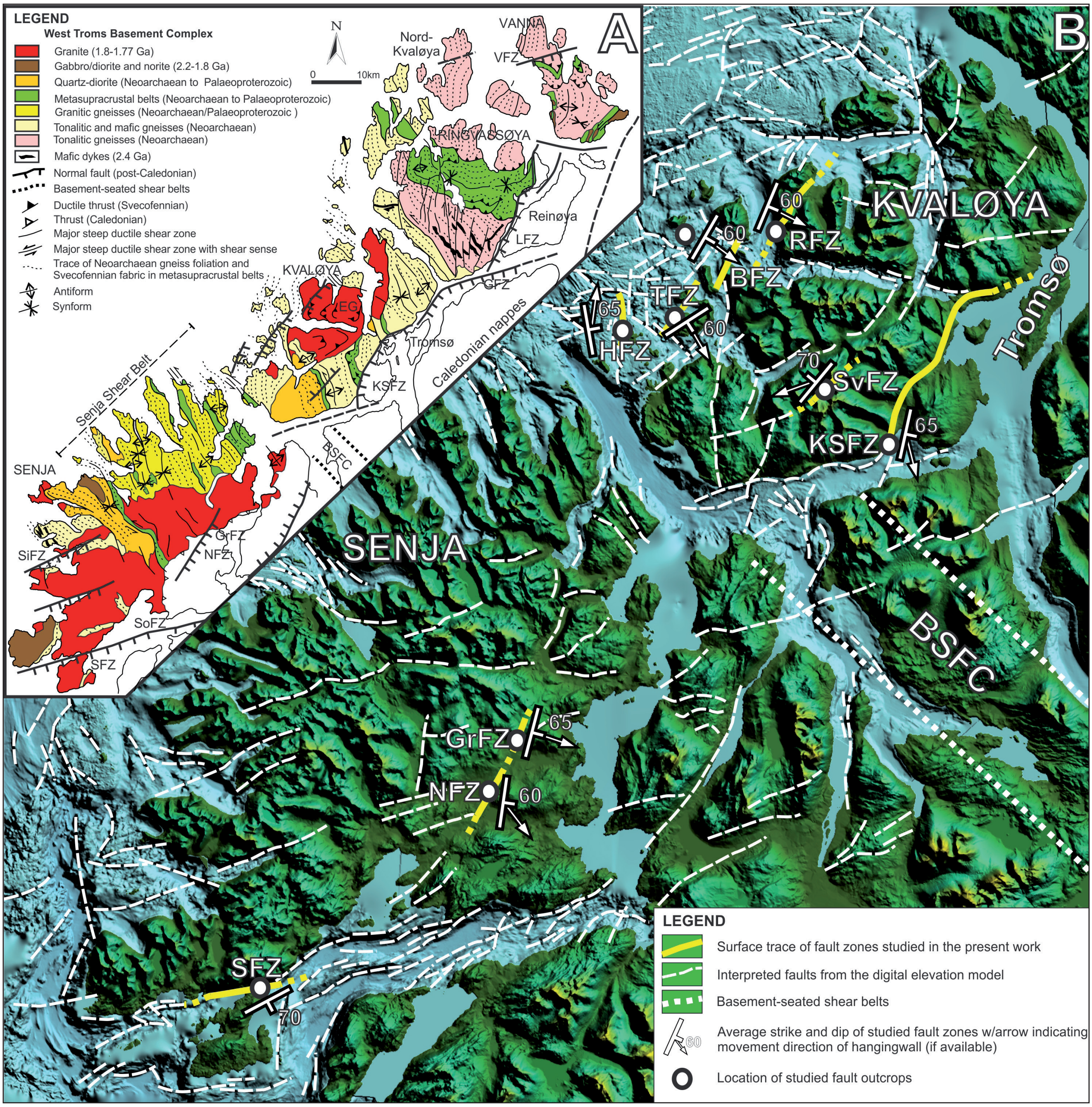


Figure 2. *(A) Detailed geological map of the West Troms Basement Complex showing the main Archaean–Palaeoproterozoic foliations and post-Caledonian brittle normal faults that separate the basement horst from down-dropped Caledonian nappes to the east and Late Palaeozoic–Mesozoic basins to the west (after Olesen et al., 1997; Bergh et al., 2010). Note the step-wise pattern of normal faults that correspond with the general orientation of fjords and sounds and offshore fault-bounding basins. (B) Digital elevation model (DEM) showing the location of studied fault outcrops from Fig. 4, with interpreted lineaments and synthesised fault data. Note that most lineaments trend NNE–SSW and ENE–WSW, with a subsidiary set trending ~NW–SE, both onshore and on the shallow shelf. Abbreviations: BFZ – Bremneset fault zone, 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.*

Geological setting and margin evolution

Precambrian structures of the West Troms Basement Complex

The West Troms Basement Complex horst (Fig. 2) is made up of various Meso- and Neoarchaean (2.9–2.6 Ga) tonalitic, trondhjemitic and granitic TTG-gneisses, metasupracrustal rocks/greenstone belts (2.85–1.9 Ga), and felsic and mafic igneous rocks (1.8–1.75 Ga) (Corfu et al., 2003; Bergh et al., 2010). The ductile deformation within the WTBC is mostly of Svecofennian age (1.8–1.7 Ga) and includes macro-scale upright and vertical folds linked to NW–SE-trending, steep deformation zones or terrane boundaries (Fig. 2A). These structural trends are largely parallel with the Archaean and Palaeoproterozoic orogenic belts of the Fennoscandian Shield that stretch from Kola Peninsula in Russia through Finland and Sweden into the Bothnian Basin of central Scandinavia (Gaal & Gorbatschev, 1987; Hölttä et al., 2008; Lahtinen et al., 2008). The younger Caledonian overprint is generally weak (Corfu et al., 2003; Bergh et al., 2010).

Post-Caledonian structures

The Palaeozoic–Mesozoic rift-related activity on the West Troms margin is manifested within the horst by widespread, NNE–SSW- and ENE–WSW-trending, brittle normal faults and fractures arranged in a zigzag pattern along its southeastern and northwestern limits (cf., Hansen et al., 2012) and a subsidiary NW–SE-trending fracture system that is best developed in Lofoten (Fig. 1; Eig & Bergh, 2011; Hansen & Bergh, 2012). The Vestfjorden–Vanna Fault Complex (VVFC, Figs. 1, 2A; Olesen et al., 1997) can be traced for hundreds of kilometres southwestwards along the North Norwegian margin, as it links up and continues along the Lofoten and Nordland ridges, as well as along the Halten terrace farther south (Dore et al., 1997, 1999). The zigzag-shaped map pattern of the VVFC in western Troms can be traced northwards to Vanna, outlined by several smaller-scale fault segments (Fig. 2; Andresen & Forslund, 1987; Forslund, 1988; Opheim & Andresen, 1989; Olesen et al., 1997), where it continues offshore as a part of the boundary fault system of the Sørvær Basin (Fig. 1; Olesen et al., 1997). From this point it has not been mapped farther northwards. The fault zones within the VVFC in general show down-to-southeast normal displacement on the order of 1–3 km based on the offset of Caledonian nappes with known thickness (Forslund, 1988; Opheim & Andresen, 1989; Olesen et al., 1997).

On the seaward side of the West Troms Basement Complex horst, no major, hard-linked boundary-fault complex similar to the VVFC on the landward side has yet been identified. Instead, less prevalent fault zones exist (Fig. 2; Olesen et al., 1997; Antonsdottir, 2006; Thorstensen, 2011) that run along the outer islands of the horst. In addition, a few fault zones within the central parts of the WTBC have been identified (Fig. 2; Opheim & Andresen, 1989; Armitage & Bergh, 2005; Gagama, 2005). The western zone of faults is not well known from previous studies. The kinematics, timing and evolution of these faults, as well as possible controlling effects on basement structures for the location of Palaeozoic–Mesozoic brittle fault reactivation, will be discussed in the present paper.

Margin evolution and fault timing

The Mid-Norwegian and SW Barents Sea continental margin experienced multiple periods of rifting during the Palaeozoic and Mesozoic that were linked to the break-up of Pangea, and the final stages of opening of the North Atlantic Ocean in the Cenozoic (cf., Gabrielsen et al., 1990; Faleide et al., 2008; Smelror et al., 2009). The earliest events occurred in Mid Carboniferous, Carboniferous–Permian and Permian–Early Triassic times (Doré, 1991). In the western Barents Sea, 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). On the Lofoten–Vesterålen margin, rifting is thought to have occurred during multiple tectonic events in the Permian–Early Triassic, Mid/Late Jurassic–Early Cretaceous and latest Cretaceous–Palaeogene (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 leading to the formation of the Harstad, Tromsø, Bjørnøya and Sørvestnaget basins in the SW Barents Sea (Gabrielsen et al., 1997; Knutsen & Larsen, 1997; Faleide et al., 2008). Similarily, the Troms–Finnmark Fault Complex experienced a long-term activity from the Carboniferous through to the Eocene, with the main fault-related subsidence in Late Jurassic to Early Cretaceous times (Gabrielsen et al., 1990; Faleide et al., 2008).

A Late Cretaceous to Palaeocene rifting event preceded the final lithospheric break-up at *c.* 55–54 Ma. This rifting event was accomplished by transform movement along the Senja Shear Zone and the Hornsund-De Geer Fault Zone west of Svalbard (Gabrielsen et al., 1990; Faleide et al., 1993, 2008), leading to the further development of the Tromsø and Harstad basins as pull-apart basins. Simultaneously, inversion occurred in the Bjørnøyrenna and Ringvassøy–Loppa fault complexes (Gabrielsen et al., 1997). Since Oligocene time, the SW Barents Sea has been a passive continental margin (Faleide et al., 2008).

Onshore, recent datings using ^{40}Ar/^{39}Ar and apatite fission-track dating methods have been interpreted to indicate that faulting in western Troms largely occurred during the Permian to Early Triassic rifting phase, corresponding with the large-scale fault activity identified in the Vestfjorden and Træna basins, with no major fault displacement during the Mesozoic and Cenozoic (Hendriks et al., 2010; Davids et al., 2013). However, Mesozoic fault activity is suggested to have taken place onshore both farther north in Finnmark (Roberts & Lippard, 2005), and to the south in Lofoten–Vesterålen and Andøya (Dalland 1981; Fürsich & Thomsen, 2005; Hansen, 2009; Hendriks et al., 2010; Osmundsen et al., 2010; Davids et al., 2013). Palaeomagnetic 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 (Forslund, 1988; Olesen et al., 1997).

Methods and databases

The present work is centred on understanding the distribution, geometry and kinematic behaviour of faults in the study area using: (1) descriptions of onshore fault characteristics, (2) the distribution of major offshore fault complexes and associated structures from interpretation of seismic data and (3) correlation and linkage of fault complexes onshore and offshore by integrating a high-resolution DEM and processed magnetic anomaly data. The data allows for a high-confidence interpretation of faults and tectonic lineaments on the shallow shelf where the coverage of seismic data is insufficient for fault interpretation.

Fieldwork

Fault zone outcrops were mapped with emphasis on gathering data on fault/fracture patterns, fault rock types, mineral precipitation on fault/fracture planes and orientation of pre-existing structures such as foliation and lithological boundaries in the host rock. Slickensided fault surfaces were used to determine slip sense. Fault orientation data are plotted as great circles and poles to planes with directions of slip-linears for the hanging wall in lower-hemisphere equal-area stereonets.

Seismic database and wells

The seismic data used in the present work include all available public 2D and 3D seismic data in the region (Fig. 3; pdp.diskos.com). Variable ages and quality of the seismic data may have influenced the fault interpretation and correlation in some areas. Horizons were picked using available public well data (Fig. 3; see later offshore section for more details). Depth conversion of seismic sections was done using the commercial *Aker hiQbe* velocity model (http://www.akersolutions.com) covering the SW Barents Sea.

Magnetic anomaly data

Magnetic anomaly data from the Geological Survey of Norway have been used to map faults and tectonic lineaments in the WTBC and adjacent coastal areas (Henkel, 1991; Olesen et al., 1997), using a similar method as for the Lofoten–Vesterålen margin (cf., Tsikalas et al., 2005; Eig, 2008; Hansen et al., 2012; Hansen & Bergh, 2012). The surveys used in this study are the tilt derivative of the HRAMS–98 and NGU69/70.

The tilt derivative (Miller & Singh, 1994) is chosen for

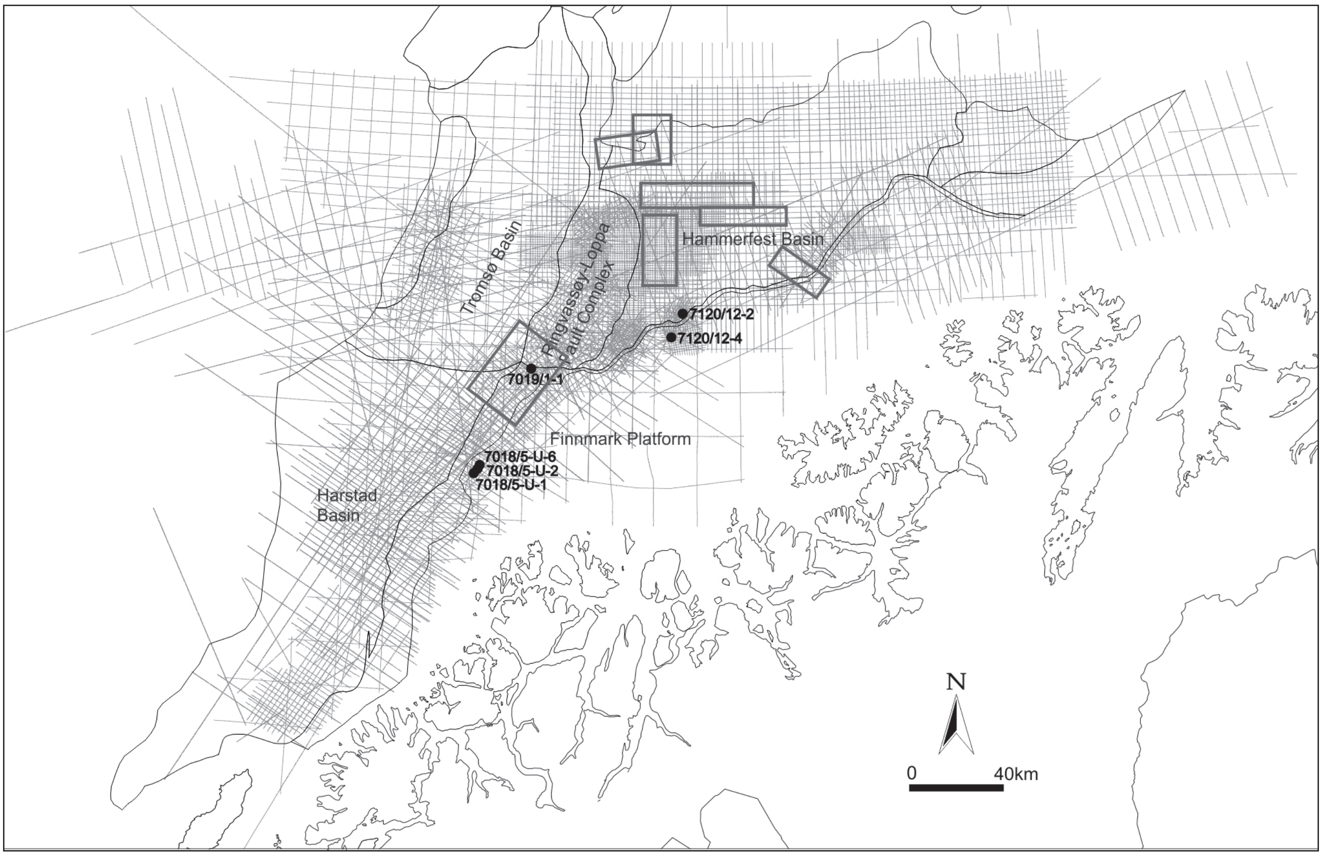


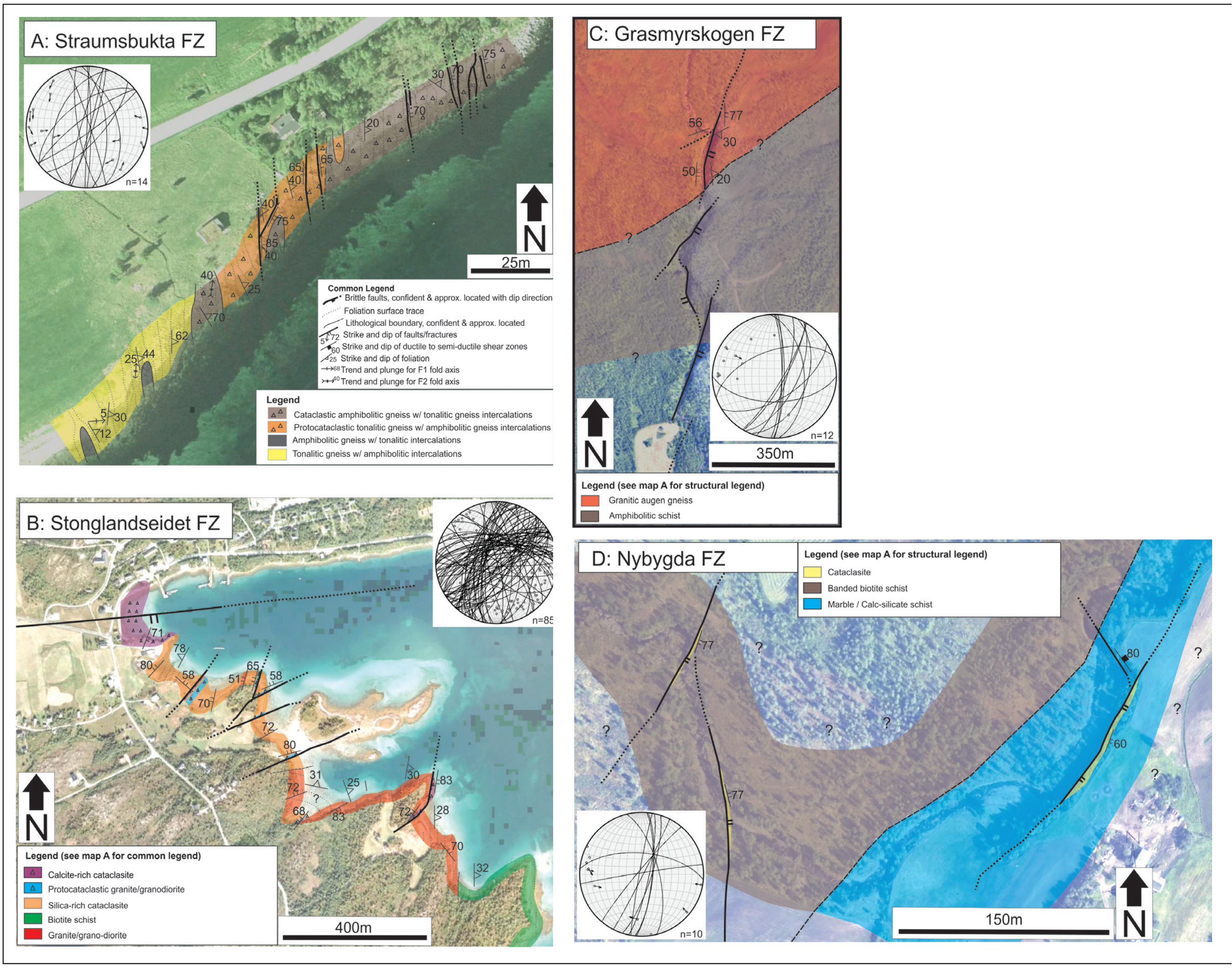
Figure 3. *Overview of the available 2D and 3D seismic data used in the study with the location of wells (numbered) used for seismic correlation (pdp.diskos.com).*

mapping because it enhances subtle magnetic anomalies in the subsurface such as those produced by faults. This is due to the nature of the arctan trigonometric function used in the calculation of the tilt derivative, restricting all values to ±90° regardless of the amplitude of the vertical or the absolute value of the total horizontal gradient (Verduzco et al., 2004).

Digital Elevation Model (DEM) data

The use of high-resolution bathymetric and topographic data for fault trace mapping is a method that has recently been adopted in the region (e.g., Roberts et al., 2011), made possible due to the availability of high-resolution bathymetry data and digital terrain models. A continuous 50 x 50 m digital elevation model (DEM) covering both onshore and offshore areas has been constructed for the area of study, based on the MAREANO (mareano.no), IBCAO (Jacobsson et al., 2012) and Norway Digital (norgedigitalt.no) databases.

The interpretation of DEM data builds on the assumption that the alpine topography is, in part, tectonically controlled and hence allows us to map tectonic lineaments from either aerial photography or terrain models (Gabrielsen et al., 2002; Gagama, 2005; Wilson et al., 2006; Bergh et al., 2008; Osmundsen et al., 2010). To assure an adequate quality of the interpretations, the method should only be used in combination with a good, field-based geological understanding of the study area. Offshore, many of the same assumptions are valid for bathymetry data. It is imperative to be able to clearly differentiate between glacial and tectonic lineaments, and bathymetric data should only be used cautiously and in combination with seismic data in order to identify true tectonic lineaments.



Results

Onshore fault zones

Several outcropping fault zones in and adjacent to the WTBC horst have been investigated (Figs. 2, 4). Many of the fault zones have been described in varying detail by other authors, but all of the mentioned fault-zone outcrops have been revisited and mapped for this work. This common platform of reference ensures a proper characterisation and comparison of fault geometries and kinematics for the different fault zones. The results presented here are therefore from this work unless stated otherwise.

The studied fault zones are located on (i) the eastern, or landward rim of the WTBC, (ii) the onshore western, seaward side, and (iii) inside the horst itself (Figs. 2, 4). In general, the fault zones delimit two major trends, NNE–SSW and ENE–WSW with variable dips to the SE and NW, and one minor structural trend striking NW–SE. The NNE–SSW- and the ENE–WSW-trending faults dominate the regional map pattern and alternate along strike, generating a zigzag pattern and enclosing fault-block domains.

Landward fault zones

The eastern horst-bounding networks of faults (i.e., the VVFC) include the NNE–SSW- to ENE–WSW-trending and ESE- and SSE-dipping Kvaløysletta–Straumsbukta, Stonglandseidet, Grasmyrskogen and Nybygda fault zones (Figs. 2, 4A–D). The SE-dipping Kvaløysletta–Straumsbukta fault zone (first described by Forslund, 1988) runs along the eastern shore of Kvaløya, juxtaposing Precambrian gneisses in the footwall with Caledonian nappes in the hanging wall. Near Straumsbukta, the damage zone of the footwall crops out within foliated tonalitic and amphibolitic gneisses (Fig. 4A). Fault surfaces

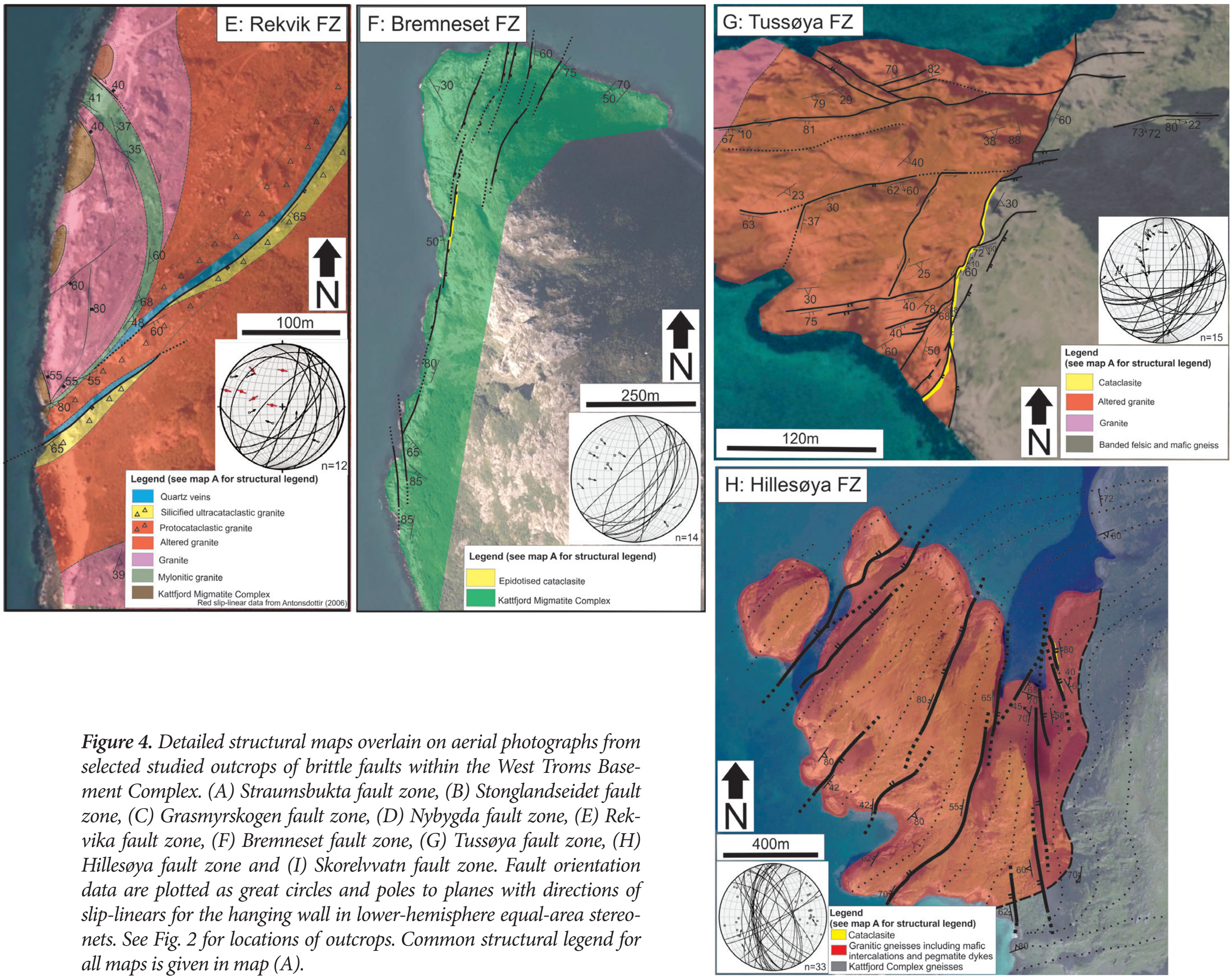


Figure 4. Detailed structural maps overlain on aerial photographs from selected studied outcrops of brittle faults within the West Troms Basement Complex. (A) Straumsbukta fault zone, (B) Stonglandseidet fault zone, (C) Grasmyrskogen fault zone, (D) Nybygda fault zone, (E) Rekvika fault zone, (F) Bremneset fault zone, (G) Tussøya fault zone, (H) Hillesøya fault zone and (I) Skorelvvatn fault zone. Fault orientation data are plotted as great circles and poles to planes with directions of slip-linears for the hanging wall in lower-hemisphere equal-area stereonets. See Fig. 2 for locations of outcrops. Common structural legend for all maps is given in map (A).

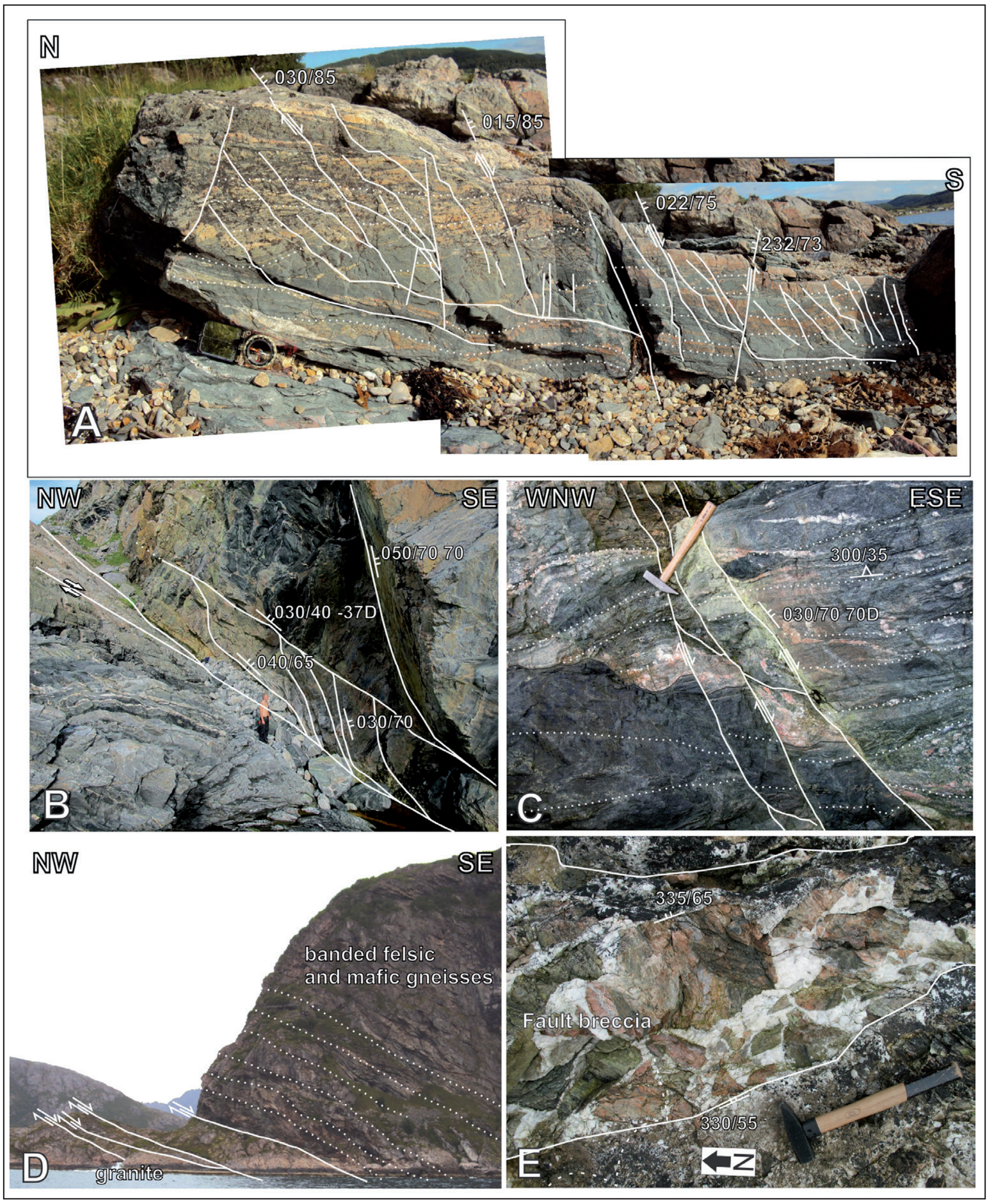


Figure 5. *Selected field photos of brittle faults studied within the WTBC. (A) Mesoscale brittle faults in outcrop from the footwall of the Kvaløysletta–Straumsbukta fault zone at Straumsbukta. Note the red-stained colour of the tonalitic gneiss bands due to hydrothermal alteration. (B) Outcrop of the Bremneset fault zone at Bremneset, showing a 2 m-wide, epidote-rich cataclastic zone that cuts the foliation of mafic gneisses at a high angle. Note splaying and deflection of fractures within the cataclastic core zone towards its boundaries, supporting a dextral component of displacement. (C) Small-scale brittle normal faults that offset foliated amphibolite gneisses within the Bremneset fault zone. The offsets indicate down-to-the-ESE fault motion. (D) Overview of the Tussøya fault zone localised at the lithological boundary between banded felsic and mafic gneisses and foliation-parallel granite. The height of the cliff is c. 300 m. (E) Calcite-rich breccia from the Hillesøya fault cropping out in a ~1.5 m-thick zone.*

commonly trend N–S, locally also NE–SW, and are parallel to a moderately E-dipping foliation in the gneisses. The footwall outcrop is increasingly deformed towards the east, with the occurrence of cataclastic rocks within the amphibolitic gneiss. The tonalitic gneisses are commonly red-stained from hydrothermal alteration (Fig. 5A) and fracture surfaces coated with chlorite are cut by fractures coated by quartz, which, in turn, are cut by fractures coated with hematite. The slip-linear fault data (Fig. 4A) indicate an oblique-dextral normal movement with down-to-the-SE displacement of the hanging wall.

The Stonglandseidet and Sifjorden fault zones on Senja occur largely within massive to weakly foliated granite (Fig. 2). The Stonglandseidet fault zone strikes *c.* ENE–WSW (Fig. 4B) and its fault core zone is *c.* 100 m wide and associated with carbonate-rich, cataclastic fault rocks. Faults trend mainly ENE–WSW with variable dips to the SE and NW, in addition to a subordinate set of faults trending NNE–SSW, also dipping both SE and NW. The damage zone on the southern, hanging-wall side extends for *c.* 400 m and comprises granitic and silica-rich fault zones. A presumed Caledonian foliation in the granites on the southern side dips gently to the southeast when approaching the biotite schist in the southernmost portion of the mapped area (Fig. 4B). The Stonglandseidet fault zone has a presumed down-to-the-SSE sense of shear (Forslund, 1988), based on an apparent down-drop of a Caledonian thrust that encircles the Stonglandeidet peninsula. The Sifjord fault zone (Fig. 2A) has not been studied in association with the present work, but defines a system of alternating NW- and SE-dipping, conjugate, normal fault zones with numerous epidote- and chlorite-rich fracture sets and slickensides indicating oblique-normal fault movement, down-to-the-SE (Gagama, 2005).

Other minor fault zones on Senja include the Grasmyrskogen and Nybygda faults (Fig. 2B), located within Caledonian rocks of the Upper Allochthon Lyngsfjellet Nappe Complex (Zwaan et al., 1998) or close to the thrust contact between the Lyngsfjellet Nappe Complex and the basement rocks in the southeastern part of Senja. The Grasmyrskogen fault (Fig. 4C) strikes NNE–SSW, dips to the E, and makes up a left-stepping, partly linked system of fault traces, partly excavated by a river that cuts through granitic augen gneiss in the outcrop's northern parts and amphibolitic schist in the southern part. The slickensided surfaces indicate a normal, dip-slip, down-to-the-ESE fault movement.

The Grasmyrskogen fault is connected to the NNE–SSW-striking and E-dipping Nybygda fault (Fig. 4D) farther south, which is located within banded biotite schist in the northwestern part of the locality and marbles and calc-silicate rocks in the southeastern part. Foliation dips gently NE. Minor faults predominantly dip steeply to ESE. A normal, down-to-the-ESE sense of movement is interpreted from slickensided surfaces (Fig. 4D).

The landward fault zones are generally poorly exposed, but they are interpreted to have had a considerable impact on the younger valley, fjord and sound topography. The fault cores and damage zones most likely caused the faults to act as preferred zones of ice-sheet drainage during the last glacial periods.

Seaward fault zones

The most important fault zones exposed on the western side of the WTBC include the NNE–SSW- to NE–SW-striking, east-dipping Rekvika, Bremneset, Tussøya and Hillesøya fault zones (Figs. 2, 4E–H). These faults do not display the same significant influence on the topography as the landward fault zones, but locally coincide with fault escarpments along strike. These western fault zones are located within variably foliated tonalitic and quartz-dioritic gneisses of the Kattfjord Complex (Zwaan et al., 1998; Bergh et al., 2010), and the enclosed Ersfjord granite, a massive to well foliated granitic intrusion (Andresen, 1980).

The Rekvika fault zone (first described by Antonsdottir, 2006) strikes NE–SW, dips SE (Fig. 4E) and cuts through the contact between weakly foliated Ersfjord granite and the Kattfjord Complex, which runs partly onshore and partly offshore along the coastline. The fault is characterised by a ~200–300 m-wide zone of hydrothermally altered red granite and minor cataclastic fault rocks that can be traced for *c.* 300 m along strike. The contact between the Ersfjord granite and the Kattfjord Complex is characterised by a boundary-parallel foliation within the granite, and with NE–SW- and NNW–SSE-striking, ductile shear zones splaying out from the contact. One large, curvilinear shear zone striking NNW–SSE bends into parallelism with the Rekvika fault zone. The latter consists mainly of protocataclastic and altered granite in the footwall, increasingly cut by quartz veins when approaching the core zone. The core zone is 2–3 m thick and consists of completely silicified ultracataclastic fault rocks with minor hematite. The damage zone in the footwall is typically 30–50 m wide, while the hanging wall shows little or no damage. The granite surrounding the Rekvika fault zone shows conspicuous hydrothermal alteration (red-coloured, iron-oxide staining in granite). Slickensided surfaces indicate oblique, normal, down-to-the-SE movement (Fig. 4E; Antonsdottir, 2006).

Farther south, at Bremneset and Tussøya (Fig. 4F, G), similar fault zones crop out (Fig. 2). They contain prominent cataclastic fault rocks and a hydrothermal alteration similar to that observed in Rekvika. The faults dip *c.* 60° southeast, largely parallel to the foliation of the host rock gneisses. At Bremneset, the fault zone occurs as a 0–3 m-thick, NNE–SSW-striking, E-dipping, cataclastic zone, *c.* 200 m long in the Kattfjord Complex (Fig. 5B). Fracture/fault surfaces commonly carry an epidote precipitate, and they are locally cut by younger faults/fractures with hematite staining. The gneiss foliation is locally at a moderate angle to the fault zone (Fig. 4F). Slickensided surfaces and minor fault offsets (Figs. 4F, 5C) suggest normal, down-to-the-ESE fault movement.

The Tussøya fault zone (Fig. 4G) strikes NNE–SSW, dips moderately southeast and juxtaposes granite in the footwall against banded gneisses in the hanging wall (Fig. 5D). Foliation in the gneisses is gently folded, but generally subparallel to the fault zone. The fault crops out as a 1–3 m-thick, proto- to ultracataclastic zone, characterised by altered granite in the host rock cut by dark bands of ultracataclasite. The granite in the footwall is red–stained through hydrothermal alteration, as observed at Rekvika, with the alteration occurring within a 200 m-thick zone approaching the fault. The footwall is more deformed than the hanging wall, although altered granite also occurs in the hanging wall. Subsidiary, ENE–WSW-trending, dextral normal faults interact with the overall main NNE–SSW fault trend and are displaced by the main fault (Fig. 4G). Slickensided surfaces suggest oblique-sinistral, normal, down-to-the-SE movement along the main fault trace (Fig. 4G).

The Hillesøya fault zone (Fig. 4H) in southwestern Kvaløya is defined by segments of parallel faults trending NNE–SSW, dipping to the east, and commonly merging with subsidiary NNW–SSE faults. It is located on the steep northwestern limb of a macro-scale subvertical fold that may have controlled its location (Thorstensen, 2011). The fault zone is parallel to the foliation in amphibolitic gneisses and confined to granitic pegmatite sheets within the gneisses. Zones of breccia, 1.5–2 m wide with angular clasts of red pegmatite granite and amphibolite embedded in a matrix of calcite, are common (Fig. 5E). Clasts are cross-cut by epidotised veins, which, in turn, are cut by calcite-bearing veins. Other, less prevalent faults with slickensides are common, revealing oblique-sinistral normal movement, down-to-the-ENE (Fig. 4H).

The subsidiary NNW–SSE-striking, ENE-dipping faults on Hillesøya are atypical compared with most other brittle fault zones in the WTBC, and are subparallel to the Svecofennian, NNW–SSE-trending Senja Shear Belt (Zwaan, 1995).

Central fault zones

Two major fault zones located in the interior parts of the WTBC horst have been studied and are further described here. These include the Vannareid–Burøysund fault zone on Vanna (first described by Opheim & Andresen, 1989) and a brittle fault zone that truncates the Mjelde–Skorelvvatn belt (Armitage, 1999; Armitage & Bergh, 2005) (Figs. 2, 4I). The ENE–WSW-trending and *c.* 60° southward-dipping Vannareid–Burøysund fault zone is developed in Neoarchaean tonalitic and quartz-dioritic gneisses and downdrops the presumed Palaeoproterozoic Skipsfjord Nappe by at least 3 km (Opheim & Andresen, 1989). The fault zone is marked in the topography by an ENE-WSW-trending valley in the northern parts of Vanna, showing an at least 20 m-wide cataclastic zone composed of proto- to ultracataclasites. Slickensided surfaces indicate a pure dip-slip, down-to-the-SSE displacement along the fault.

The Skorelvvatn fault zone (Fig. 4I) strikes ENE–WSW, dips steeply NNW and offsets distinctive metavolcanic rocks of the Palaeoproterozoic Skorelvvatn Formation (Armitage, 1999) as well as adjacent host-rock migmatites and diorites of the Neoarchaean gneisses. Cataclasites, 0.5–5 m thick, occur along the escarpment, and individual fault surfaces show great variation in geometry, with interacting ENE–WSW and NE–SW fault segments constituting the main fault zone. The main fault zone displays oblique-sinistral, normal fault movement (Fig. 4I). The fault is at a high angle to foliation and fault surfaces are in general epidotised with minor faulting increasing in frequency from <100 m when approaching the core zone. Slickensides on the main fault surfaces indicate an oblique-sinistral, normal sense of shear (Fig. 4I). A minimum of 250 m down-to-the-SSE displacement is calculated for the fault zone, by assuming *c.* 100 m apparent dextral, horizontal displacement of the Bakkejord diorite and perpendicular surface traces of the fault relative to the host-rock foliation.

Offshore fault complexes and associated basins

The relationship between onshore fault complexes and faults on the Finnmark Platform, and how they correlate, both spatially and temporally with basin-bounding faults in the SW Barents Sea, is not well understood. The present work is focused on linking major faults associated with the Tromsø, Hammerfest and Harstad basins, including the Troms–Finnmark, Ringvassøy–Loppa, Måsøy and Nysleppen fault complexes (Fig. 1), with faults on the Finnmark Platform and onshore fault complexes (Fig. 6).

Seismic stratigraphy

The seismic stratigraphy within different offshore basins and platforms was determined based on correlation with available well data (Fig. 3). Horizons in the Hammerfest Basin were tied to the well 7120/12–2 which penetrates most of the Palaeozoic and Mesozoic succession and terminates in crystalline basement composed of biotite augen gneisses. In the Harstad Basin, well 7019/1–1 and IKU's shallow stratigraphic cores (Fig. 3; wells 7018/5 –1, –2 & –6, cf., Smelror et al., 2001) have been used to tentatively identify top Cretaceous and top Jurassic seismic reflection events (Fig. 7A, B). Since none of these wells penetrate deeper than Mid Jurassic, top crystalline basement in the Harstad Basin has been picked on a deep, gently dipping, seismic reflection into which the interpreted faults deflect and merge (Fig. 7A, B). This seismic reflection is interpreted to represent a low–angle detachment zone forming the continuation of the listric TFFC in depth. Due to the extreme extension and rotation of basement fault blocks along the TFFC in this region, the detachment is interpreted to represent the boundary between Palaeozoic–Mesozoic sedimentary strata and basement. On the Finnmark Platform, the top of the crystalline basement may be traced as a seismic unconformity, dipping gently seawards towards the Harstad and Hammerfest basins from the WTBC and terminating against the TFFC (Fig. 7A–D). The unconformity clearly divides younger strata from the acoustically chaotic to transparent reflection pattern interpreted to represent basement rocks. The depth of the unconformity is verified by well 7120/12–4 on the Finnmark Platform that terminates in the Late Carboniferous Ugle Formation. In the adjacent well 7120/12–2, located ~10 km north of 7120/12–4 in the Hammerfest Basin, the Ugle Formation is ~100 m thick, overlying basement.

Description of offshore structures

The Troms–Finnmark Fault Complex (TFFC) is one of the most distinct fault complexes offshore and is composed of alternating NNE–SSW and ENE–WSW- to E–W-striking fault segments linked together in a zigzag pattern similar to that seen onshore (Fig. 6). The fault complex can be traced from Andfjorden in the south, as a northward continuation of the fault systems of the Lofoten Ridge, running outboard and parallel to the West Troms Basement Complex (Fig. 1). In this region, the TFFC is composed of a set of parallel, NW-dipping, listric faults with a large amount of displacement, down-faulting the basement from about 4 s twt, or ~4–5 km depth on the Finnmark Platform, to possibly more than ~7 s twt, corresponding to ~10 km depth in the Harstad Basin (Fig. 7A, B). The Finnmark Platform in this region is characterised by Late Palaeozoic to Early Mesozoic sedimentary strata overlying presumed crystalline basement (Smelror et al., 2001). The presence of a thick

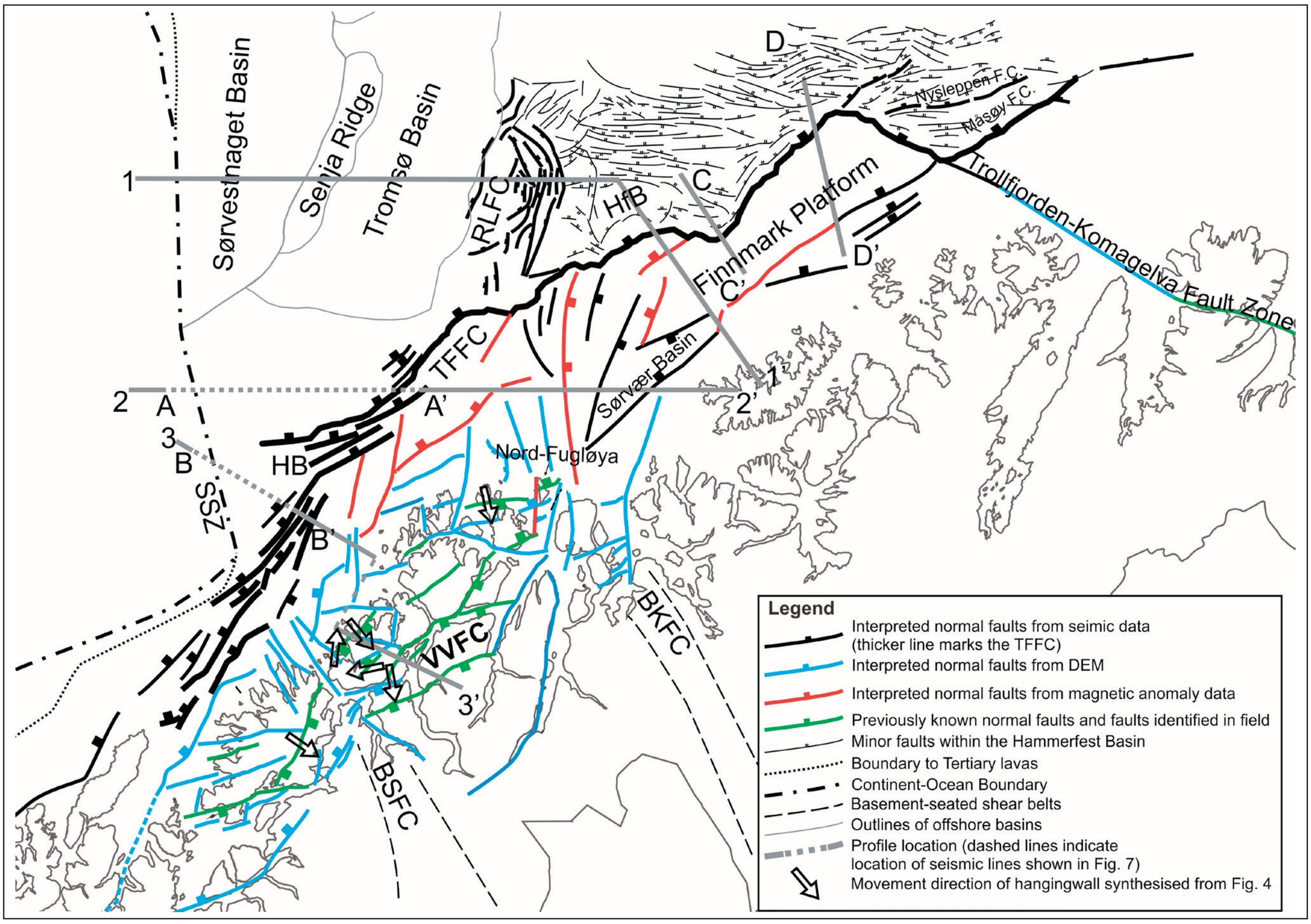


Figure 6. *Regional map summarising the architecture of the SW Barents Sea margin based on interpreted lineaments from onshore fieldwork (green lines), DEM (blue lines), magnetic anomaly data (red lines) and seismic interpretation (black lines). Arrows indicate synthesised hanging-wall movement direction from the different fault zones given in Fig. 4. Profiles 1–1', 2–2' and 3–3' are shown in Fig. 10. The dashed parts of the profile lines indicate location of seismic sections A–A' to D–D' given in Fig. 7. Abbreviations: BKFC – Bothnian–Kvænangen Fault Complex, BSFC – Bothnian–Senja Fault Complex, RLFC – Ringvassøy–Loppa Fault Complex, SSZ – Senja Shear Zone, TFFC – Troms–Finnmark Fault Complex, VVFC – Vestfjorden–Vanna Fault Complex.*

Cretaceous sedimentary succession in the Harstad Basin indicates that the southern portion of the TFFC had its most important phase of activity in the Cretaceous (cf., Gabrielsen et al., 1990). Close to the intersection between the TFFC and the Ringvassøy–Loppa Fault Complex, the TFFC changes its orientation to an ENE–WSW strike, and becomes a complex, anastomosing series of left-stepping fault segments (Fig. 6). East of the intersection between the Troms–Finnmark and Ringvassøy–Loppa fault complexes, the amount of displacement along the TFFC decreases to less than 3 km of down-to-the-NW movement in the Hammerfest Basin (Fig. 7C, D; cf., well 7120/12–2 and 7120/12–4, npd.no). Seismic interpretation reveals that N–S-striking steep faults dominate on the Finnmark Platform side of the TFFC in the area of shift, and that this may be linked to a change in TFFC characteristics (Fig. 6). The TFFC is therefore divided into a northern and a southern segment in the description herein, based on structural style and orientation, with the divide marked by the intersection with the Ringvassøy–Loppa Fault Complex (Fig. 8).

The Ringvassøy–Loppa Fault Complex (Fig. 6) divides the relatively shallow Hammerfest Basin in the east from the deep Tromsø Basin in the west, down-faulting base Cretaceous from less than 2 s twt in the Hammerfest Basin to more than 7 s twt in the Tromsø Basin within a distance of 30 km (Brekke et al., 1992). The fault complex is made up of a series of west-dipping curvilinear faults, and a very thick sequence of Cretaceous strata reveals that the main subsidence of the Tromsø Basin occurred during the Cretaceous. Even so, early phases of subsidence during the Carboniferous may have allowed for the deposition of evaporites within the Tromsø Basin, visible today by the occurrence of salt diapirs within younger strata in the basin (e.g., Brekke et al., 1992).

The northern segment of the TFFC separates the Finnmark Platform on the landward side from the Hammerfest Basin in the north (Fig. 6). This segment of the TFFC is characterised by faulting localised on one major fault, not several, at least as observed within the given seismic resolution. On the Finnmark Platform, top basement dips gently northwards and can be traced

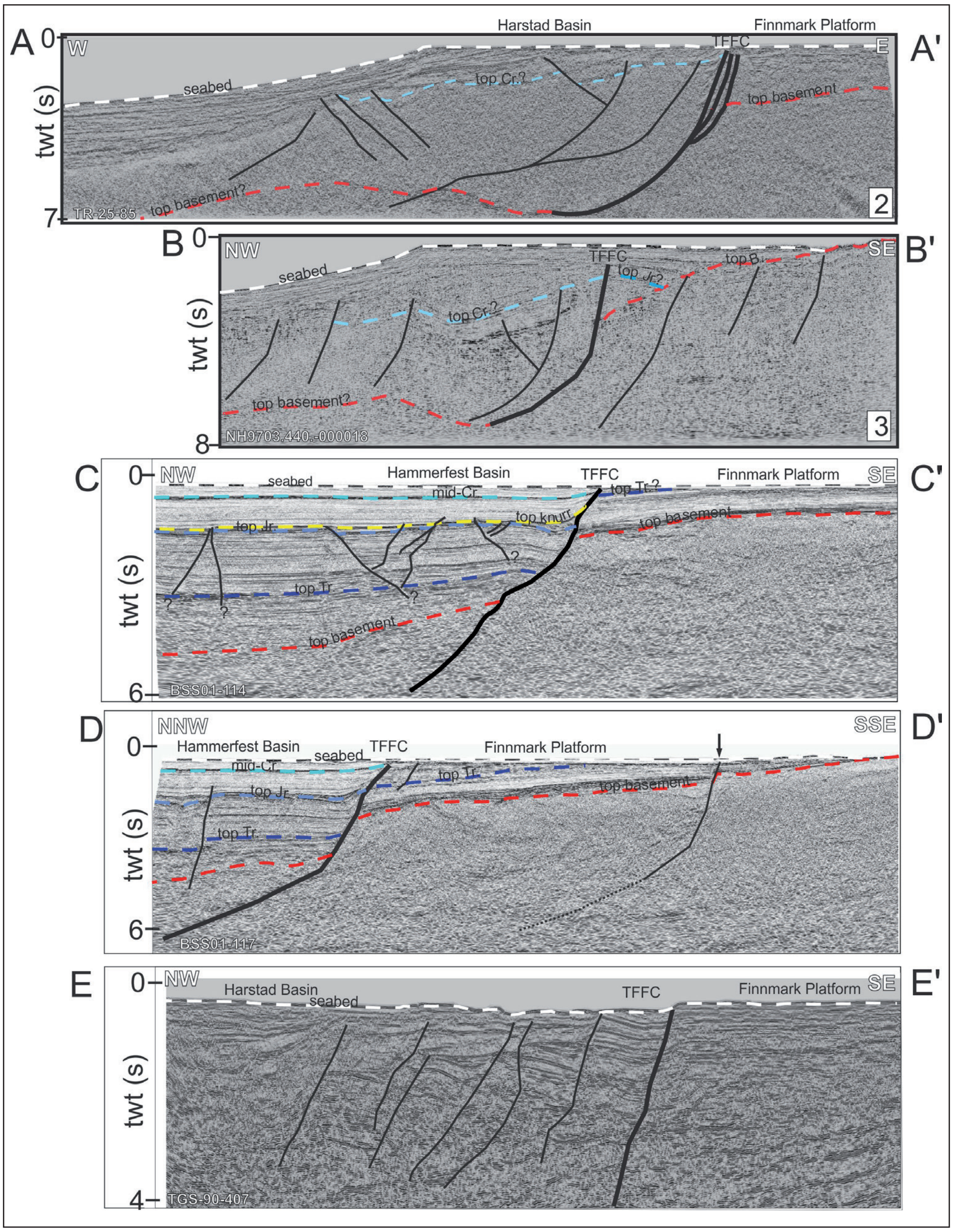


Figure 7. *Examples of interpreted seismic sections from the SW Barents Sea margin. (A) Interpreted seismic section showing faults and important horizons along profile B (Fig. 6) from the Finnmark Platform into the Harstad Basin. This section is part of onshore-offshore profile 2 in Fig. 10. (B) Interpreted section along profile C (Fig. 6). Note how basement is down-faulted along the listric Troms–Finnmark Fault Complex in the Harstad Basin. This section is part of onshore-offshore profile 3 in Fig. 10. (C) Interpreted seismic section C–C' (Fig. 6) showing faults and important horizons traced from the Finnmark Platform into the Hammerfest Basin. Note that the basement is much less down-faulted than in the Harstad Basin and is overlain by Late Palaeozoic and Early Mesozoic sedimentary strata on the Finnmark Platform. (D) Interpreted seismic section D–D' (Figs. 6, 9B) showing that the magnetic anomaly lineament identified in Fig. 9B is a listric normal fault, dipping towards the NW (black arrow). (E) Interpreted seismic section E–E' (Figs. 6, 9A) showing how the Troms–Finnmark Fault Complex reaches the seabed and influences seabed morphology in the Håkjerringdjupet.*

from the coast, where it crops out at the seabed, towards the TFFC where it lies at ~2.5 km depth (Larssen et al., 2002; cf., 7120/12–4, npd.no). Basement is overlain by a wedge-shaped prism of Carboniferous to Early Triassic sediments that onlap crystalline basement southward towards the Norwegian mainland (Fig. 7C). Internally, the Hammerfest Basin shows distributed Late Jurassic/Early Cretaceous faults that control the distribution of the Ryazanian–Hauterivian Knurr Formation which thickens toward the TFFC, indicating that the main subsidence started in the Late Jurassic, with displacement localising to the TFFC during the Early Cretaceous (Fig. 7C).

Farther east-northeast, along the northern segment of the TFFC, the Måsøy and Nysleppen fault complexes are situated where the seaward extension of the Trollfjorden–Komagelva Fault Zone truncates the TFFC, northwest of Nordkapp (Fig. 6). Notably, the northeastern portion of the TFFC and the Måsøy Fault Complex are composed of a series of linked fault segments that trend NE–SW and E–W to NW–SE. NE–SW-striking fault segments commonly splay out from the main TFFC trace where fault segments of different orientations meet, continuing onto the Finnmark Platform (Fig. 6).

Onshore-offshore relationships using DEM and magnetic anomaly data

It is challenging to link the offshore parts of the fault complexes to the onshore parts on account of the physical separation of the datasets and the differences in their spatial resolution. However, a link may be provided from

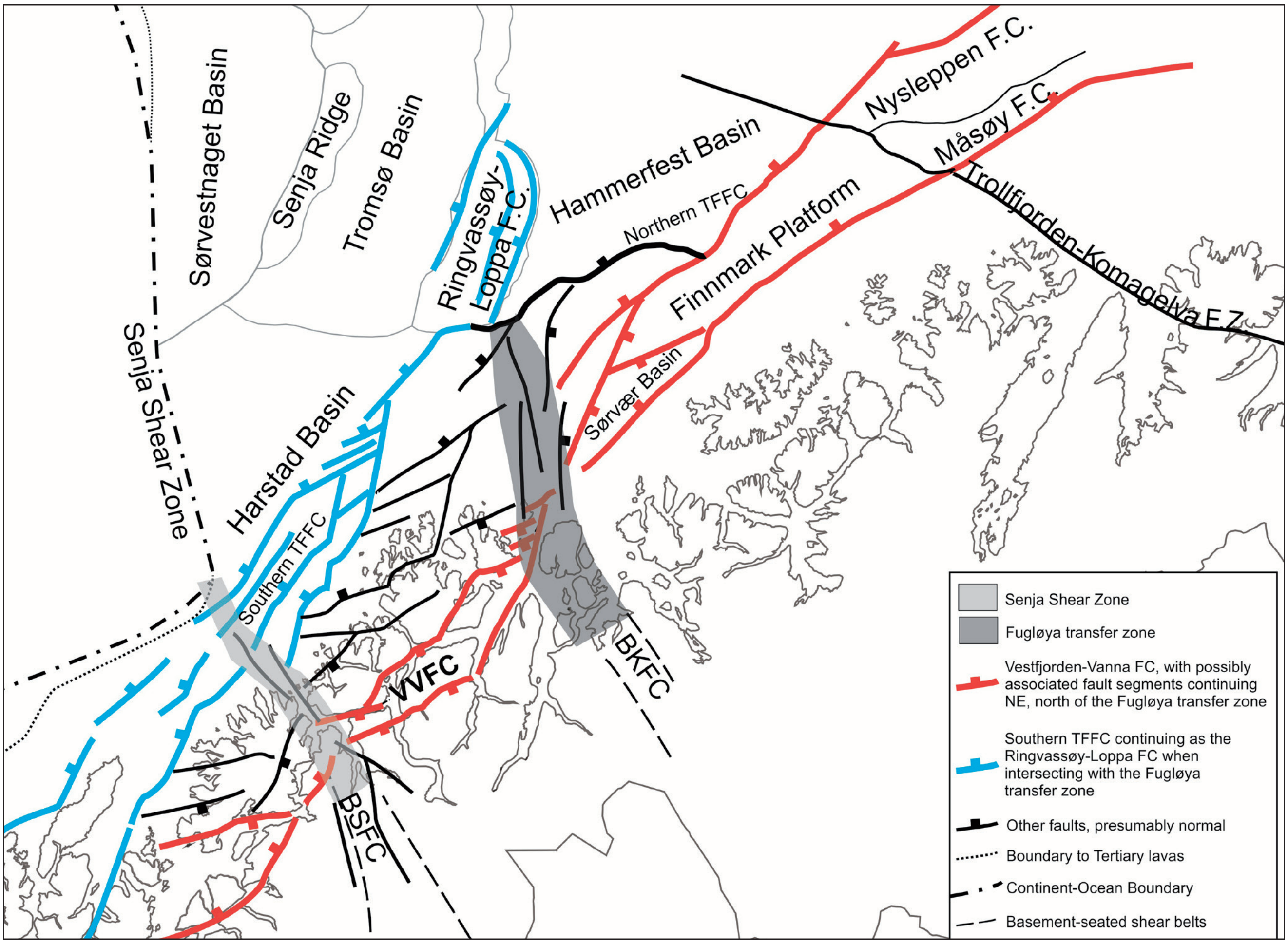


Figure 8. *Simplified tectonic map of the SW Barents Sea region linking major NNE–SSW- and ENE–WSW-trending fault complexes onshore and offshore. At least two major transfer zones accomodate change in polarity and stepping of fault zones along the margin: (i) The Senja Shear Zone, located along the reactivated Precambrian Senja Shear Belt and Bothnian-Senja Fault Complex (BSFC) and (ii) the Fugløya transfer zone, a possible continuation and reactivated section of the Bothnian Kvænangen Fault Complex (BSFC).*

bathymetry (DEM) and magnetic anomaly data from the shallow shelf portion of the margin, and consequently a valid fault correlation may thus be possible. In order to correlate and/or extend offshore and onshore fault traces, we mapped tectonic lineaments onshore and on the shallow and deep shelf areas, where seismic data coverage is insufficient, using DEM and magnetic data (Figs. 2B, 9).

Onshore DEM data show that relatively high mountain peaks and deep fjords, typical for glaciated margins, characterise the coastal region of western Troms and Finnmark. The fjords, sounds and large valleys are commonly oriented NNE–SSW and ENE–WSW, possibly reflecting the network of brittle faults in the region and resulting in a zigzag pattern of the fjords and sounds (Fig. 2). Where fault zones splay out and converge again, e.g., near the islands of Tromsø and Reinøya, they leave behind rhombohedra-shaped islands (Fig. 2A).

The shallow shelf is characterised by a gentle relief surface at 0–100 m below sea level with many shallow, semi-linear, elongated depressions up to tens of kilometres long (Figs. 2B, 9A). Locally, these features can be traced onshore as continuous lineaments (Fig. 2B). The shallow shelf appears as a 5–15 km-wide zone between the islands and the deep shelf, and is identified as a strandflat (Fig. 9A; Thorsnes et al., 2009), i.e., flat coastal regions eroded into crystalline basement rocks. Any minor relief produced by brittle palaeo-faults and/or fractures such as narrow scarps, ridges and/or depressions would therefore be easy to identify. The same is apparent for Precambrian (ductile) elements such as folds, foliations and ductile shear zones (cf., Thorstensen, 2011) that may have controlled the location of brittle faulting. Interpretation of lineaments on the strandflat is therefore a very useful tool in mapping orientations of faults and fractures close to shore.

A key observation in verifying bathymetry (DEM) as a valid correlation tool on the shallow shelf is where bathymetric lineaments can be traced onshore where they coincide with known onshore fault outcrops, for instance at the Stonglandseidet and Kvaløysletta–Straumsbukta fault zones (Fig. 2B). Another key observation is when the transition from strandflat to glacial deposits is linear and sharp. In such cases, if these sharp transitions define the same geometric (map) patterns and orientations as the observed (onshore-offshore) faults, the transition is then interpreted to mark the surface trace of a fault. Our interpretation reveals that NNE–SSW- and ENE–WSW-trending faults/fractures caused by down-faulting of the crystalline basement, allowing it to be covered by glacigenic sedimentary strata, are common on the strandflat (Fig. 9A). Furthermore, interpreted faults/fractures on the internal portions of the strandflat generally show the same orientations as onshore faults (Figs. 2B, 9A).

NW–SE-trending lineaments locally dominate the seabed relief, such as between Senja and Kvaløya near the location of the Svecofennian Senja Shear Belt. A similar area, dominated by NW–SE- to N–S-trending lineaments in the crystalline bedrock, occurs around Nord-Fugløya (Fig. 9A). The lineaments there continue N to NW off Nord-Fugløya and presumably extend all the way to the TFFC, although the northern part is covered by glacigenic sediments on Nordvestbanken (Fig. 9A).

The deep portion of the shelf in the region has, in general, a glacially controlled morphology with troughs, banks and other glacial features (cf., Rydningen et al., 2013),

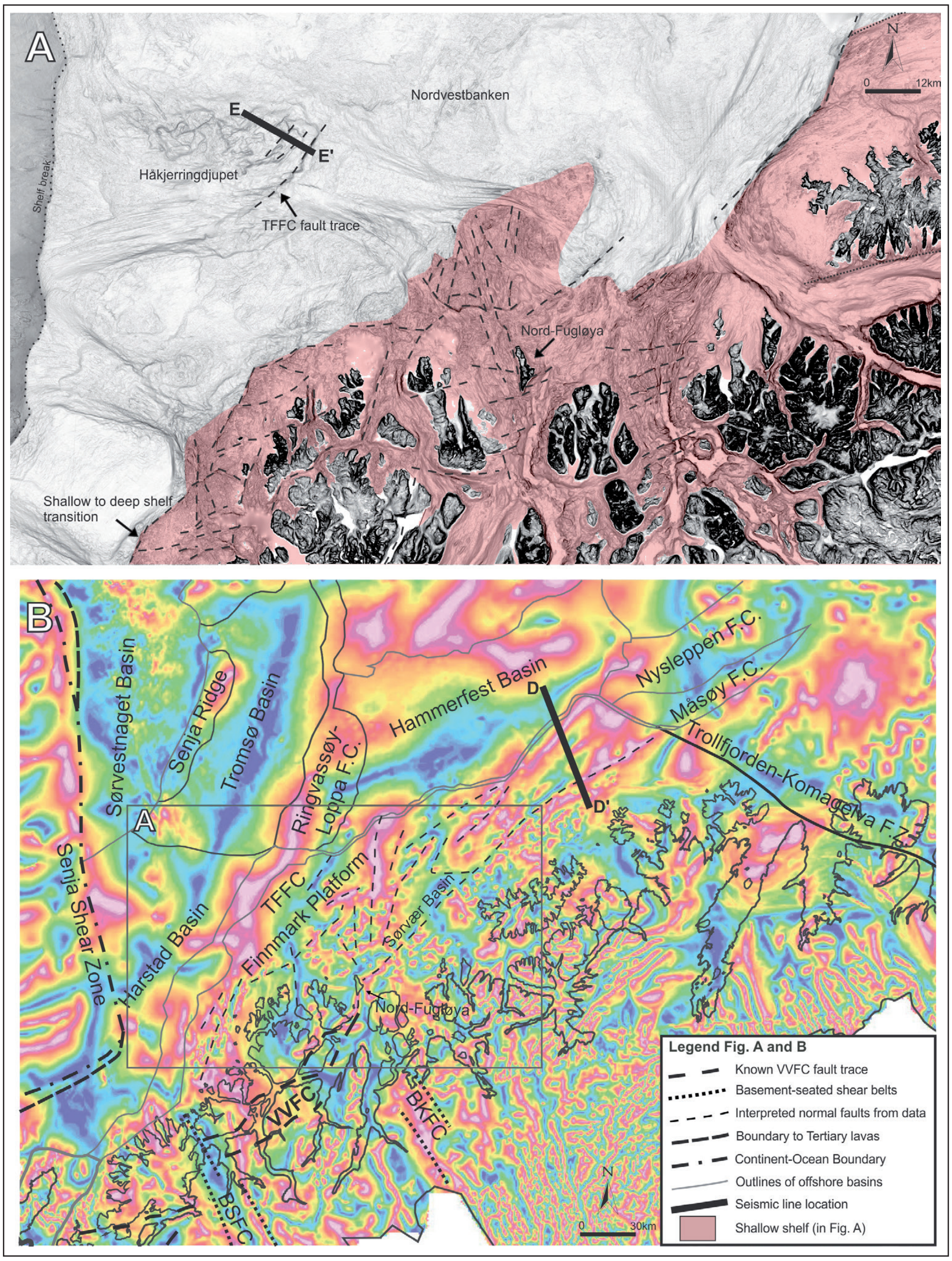


Figure 9. *Examples of interpreted DEM and magnetic data from the SW Barents Sea margin. (A) Enlargement of the DEM showing the strandflat (light pink) and interpretations of lineaments within the onshore- and strandflat portion of the margin (see Fig. 9B for location). Note the shallow to deep shelf transition traceable as interchanging NNE–SSW- and ENE–WSW-trending lineaments, interpreted as normal faults, and the NW–SE-trending lineaments around Nord-Fugløya, proposed to be the surface traces of a transfer fault zone. The Håkjerringdjupet area is the only part of the deep shelf where bathymetry lineaments have positively been identified as tectonic, in this case the surface trace of the TFFC. Seismic line E–E' is shown in Fig. 7. (B) The tilt-derivative of the HRAM–98 and NGU69/70 provided by the Geological Survey of Norway. Major structures are shown offshore. Thin lines show lineaments which are interpreted to be normal faults. Profile D–D' is shown in Fig. 7 and confirms that the lineament shown is a normal fault dipping NW. Boxed area shows location of Fig. 9A.*

and lineaments on the deep shelf are largely a product of glacial erosion and deposition rather than tectonically generated lineaments. Even the prominent structural elements such as the TFFC and the Ringvassøy–Loppa Fault Complex do not influence the seafloor morphology in any clear way, except at one locality in the Håkjerringdjupet where likely glacial erosion has exposed the TFFC escarpment by plucking blocks of sediment that detached along the fault plane (Figs. 7E, 9A).

The magnetic anomaly data (Fig. 9B) show many distinct lineaments traceable over tens of kilometres, defined by either continuous high or low values or as changes in the appearance of anomalies across a lineament, such as wavelength (Fig. 9B). From seismic interpretation the mapped TFFC locally coincides well with a high-value, subcontinuous, anomaly lineament traceable along the coast and thereby supports the notion that some visible magnetic lineaments may be the product of faults (Fig. 9B). Even so, the known boundary faults of the West Troms Basement Complex, i.e., the Vestfjord–Vanna Fault Complex, only partly produce a linear anomaly pattern, expressed at its clearest along its northern portion, southwest of Nord-Fugløya (Fig. 9B). Anomalies produced by the VVFC are thus interpreted to be locally too weak in comparison with other magnetic sources (e.g., the Ersfjord granitic intrusion) and cannot, at least onshore, be mapped with sufficient confidence, as other sources, such as spatial variations in crust lithology (e.g., magmatic intrusions, shear zones, mafic and felsic rocks, etc.), may also influence the signal.

However, the magnetic data may be used to support the interpretation of the DEM and seismic data, to provide an additional basis for correlation of faults, and to strengthen interpretations in areas on the shelf where the crystalline basement is covered by glacigenic sediments and therefore not visible on the DEM. For instance, in the area around and north of Nord-Fugløya (Fig. 9A), bathymetric lineaments strike NW–SE and N–S and presumably continue across the sediment-covered Nordvestbanken. The magnetic anomaly data show a distinct high-value anomaly, trending ~N–S and continuing all the way to the TFFC (Fig. 9B), suggesting that the bathymetric lineaments identified in the vicinity of Nord-Fugløya on the DEM are part of a feature that may link with the TFFC. Other magnetic lineaments also coincide with the transition between the strandflat and the deeper shelf outboard of western Troms and on the Finnmark Platform, thereby supporting the interpretation that these transitions represent faults where the basement has been down-faulted adequately to produce a notable change in magnetic anomaly pattern, thus indicating that this transition is tectonically controlled. Another example is in regions where the TFFC changes strike from NE–SW to E–W or ESE–WNW along the southern border of the Hammerfest Basin (Fig. 9B). Magnetic lineaments suggest that fault segments splay out from the TFFC, southwest onto the Finnmark Platform (Fig. 9B). These faults, which can partly be confirmed by seismic data (Fig. 7D), may be traced for tens of kilometres onto the Finnmark Platform, running parallel to the coast. In fact, the easternmost of these lineaments can be traced southwestwards from the Måsøy Fault Complex, parallel to the coast, continuing along the southeastern boundary fault of the Sørvær Basin and all the way to the island of Nord-Fugløya, where it meets up with the Vestfjorden–Vanna Fault Complex (Fig. 9B). Seismic data from this area show that this lineament is a likely listric normal fault zone dipping towards the NW with *c.* 500 m of displacement (Figs. 7D, 9B). Similarly, a magnetic anomaly lineament can be traced southwestwards from the intersection between the TFFC and the Nysleppen Fault Complex, trending parallel to the TFFC and onto the Finnmark Platform, and continuing SW to the above-described, ~N–S-trending anomaly close to Nord-Fugløya (Fig. 9B).

All the above-mentioned lineaments visible on the available magnetic anomaly data are expressed more clearly in newer data, published by Gernigon & Brönner (2012, their Fig. 3). Their data show that the NW–SE- to N–S-trending lineaments in the vicinity of Nord-Fugløya can be traced outboard to the TFFC (Fig. 9B), and that the lineament produced by the NE–SW-trending, NW-dipping listric fault as identified in Figs. 7D & 9B defines the southeastern boundary fault of the Sørvær Basin and merges with the southeastern boundary fault of the Nordkapp Basin in the northeast.

Discussion

In this section we argue for a correlation of onshore and offshore major fault zones based on the field mapping and interpretation of seismic, DEM and magnetic anomaly data. We use the structural relationships as a basis for discussing structural architecture, fault timing, basement control and evolution of the SW Barents Sea margin. We focus the discussion on faults linked to the WTBC and surrounding coastal areas of western Troms (Figs. 1, 2).

Correlation and margin architecture

The West Troms Basement Complex horst is bounded to the southeast by the SE-dipping VVFC (Figs. 6, 8), which displays 1–3 km of down-to-the-SE normal movement (Andresen & Forslund, 1987; Forslund, 1988; Opheim & Andresen, 1989; Olesen et al., 1997). Interpreted magnetic anomaly and seismic data (Figs. 6, 9B) show that the onshore VVFC largely mimics the zigzag geometry of the offshore TFFC. Offshore, just east of the island of Vanna, the VVFC is replaced by a set of NW-dipping fault segments that is interpreted to link up with the Måsøy Fault Complex and continue farther NE into the Nordkapp Basin (Smelror et al., 2009).

The westernmost mapped fault zones of the WTBC include the Rekvika, Bremneset, Tussøya and Hillesøy fault zones (Fig. 8). These individual fault zones show similarities in geometry, fault rocks and movement character (Figs. 2, 4E–H), indicating that they are associated with each other and constitute fault segments within a common fault system running along the outer rim of the islands of the WTBC. These western fault zones of the WTBC are characterised by NE–SW- to N–S-trending fault segments that commonly show red staining of host-rock granites, and comprise cataclastic fault rocks and hydrothermal alteration zones with precipitates of epidote, chlorite, quartz, calcite and/or hematite on fault/fracture surfaces. Kinematic data mostly reveal normal to oblique-normal, down-to-the–SE fault movement. From these similarities, we suggest that the fault zones may link up as en échelon, right-stepping, fault segments that run parallel to the VVFC. On the other hand, these fault zones clearly do not define the northwestern limit of the WTBC horst, since: (i) the kinematic data yield down-to-the-SE displacement, opposite of what would be expected for the bounding fault complex, (ii) the observed data do not match the VVFC in the form of amount of displacement, damage-zone width or impact on topography, and (iii) they do not juxtapose WTBC rocks with other (e.g., Caledonian) rocks. It is suggested that these fault zones only accommodated horst-internal displacement in the order of hundreds of metres or less, based on similarity with the Skorelvvatn fault zone, where the minimum displacement was estimated to 250 m. Instead, the actual west-bounding limit or boundary fault(s) of the WTBC horst is located farther northwest, at the southern segment of the TFFC (Figs. 6, 8). Seismic interpretation (Fig. 7A, B) suggests that the WTBC horst stretches all the way to the TFFC with only minor, horst-internal, down-faulting of basement occurring on the Finnmark Platform.

The northern segment of the TFFC (northeastwards from the intersection with the Ringvassøy–Loppa Fault Complex) is clearly different from the southern segment, displaying considerably less displacement and, locally, a WNW–ESE trend (Figs. 7C, 8). The Ringvassøy–Loppa Fault Complex, however, based on similarities in fault segment orientations and amount of displacement, is suggested to be the natural continuation of the southern segment of the TFFC (Figs. 6, 8).

The above-mentioned changes in the characteristics of the TFFC where it intersects with the Ringvassøy–Loppa Fault Complex are suggested to be due to the interaction with an inferred NW–SE- to N–S-trending zone that continues onto the Finnmark Platform with a comparable trend to that of the Trollfjorden–Komagelva Fault Zone and the Senja Shear Zone (Figs. 1, 8). This NW–SE-trending zone is confirmed by studies of shallow shelf bathymetry, onshore DEM data and magnetic anomaly data, showing a complex pattern of interacting lineaments trending NW–SE to N–S (Figs. 6, 9) across the Finnmark Platform close to Nord-Fugløya. Moreover, the NE–SW-trending fault segments traceable across the Finnmark Platform from the Troms–Finnmark, Nysleppen and Måsøy fault complexes, meet up and terminate against this same zone (Figs. 6, 8). From the south, the VVFC and the horst-internal fault zones, such as the Vannareid–Brurøysund fault zone, also terminate against the same NW–SE-trending zone. Thus, we suggest the presence of a previously not described transfer zone that runs NW–SE from the mainland near Nord-Fugløya, as a continuation of the Bothnian–Kvænangen Fault Complex, to link up with the TFFC. This transfer zone is termed the Fugløya transfer zone (Fig. 8). The fault segments bounding the Sørvær Basin and continuing northeastward may, tentatively, all be associated with the VVFC. This interpretation is supported by the similarities in fault trends and amount of displacement. If so, the fault segments change polarity and are apparently offset sinistrally across the Fugløya transfer zone. Comparable domains or segments where the fault zones define a shift in polarity and/or step to a new position along strike can be observed farther south, where the VVFC intersects with the Senja Shear Zone, a possible continuation of the reactivated Precambrian Senja Shear Belt and Bothnian–Senja Fault Complex (Figs. 2, 8; Henkel, 1991; Olesen et al., 1997).

In summary, the architecture of the SW Barents Sea margin is controlled by at least two major fault complexes, the VVFC and the TFFC, which define the southeastern and northwestern boundary faults of the WTBC horst, respectively. The WTBC horst and potentially also other segments along strike of the horst are cut by widespread, internally distributed, fault zones with only modest displacements, as illustrated by the seaward fault zones of the WTBC (Figs. 2, 6). Faulting is clearly controlled by, and possibly offset across, the Senja Shear Zone and the Fugløya transfer zone, causing fault stepping and polarity change across the transfer zones. The Fugløya transfer zone also marks a change in characteristics of the TFFC, both in the amount of displacement and in geometry.

Basement control

The network of brittle faults that frame the SW Barents Sea margin (Figs. 6, 8) may, to some extent, have been controlled by ductile basement fabrics, such as the Svecofennian and/or Caledonian foliations and ductile shear zones, and possible later reactivation of these pre-existing structures. The Svecofennian fabrics are largely steeply inclined, NW–SE-trending, gneissic foliations and ductile shear zones (Bergh et al., 2010), whereas the Caledonian fabrics are gently NW- and SE-dipping (NE–SW-trending) thrusts and intra-nappe foliations (e.g., Roberts et al., 2007). Although it is not an easy task to document inheritance from older structures, some obvious controls may be inferred, at least on a local scale, from the onshore fault data:

Firstly, the Kvaløysletta–Straumsbukta and Rekvika fault zones are oriented parallel to Svecofennian foliations and/or ductile shear zones (Fig. 4A, E), and the Hillesøya fault zone (Fig. 4H), notably, is situated on the steep western limb of a Svecofennian macro-fold (Thorstensen, 2011). Furthermore, the core of the Tussøya fault zone (Fig. 4G) is located along a SE-dipping boundary between granite and foliated amphibolite gneisses, thus demonstrating that lithological boundaries, at least on a local scale, controlled localisation of brittle faulting.

Secondly, basement-seated, NW–SE-trending, Svecofennian ductile shear zones seem to have exerted a controlling effect on, e.g., the right-stepping, zigzag nature of Palaeozoic–Mesozoic brittle faults on the SE boundary of the WTBC. Similarly to the possible controlling element of the Precambrian Bothnian-Senja Fault Complex and Senja Shear Belt on the Senja Shear Zone, the NW–SE-trending, Bothnian–Kvænangen Fault Complex (Doré et al., 1997; Olesen et al., 1997) (Figs. 1, 2) may extend offshore as a controlling element for the Fugløya transfer zone (Fig. 8), the Ringvassøya–Loppa and Bjørnøyrenna fault complexes (Gabrielsen et al., 1997) and potentially also for the transform Hornsund–De Geer Fault Zone (Faleide et al., 1993) farther north (Fig. 1, inset map).

Implications for timing of margin evolution and exhumation

The finite stage architecture of the SW Barents Sea margin in western Troms is a complex network of Late Palaeozoic–Mesozoic, rift-related, brittle fault zones bounding onshore basement horsts and adjacent offshore basins (Fig. 6). It is apparent from the proposed correlation of margin fault systems (Fig. 8) that not only were the offshore Barents Sea basins affected by Late Palaeozoic–Mesozoic rift tectonics, but also a large portion of its surrounding onshore continental margin, including the Finnmark Platform, the WTBC and even areas east of the VVFC. The timing of faulting onshore in relation to offshore faulting, however, is still a matter of uncertainty and debate (Gabrielsen et al., 1990; Faleide et al., 2008; Davids et al., 2013).

The timing of initial (pre-) and syn-rift tectonic activity on the SW Barents Sea margin that led to the formation and evolution of the Harstad, Tromsø and Sørvestnaget basins and adjoining ridges, is constrained to the Carboniferous–Early Triassic from seismic data (Faleide et al., 2008), whereas onshore faults have recently been radiometrically dated to show Permian/Early Triassic movement (Davids et al., 2013). From the correlation of margin-bounding fault complexes in western Troms and Finnmark, one may infer that, as the precursor rift basins to the opening of the North Atlantic continued from south to north along the Norwegian margin, distributed Carboniferous–Early Triassic rifting propagated northward into the SW Barents Sea. The rifting occurred along at least two major, NE–SW-trending fault complexes, the southern segment of the TFFC and the VVFC, including fault segments continuing northeastwards north of the Fugløya transfer zone (Fig. 8). These faults then became the precursor boundary faults of, e.g., the Nordkapp and Hammerfest Basins, which further evolved in the Late Jurassic to Early Cretaceous (Gabrielsen et al., 1990; Faleide et al., 2008). In the Early Cretaceous, in association with the formation of the Hammerfest Basin, these early faults were linked by E–W- to ESE–WNW-trending faults to form the northern segment of the TFFC. In the same period, transform plate movements initiated along the Hornsund–De Geer Fault Zone (Faleide et al., 1993) causing a switch in strain, with localisation of displacement along the southern TFFC and the Ringvassøy–Loppa Fault Complex. This switch led to the deepening of the Harstad, Tromsø and Sørvestnaget basins and their further evolution as pull-apart basins throughout Cretaceous times (Faleide et al., 2008).

In the Late Cenozoic, the coastal part of the SW Barents Sea margin was uplifted as part of the Scandes mountains (Corner, 2005). The timing and nature of such uplift(s), including exhumation of basement ridges like the Lofoten Ridge and the West Troms Basement Complex and the corresponding rejuvenation of the margin, are still much debated (cf., Olesen et al., 1997; Mosar et al., 2002; Eig, 2008; Osmundsen & Ebbing, 2008; Steltenpohl et al., 2009; Hendriks et al., 2010; Redfield & Osmundsen, 2013). Various causes of uplift have been proposed, e.g., rapid switches in the regional strain and stress fields (Bergh et al., 2007; Eig, 2008), stress perturbations within transfer zones (Eig & Bergh, 2011), passive margin exhumation due to NW–SE–aligned ridge-push forces (cf., Grønlie et al., 1991; Gabrielsen et al., 2002; Mosar et al., 2002) and asthenospheric diapiric rise due to emplacement of the Iceland Plume and later climate deterioration with increased erosion (e.g., Rohrman & van der Beek, 1996; Nielsen et al., 2002; Pascal & Olesen, 2009). Recent work by Osmundsen & Redfield (2011) and Redfield & Osmundsen (2013) has proposed yet another driving force, suggesting that the uplift has been controlled by the hyperextended character of the Norwegian passive margin (e.g., Lundin & Doré, 2011). Even though the character of the hyperextended margin when crossing the Senja Shear Zone has not yet been discussed in the literature, the margin along the southern portion of the WTBC horst is characterised by a relatively short taper length (Redfield & Osmundsen, 2013). Due to the large amount of down-faulting of the basement along the southern segment of the TFFC, identified from interpreted seismic sections (Fig. 7A, B), the taper break is identified to run just west of, and parallel to the TFFC northwards in the Harstad Basin and into the Tromsø Basin, using depth-to-MOHO estimates from Faleide et al. (2008) and top-basement estimates from this study (Fig. 10). A short taper length is thought to give increased uplift due to unloading and flexure of the crust, resulting in a higher topography in the hinterland and proximal margin (onshore regions) compared to portions of the margin with longer taper lengths (Osmundsen & Redfield, 2011). Our interpreted cross-sections of the West Troms margin (Fig. 10) illustrate how the different fault zones identified on land and offshore may have interacted to produce an overall narrow taper margin, thus providing a frame for discussing taper-controlled uplift and exhumation.

Onshore in the study area, faulting is characterised by presumably planar fault zones with modest displacements (hundreds of metres) within the WTBC horst, and steep, most likely deep-seated, horst-bounding major faults (VVFC) with 1–3 km displacement. These landward faults are presumed to be planar as no roll-over of foliation is observed when approaching the fault zones, as would be expected if the faults were listric. On the other hand, the corresponding northwestern limit of the WTBC horst is identified as the major listric, deep-seated, southern segment of the TFFC, which down-drops basement more than 5 km in the Harstad Basin (Fig. 10). Thus, the WTBC horst is clearly not a symmetric basement horst as seen, e.g., in the Lofoten or Senja ridges (Figs. 1, 10), where both sides of the horst are marked by major listric, deep-seated normal faults, but rather an asymmetric horst where most of the displacement was localised along the listric TFFC and the Ringvassøy–Loppa Fault Complex during the main phases of continental rifting. This geometry of the WTBC horst leads to a narrow taper length with a relatively high topography in the hinterland compared to areas of longer taper length, e.g., as in Mid Norway (see sections in Faleide et al., 2008; Osmundsen & Redfield, 2011; Redfield & Osmundsen, 2013). This relationship is inferred for the Troms region, as illustrated by the high peaks of the WTBC and the Lyngen Alps to the east of the WTBC. As final break-up occurred along this portion of the margin, the short tapered margin acted as a stiff body of crust rebounding due to unloading and ridge-push forces along the break-up axis. These forces may have been the controlling factors in the uplift of the WTBC, reactivating fault complexes such as the VVFC. A reactivation of brittle faults has been recorded in Mid Norway, constrained to have taken place after 100 Ma, suggesting displacements during reactivation of up to 2–3 km (Redfield et al., 2005). Similar reactivation may have occurred in western Troms as indicated by the presence of Cenozoic to recent fault gouge along some of the major fault zones (Olesen et al., 1997). Recent radiometric dating, however, suggests that any recent reactivation must have been only moderate in the Troms region in order to prevent a reset of the recorded Late Permian/Early Triassic, K–Ar and Ar–Ar ratios and fission-track ages within the fault rocks (Davids et al., 2013).

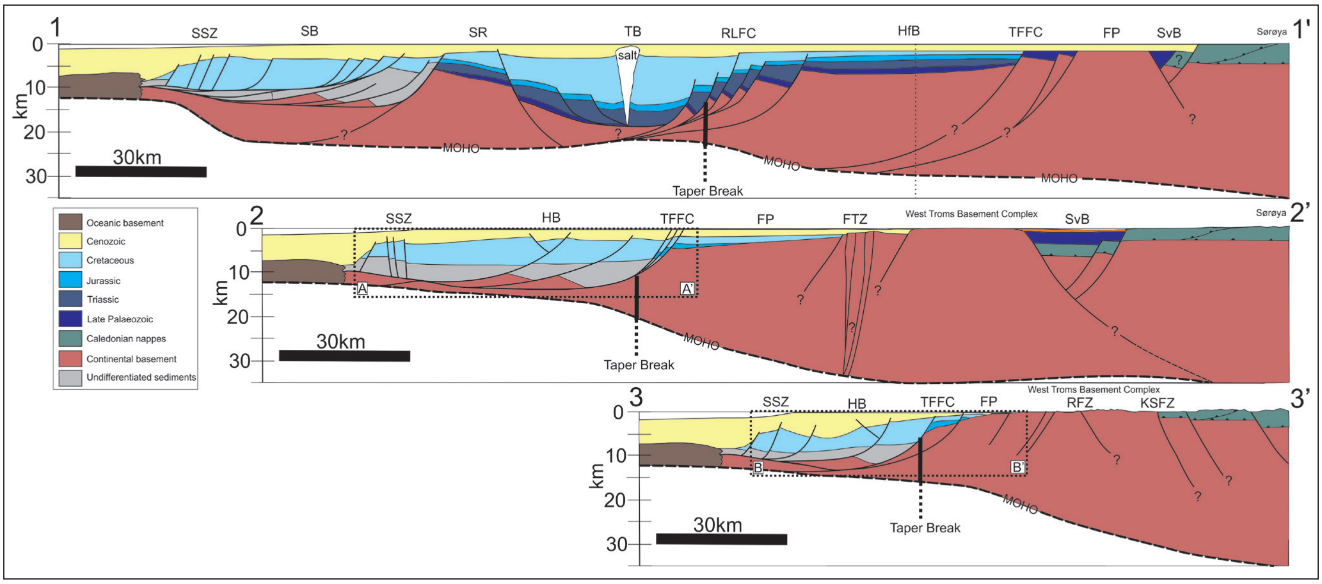


Figure 10. *Tentative crustal-scale, onshore-offshore sections across the SW Barent Sea margin based on interpreted seismic profiles and onshore fault data. Locations of the profiles are shown in Fig. 6. Location of the taper break is inferred from the seismic sections B–B' and C–C'. Moho depth is from Faleide et al. (2008). Dashed boxes in profiles B and C show the locations of seismic sections in Fig. 7. 1–1': Interpreted section extending from Sørøya westward to the continent-ocean transition. Note the moderate down-faulting of basement in the Hammerfest Basin compared to the significant down-faulting within the Tromsø Basin. From the RLFC westward, the section is based on Faleide et al. (2008). 2–2': Section running from Sørøya and into the Harstad Basin. Note that the basement is down-dropped considerably in the Harstad Basin. 3–3': Section extending from the mainland east of Tromsø and into the Harstad Basin. Note the asymmetric shape of the West Troms Basement Complex horst. Abbreviations: FP – Finnmark Platform; HB – Harstad Basin, HfB – Hammerfest Basin, FTZ – Fugløya transfer zone, RFZ – Rekvika fault zone, RLFC – Ringvassøy–Loppa Fault Complex, KSFZ – Kvaløysletta–Straumsbukta fault zone, SB – Sørvestnaget Basin, SSZ – Senja Shear Zone, SvB – Sørvær Basin, SR – Senja Ridge, TB – Tromsø Basin, TFFC – Troms–Finnmark Fault Complex.*

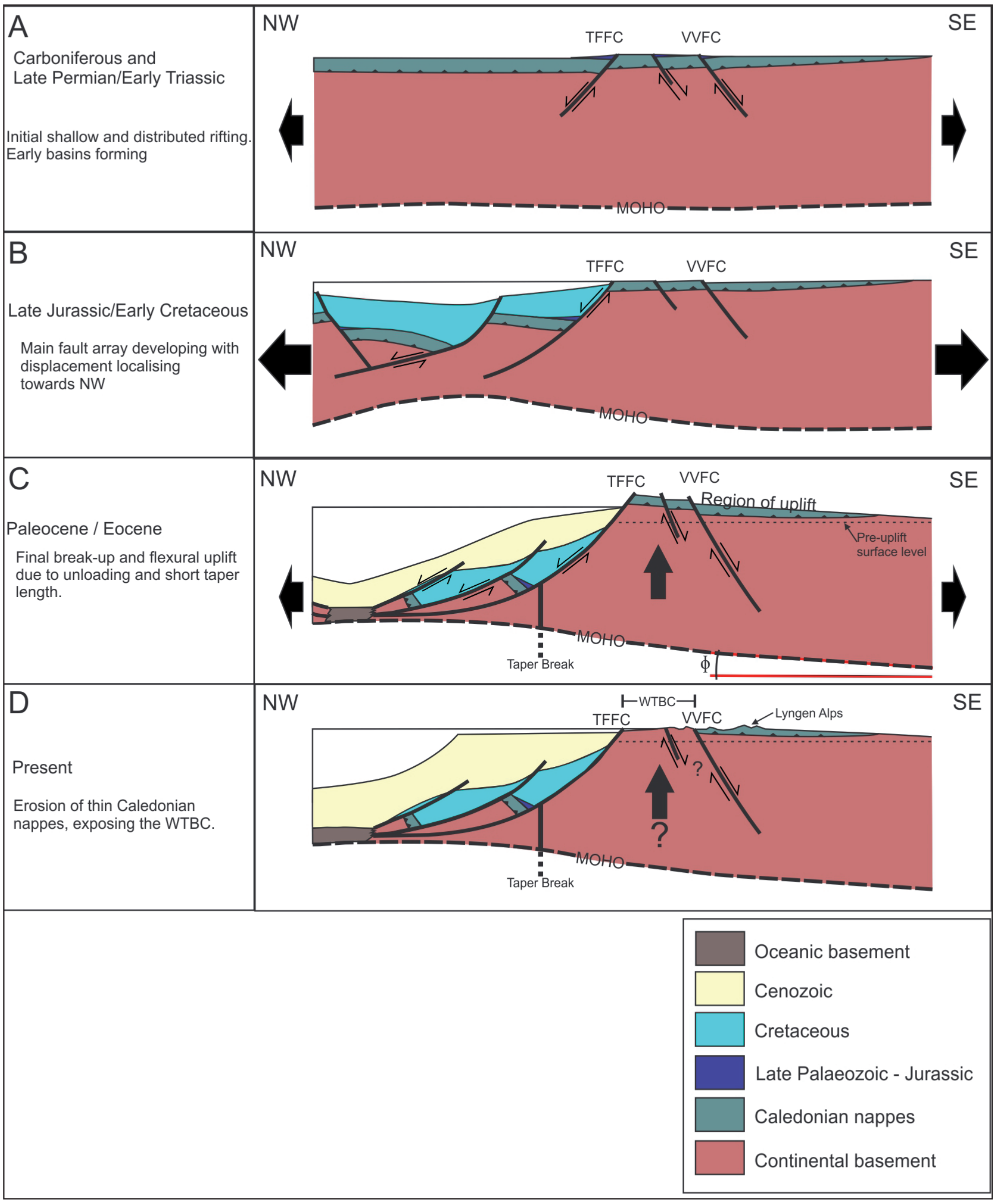


Figure 11. *Schematic proposed tectonic evolution of the SW Barents Sea margin and the exhumation of the West Troms Basement Complex. (A) Initial shallow and distributed NE–SW faulting in the Carboniferous and Late Permian/Early Triassic along major fault complexes, the Troms–Finnmark Fault Complex, Ringvassøy–Loppa Fault Complex and the Vestfjorden–Vanna Fault Complex. (B) Late Jurassic/Early Cretaceous syn-rift extension in the Hammerfest Basin and adjoining Ringvassøy–Loppa Fault Complex and Troms–Finnmark Fault Complex. Note the listric geometry and large amount of displacement of the basin-boundary faults offshore, and the planar geometry of the onshore Vestfjorden–Vanna Fault Complex, resulting in the formation of a short-tapered, hyperextended margin after final break-up in the Palaeocene/Eocene. (C) Palaeocene/Eocene extension and further listric faulting and deposition of Cenozoic units in the offshore Harstad, Tromsø and Sørvestnaget basins and reactivation of the basins by transform motion. In onshore areas, the WTBC was uplifted and exhumed as a short-tapered margin due to unloading and crustal flexure. (D) Continued uplift and erosion to the present-day level, resulting in the development of high topographic relief, as illustrated by e.g., the Lyngen Alps, east of the Vestfjorden–Vanna Fault Complex.*

We propose an evolutionary model of brittle faulting in the western Troms part of the SW Barents Sea margin as outlined in Fig. 11, based on the above data and discussion. 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 faults (Fig. 11A). This event was followed by a Late Jurassic/Early Cretaceous extension in the Hammerfest Basin, activating the adjoining Ringvassøy–Loppa and Troms–Finnmark fault complexes (Fig. 11B). The listric geometry and large amount of displacement along these basin-boundary faults offshore, and the planar geometry of the onshore VVFC, resulted in the formation of a short-tapered, hyperextended margin after final break-up in the Palaeocene/Eocene (Fig. 11C). Offshore, further reactivation, listric faulting and sediment deposition in the offshore basins (e.g., Harstad and Tromsø Basins) followed in the Cenozoic, due to transform plate motion in the North Atlantic. In onshore areas, the WTBC was uplifted and exhumed as a short-tapered margin due to unloading and crustal flexure with continued uplift, reactivation of faults and erosion to the present stage level, forming high mountains in, for instance, the Lyngen area, east of the VVFC (Fig. 11D).

Conclusions

- The SW Barents Sea margin in western Troms is characterised by a network of onshore and offshore, steeply to moderately dipping, brittle normal faults, trending NNE–SSW and ENE–WSW, bounding major horsts (onshore) and basins (offshore). This fault pattern is also present on the Finnmark Platform farther north, where it connects with segments of the

major, offshore, basin-bounding Troms–Finnmark Fault Complex.
- Two major fault complexes, the Vestfjorden–Vanna and the Troms–Finnmark fault complexes, are localised partly onshore and partly offshore, and bound a major horst, the West Troms Basement Complex. The southern portion of the Troms–Finnmark Fault Complex, which defines the northwestern boundary of this horst, changes character northeastwards as it merges into the N–S–trending Ringvassøy–Loppa Fault Complex. The Ringvassøy–Loppa Fault Complex is interpreted as the northward continuation of the southern segment of the Troms–Finnmark Fault Complex, based on similarities in geometry, kinematics and amount of displacement. The northern segment of the Troms–Finnmark Fault Complex shows less displacement and is suggested to be younger than the southern segment of the Troms–Finnmark Fault Complex and formed in association with the formation of the Hammerfest Basin.
- The horst-bounding faults, including the Vestfjorden–Vanna Fault Complex, change character along strike northwards near the island of Nord-Fugløya, where they terminate and/or are offset sinistrally against a probable major, margin-wide transfer zone, the Fugløya transfer zone. This transfer zone marks a pronounced switch in the fault polarity and/or amount of displacement of the Vestfjord–Vanna and the Troms–Finnmark fault complexes. North of the Fugløya transfer zone, major NW-dipping fault segments occur on the Finnmark Platform, possibly representing a continuation of the Vestfjorden–Vanna Fault Complex, and inferred to link up with the Nysleppen and Måsøy fault complexes.
- The studied onshore brittle fault zones, at least on a local scale, formed close to, or along favourably oriented Precambrian or Caledonian structures such as lithological boundaries, foliations and/or ductile shear zones, suggesting a reactivation of these pre-existing structures. On a larger scale, steep, basement-seated, Precambrian ductile shear zones, e.g., the NW-SE-trending Botnian-Senja Fault Complex and the Senja Shear Belt and the Bothnian–Kvænangen Fault Complex, seem to have affected the NE–SW-trending brittle fault complexes by accommodating shifts in polarity and/or the stepping of fault segments to a new position along strike. The ~NW-SE-trending Bothnian-Kvænangen Fault Complex may thus be the controlling element for the Fugløya transfer zone, the Ringvassøya–Loppa Fault Complex, and potentially also the transform Hornsund–De Geer Fault Zone farther north on the Barents Sea margin.
- In the context of rifting along the SW Barents Sea margin, our data suggest initial distributed rifting in the Carboniferous and Late Permian/Early Triassic along at least two NE–SW-striking fault complexes. This early event was followed by a main, Late Jurassic/Early Cretaceous, syn-rift extension in the Hammerfest Basin, and a corresponding northwestward localisation of displacement along the Troms–Finnmark and Ringvassøy–Loppa fault complexes offshore. These offshore, basin-bounding faults are characterised by a listric geometry and large-magnitude displacement/extension, whereas a planar geometry is inferred for the onshore Vestfjorden–Vanna Fault Complex and related horst-internal faults. This contrast in fault geometry, with displacement largely localising to the Troms–Finnmark Fault Complex, may have resulted in the formation of a short-tapered, hyperextended margin after final break-up in the Palaeocene/Eocene (at *c.* 55 Ma). The West Troms Basement Complex was finally uplifted and exhumed in the Late Cenozoic as a short-tapered margin due to unloading and crustal flexure with continued uplift and erosion to its present-day level.

Acknowledgements. This work was part of the Industrial Ph.D. scheme organised by the Norwegian Research Council. The project is a collaboration between DONG Energy and the University of Tromsø, financed by DONG Energy and the Norwegian Research Council. We would like to show our gratitude to all persons involved from these institutions. We would also like to acknowledge NGU for sharing and allowing us to publish the magnetic anomaly surveys NGU69/70 and HRAM–98. Lastly, we would like to thank Rikke Bruhn and the referees Per Terje Osmundsen and Roy H. Gabrielsen for constructive feedback during the review process.

References

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

Andresen, A. & Forslund, T. 1987: Post-Caledonian brittle faults in Troms: geometry, age and tectonic significance. *The Caledonian and Related Geology of Scandinavia, Cardiff, 22–23 Sept., 1989 (Conf. Abstract).*

Antonsdòttir, V. 2006: *Structural and kinematic analysis of the post-Caledonian Rekvika Fault Zone, Kvaløya, Troms.* MSc thesis, University of Tromsø, 84 pp.

Armitage, P.E.B. 1999: *Kinematic analysis of a Precambrian metasupracrustal deformation zone between Mjelde and Skorelvvatn, Kvaløya, Troms.* Cand. scient. thesis, University of Tromsø, 173 pp.

Armitage, P.E.B. & Bergh, S.G. 2005: Structural development of the Mjelde–Skorelvvatn Zone on Kvaløya, Troms: a metasupracrustal Shear Belt in the Precambrian West Troms Basement Complex, North Norway. *Norwegian Journal of Geology 85*, 117–132.

Bergh, S.G., Eig, K, Kløvjan, O.S., Henningsen, T., Olesen, O. & Hansen, J.-A. 2007: The Lofoten–Vesteralen continental margin: a multiphase Mesozoic–Palaeogene rifted shelf as shown by offshore-onshore brittle fault-fracture analysis. *Norwegian Journal of Geology 87*, 29–58.

Bergh, S.G., Corfu, F. & Corner, G.D. 2008: Proterozoic igneous and metamorphic rocks: a template for Mesozoic–Cenozoic brittle faulting and tectonic inherited landscapes in Lofoten–Vesterålen, North Norway. *33 IGC Excursion Guidebook No 38, IGC The Nordic Countries*, 71 pp.

Bergh, S.G., Kullerud, K., Armitage, P.E.B., Zwaan, K.B., Corfu, F., Ravna, E.J.K. & Myhre, P.I. 2010: Neoarchaean through Svecofennian tectono-magmatic evolution of the West Troms Basement Complex, North Norway. *Norwegian Journal of Geology 90*, 21–48.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J. & Tørudbakken, B. 1995: Structural elements of the Norwegian continental shelf, Part II. The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin 8*, 45 pp.

Brekke, H. 2000: The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre basins. *Geological Society of London Special Publication 136*, 327–378.

Brekke, H., Kalheim, J.E., Riis, F., Egeland, B., Blystad, P., Johnson, S. & Ragnhildstveit, J. 1992: Two-way time map of the unconformity at the base of Upper Jurassic (north of 69°N) and the unconformity at the base of the Cretaceous (south of 69°N), offshore Norway, including the main geological trends onshore, scale 1:2 million. *NPD Continental Shelf Map No. 1, The Norwegian Petroleum Directorate / The Geological Survey of Norway.*

Brekke, H., Sjulstad, H.I., Magnus, C. & Williams, R.W. 2001: Sedimentary environments offshore Norway – an overview. *Norwegian Petroleum Society Special Publication 10*, 7–37.

Corfu, F., Armitage, P.E.B., Kullerud, K. & Bergh, S.G. 2003: Preliminary U–Pb geochronology in the West Troms Basement Complex North Norway: Archaean and Palaeoproterozoic events and younger overprints. *Geological Survey of Norway Bulletin 441*, 61–72.

Corner, G.D. 2005: Atlantic coast and fjords. *In* Seppälä, M. (ed.): *The physical Geography of Fennoscandia*, Oxford Regional Environments Series, Oxford University Press, pp. 203–228.

Dalland, A. 1981: Mesozoic sedimentary succession at Andøya, Northern Norway, and relation to structural development of the North Atlantic area. *In* Kerr, J.W. & Fergusson, A.J. (eds.): *Geology of the North Atlantic borderlands*. Canadian Society of Petroleum Geologists, Memoir 7, pp. 563–584.

Davids, C., Wemmer, K., Zwingmann, H., Kohlmann, F., Jacobs, J. & Bergh, S.G. 2013: K–Ar illite and apatite fission track constraints on brittle faulting and the evolution of the northern Norwegian passive margin. *Tectonophysics 608*, 196–211.

Doré, A.G. 1991: The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. *Palaeogeograhy, Palaeoclimatology, Palaeoecology 87*, 441–492.

Doré, A.G. & Lundin, E.R. 1996: Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. *Petroleum Geoscience 2*, 299–311.

Doré, A.G., Lundin, E.R., Fichler, C. & Olesen, O. 1997: Patterns of basement structure and reactivation along the NE Atlantic margin. *Journal of the Geological Society of London 154*, 85–92.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E. & Fichler, C. 1999: Principal tectonic events in the evolution of the northwest European Atlantic margins. *In* Fleet, A.J. & Boldy, S.A.R. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society of London, pp. 41–61.

Eig, K. 2008: *Onshore and offshore tectonic evolution of the Lofoten passive margin, North Norway*. PhD thesis, University of Tromsø, 256 pp.

Eig, K. & Bergh, S.G. 2011: Late Cretaceous–Cenozoic fracturing in Lofoten, North Norway: Tectonic significance, fracture mechanisms and controlling factors. *Tectonophysics 499*, 190–205.

Faleide, J.I., Vågnes, E. & Gudlaugsson, S.T. 1993: Late Mesozoic–Cenozoic evolution of the southwestern Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology 10*, 186–214.

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

Forslund, T. 1988: *Post-Kaledonske forkastninger i Vest-Troms, med vekt på Kvaløyslettaforkastningen, Kvaløya*. Cand. Scient. thesis, University of Tromsø. 173 pp.

Fürsich, F. & Thompsen, E. 2005: Jurassic biota and biofacies in erratics from the Sortland area, Vesterålen, northern Norway. *Geological Society of Norway Bulletin 443*, 37–53.

Gaal, G. & Gorbatschev, R. 1987:An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research 35*, 15–52.

Gabrielsen, R.H., Færseth, R.B., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf — Part I: the Barents Sea Region. *Norwegian Petroleum Directorate Bulletin 6*, 33 pp.

Gabrielsen, R.H., Grunnaleite, I. & Rasmussen, E. 1997: Cretaceous and Tertiary inversion in the Bjørnøyrenna Fault Complex, south-western Barents Sea. *Marine and Petroleum Geology 14*, 165–178.

Gabrielsen, R.H., Braathen, A., Dehls, J. & Roberts, D. 2002: Tectonic lineaments of Norway. *Norwegian Journal of Geology 82*, 153–174.

Gagama, M.F.V. 2005: *Strukturell analyse av post-kaledonske lineamenter ved Sifjorden, Vest-Senja, Troms*. Master thesis, University of Tromsø, 85 pp.

Gernigon, L. & Brönner, M. 2012: Late Palaeozoic architecture and evolution of the southwestern Barents Sea: insights from a new generation of aeromagnetic data. *Journal of the Geological Society of London 169*, 449–459.

Grønlie, A., Nilsen, B. & Roberts, D. 1991: Brittle deformation history of fault rocks on the Fosen Peninsula, Trøndelag, Central Norway. *Geological Survey of Norway Bulletin 421*, 39–57.

Gudlaugsson, S.T., Faleide, J.I., Johansen, S.E. & Breivik, A.J. 1998: Late Paleozoic structural development of the south-western Barents Sea: *Marine and Petroleum Geology 15*, 73–102.

Hansen, J.-A. 2009: *Onshore-offshore tectonic relations on the Lofoten and Vesterålen Margin – Mesozoic to early Cenozoic structural evolution and morpological implications*. PhD thesis, University of Tromsø, 229 pp.

Hansen, J.-A & Bergh, S.G. 2012: Origin and reactivation of fracture systems adjacent to the Mid-Norwegian continental margin on Hamarøya, North Norway: use of digital geological mapping and morphotectonic lineament analysis. *Norwegian Journal of Geology 92*, 391–403.

Hansen, J.-A., Bergh, S. G. & Henningsen, T. 2012: Mesozoic rifting and basin evolution on the Lofoten and Vesterålen Margin, North-Norway; time constraints and regional implications. *Norwegian Journal of Geology 91*, 203–228.

Hendriks, B.W.H., Osmundsen, P.T. & Redfield, T.F. 2010: Normal faulting and block tilting in Lofoten and Vesterålen constrained by apatite fission track data. *Tectonophysics 485*, 154–163.

Henkel, H. 1991: Magnetic crustal structures in Northern Fennoscandia. *Tectonophysics 192*, 57–79.

Hölttä, P., Balagansky, V., Garde, A.A., Mertanen, S., Peltonen, P., Slabunov, A., Sorjonen-Ward, P. & Whitehouse, M. 2008: Archean of Greenland and Fennoscandia. *Episodes 31*, 13–19.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G. & Weatherall, P. 2012: The international bathymetric chart of the Arctic Ocean (IBCAO) version 3.0. *Geophysical Research Letters 39*, doi:10.1029/2012GL052219.

Knutsen, S.M. & Larsen, K.I. 1997: The late Mesozoic and Cenozoic evolution of the Sørvestsnaget Basin: A tectonostratigraphic mirror for regional events along the Southwestern Barents Sea margin? *Marine and petroleum geology 14*, 27–54.

Lahtinen, R., Garde, A.A. & Melezhik, V.A. 2008: Paleoproterozoic evolution of Fennoscandia and Greenland. *Episodes 31*, 20–28.

Larssen, G.B., Elvebakk, G., Henriksen, L.B., Kristensen, S.E., Nilsson, I., Samuelsberg, T. J., Svånå, T.A., Stemmerik, L. & Worsley, D. 2002: Upper Palaeozoic lithostratigraphy of the Southern Norwegian Barents Sea. *Norwegian Petroleum Directorate Bulletin 9*, 76 pp.

Lundin, E.R. & Doré, A.G. 2011: Hyperextension, serpentinization, and weakening: A new paradigm for rifted margin compressional deformation. *Geology 39*, 347–350.

Miller, H.G. & Singh, V. 1994: Potential-field tilt—a new concept for location of potential-field sources. *Journal of Applied Geophysics 32*, 213–217.

Mosar, J., Torsvik, T.H. & the BAT team 2002: Opening the Norwegian and Greenland Seas: Plate tectonics in Mid Norway since the Late Permian. *In* Eide, E.A. (coord.): *BATLAS – Mid Norway plate reconstruction atlas with global Atlantic perspectives*, pp. 48–59.

Nielsen, S.B., Paulsen, G.E., Hansen, D.L., Gemmer, L., Clausen, O.R., Jacobsen, B.H., Balling, N., Huuse, M. & Gallagher, K. 2002: Paleocene initiation of Cenozoic uplift in Norway. *In* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*, Geological Society of London Special Publication 196, pp. 45–65.

Olesen, O., Torsvik, T.H., Tveten, E., Zwaan, K.B., Løseth, H. & Henningsen, T. 1997: Basement structure of the continental margin in the Lofoten–Lopphavet area, northern Norway: constraints from potential field data, on-land structural mapping and palaeomagnetic data. *Norwegian Journal of Geology 77*, 15–30.

Olesen, O., Ebbing, J., Lundin, E., Mauring, E., Skilbrei, J.R., Torsvik, T.H., Hansen, E.K., Henningsen, T., Midbøe, P. & Sand, M. 2007: An improved tectonic model for the Eocene opening of the Norwegian–Greenland Sea: Use of modern magnetic data. *Marine and Petroleum Geology 24*, 53–66.

Opheim, J.A. and Andresen, A. 1989: Basement-cover relationships on northern Vanna, Troms, Norway. *Norwegian Journal of Geology 69*, 67–81.

Osmundsen, P.T. & Ebbing, J. 2008: Styles of extension offshore mid Norway and implications for mechanisms of crustal thinning at passive margins. *Tectonics 27*, DOI:10.1029/2007TC002242.

Osmundsen, P.T. & Redfield, T.F. 2011: Crustal taper and topography at passive continental margins. *Terra Nova 23*, 349–361.

Osmundsen, P.T., Sommaruga, A., Skilbrei, J.R. & Olesen, O. 2002: Deep structure of the Mid Norway rifted margin. *Norwegian Journal of Geology 82*, 205–224.

Osmundsen, P.T., Redfield, T.F., Hendriks, B., Bergh, S.G., Hansen, J.-A., Henderson, I., Dehls, J., Lauknes, T.R., Larsen, Y., Anda, E., Fredin, O. & Davidsen, B. 2010: Fault-controlled alpine topography in Norway. *Journal of the Geological Society of London 167*, 83–98.

Pascal, C. & Olesen, O. 2009: Are the Norwegian mountains compensated by a mantle thermal anomaly at depth? *Tectonophysics 475*, 160–168.

Ramberg, I.B., Bryhni, I., Nøttvedt, A. & Rangnes, K. 2008. *The making of a land. Geology of Norway.* The Norwegian Geological Association, Oslo.

Redfield, T.F., Osmundsen, P.T. & Hendriks, B.W.H. 2005: The role of fault reactivation and growth in the uplift of western Fennoscandia. *Journal of the Geological Society of London 162*, 1013–1030.

Redfield, T.F. & Osmundsen, P.T. 2013: The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. *Geological Society of America Bulletin 125*, 184–200.

Roberts, D. & Lippard, S.J. 2005: Inferred Mesozoic faulting in Finnmark: current status and offshore links. *Geological Survey of Norway Bulletin 443*, 55–60.

Roberts, D., Nordgulen, Ø. & Melezhik, V. 2007: The Uppermost Allochthon in the Scandinavian Caledonides: From a Laurentian ancestry through Taconian orogeny to Scandian crustal growth on Baltica. *In* Hatcher Jr., R.D., Carlson, M.P., McBribde, J.H. & Martínez Catalán, J.R. (eds.): *4-D Framework of Continental Crust*, Geological Society of America Memoir 200, pp. 357–377.

Roberts, D., Chand, S. & Rise, L. 2011: A half-graben of inferred Late Palaeozoic age in outer Varangerfjorden, Finnmark: evidence from seismic-reflection profiles and multibeam bathymetry. *Norwegian Journal of Geology 91*, 191–200.

Rohrman, M. & van der Beek, P. 1996: Cenozoic postrift domal uplift of North Atlantic margins: an asthenospheric diapirism model. *Geology 24*, 901–904.

Rydningen, T.A., Vorren T.O., Laberg, J.S. & Kolstad, V. 2013: The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms. *Quaternary Science Reviews 68*, 126–141.

Smelror, M., Mørk, A., Mørk, M.B.E., Weiss, H.M. & Løseth, H. 2001: Middle Jurassic–Lower Cretaceous transgressive-regressive sequences and facies distribution off northern Nordland and Troms, Norway. *Norwegian Petroleum Society Special Publications 10*, 211–232.

Smelror, M., Petrov, O.V., Larssen, G.B. & Werner, S.C. (eds.) 2009: *Geological history of the Barents Sea*. Geological Survey of Norway, Trondheim, 135 pp.

Steltenpohl, M.G., Carter, B.T., Andresen, A. & Zeltner, D.L. 2009: ^{40}Ar/^{39}Ar thermochronology of late- and postorogenic extension in the Caledonides of north–central Norway. *The Journal of Geology 117*, 399–414.

Thorsnes, T, Erikstad, L., Dolan, M.F.J. & Bellec, V.K. 2009: Submarine landscapes along the Lofoten–Vesterålen–Senja margin, northern Norway. *Norwegian Journal of Geology 89*, 5–16.

Thorstensen, L. 2011: *Land-sokkel korrelasjon av tektoniske elementer i ytre del av Senja og Kvaløya i Troms*. MSc thesis, University of Tromsø, 107 pp.

Tsikalas, F., Faleide, J.I. & Eldholm, O. 2001: Lateral variations in tectono-magmatic style along the Lofoten–Vesterålen volcanic margin off Norway. *Marine and Petroleum Geology 18*, 807–832.

Tsikalas, F., Eldholm, O. & Faleide, J.I. 2005: Crustal structure of the Lofoten–Vesterålen continental margin, off Norway. *Tectonophysics 404*, 151–174.

Tsikalas, F., Faleide, J. I. & Kusznir, N. J. 2008: Along-strike variations in rifted margin crustal architecture and lithosphere thinning between northern Vøring and Lofoten margin segments off mid-Norway. *Tectonophysics 458*, 68–81.

Verduzco, B., Fairhead, J.D., Green, C.M. & MacKenzie, C. 2004: New insights into magnetic derivatives for structural mapping. *The Leading Edge 23*, 116–119.

Wilson, R.W., McCaffrey, K.J.W., Holdsworth, R.E., Imber, J., Jones, R., Welbon, A. & Roberts D.J. 2006: Complex fault pattern, transtension and structural segmentation of the Lofoten Ridge, Norwegian Margin: Using digital mapping to link onshore and offshore geology. *Tectonics 25*, doi:10.1029/2005TC001895.

Zwaan, K.B. 1995: Geology of the West Troms Basement Complex, northern Norway, with emphasis on the Senja Shear Belt: a preliminary account. *Geological Survey of Norway, Bulletin 427*, 33–36.

Zwaan, K.B., Fareth, E. & Grogan, P.W. 1998: Tromsø, bedrock geology map, scale 1:250,000, *Geological Survey of Norway*.