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Analysis of Late Paleozoic-Mesozoic brittle faults and fractures in West-Finnmark: geometry, kinematics, fault rocks and the relationship to offshore structures on the Finnmark Platform in the SW Barents Sea.

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Abstract

The present work focuses on the onshore/offshore analysis and correlation of brittle faults and fractures on the Porsanger Peninsula area in west-Finnmark, the shelf areas and the immidiate offshore areas (Finnmark Platform and Gjesvær low). Structural field observation, microstructural and SEM analysis provide the basis for the characterization of the geometry, kinematics and fault rocks. This data has been combined with interpreted DEM/bathymetric, aeromagnetic and seismic data to get a better understanding of the regional structural character.

This study demonstrates that Porsanger Peninsula area are characterized by two major fault-fracture trends: NW-SE and NE-SW, and a subsidary E-W fault-fracture trend. The NW-SE fault trending parallel to the Trollfjord-Komagelv Fault Zone and show dominantly oblique slip and lateral displacement. The NE-SW and E-W faults show mainly normal dip-slip movement and are likely related to the offshore Troms-Finnmark Fault Complex and Måsøya Fault Complex. The relative timing of the the brittle faults-fracture trends are uncertain, but are all possibly related to the WNW-ESE directed extension event that led to the opening of the NE Atlantic Ocean.

The observed fault rocks indicate mostly mechanically frictional brittle deformation, and show greenschist and zeolite mineral assemblages indicative of shallow cataclastic fracturation. The juxtaposition of lower amphibolite facies host rock with greenschist facies fracturation and zeolite facies fracturation may indicate that the study area is part of a progressively exhumed margin.

Based on the onshore-offshore structural analysis, an evolutionary model is suggested for the structural development of Gjesvær low on the Finnmark Platform. Gjesvær low is possibly a Late Devonian- Early Carboniferous basin that likely initiated during fault linkage of the overlapping fault segments of the major NE-SW to ENE-WSW basin-bounding faults (Troms-Finnmark Fault Complex and Måsøya Fault Complex) in late Devonian times. The NW-SE branch fault segment connects Troms-Finnmark Fault Complex and Måsøya Fault Complex in the east end of Gjesvær low. This NW-SE fault appears to be related to the major Trollfjord-Komagelv Fault Zone. Fault activity continued along the major basin-bounding faults and the branching NE-SW trending segment. This resulted in further subsidence of Hammerfest Basin and Nordkapp Basin, while Gjesvær low is shallower due to the inactive termination of the Måsøya Fault Complex on the platform. This suggests that the NW-SE trending fault segment acted as transfer faults that decoupled the Gjesvær low from deep-basins such as the Nordkapp and Hammerfest basins.

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Halldis Lea, 25th May 2016

Contents

1 Introduction

1.1 Background and frame for the project

This master thesis is part of an ongoing project by the Research Centre for Arctic Petroleum Exploration (ARCEX) focusing on onshore-offshore tectonic correlations along the Northern-Norwegian shelf and the Barents Sea margin. This project is supported by The Arctic University of Norway (UiT), The University of Oslo (UiO), Statoil Harstad, The Norwegian University of Science and Technology (NTNU) and the Geological Survey of Norway (NGU). The project is a follow-up of previous work that focused on land-shelf tectonics in Lofoten-Vesterålen and western Troms (Fig. 1.1). Structural geology, bedrock geology, geomorphology, bathymetry and seismic interpretations were combined to provide a greater degree of understanding by using an interdisciplinary approach. The overall aim of the ongoing regional project is to gain a better understanding of the tectonic development of the Barents Sea margin and determine age and kinematics of rift-related basins and faults on the Finnmark Platform (Johansen et al., 1994; Roberts et al., 2011)

Previous studies on land in Lofoten-Vesterålen and western Troms show indication of lineaments that are fault controlled, and are possibly found further north in Finnmark as well (Fig. 1.1). These lineaments are seen as narrow sounds, fjords and escarpments and largely coincide with the regional normal faults of Paleozoic-Mesozoic age at the shelf (Davidsen et al., 2001; Hansen et al., 2011). High-resolution bathymetry data of the shallow shelf along the whole margin display structures in the bedrock. This permits direct correlation of faults from land to deeper basins.

The overall NE-SW trending Paleozoic-Mesozoic Harstad, Tromsø, Hammerfest and Nordkapp basins offshore and the coast of northern Norway are bounded by major faults striking NNE-SSW and ENE-WSW (i.e. the Troms–Finnmark Fault Complex and Vestfjord-Vanna Fault Complex). The same faults are traced in the coastal areas of Lofoten, Vesterålen and western Troms where they delineate a regional onshore horst consisting of Precambrian rocks (Bergh et al., 2010). Studies from Vesterålen show rotated and partly down eroded Jurassic-Cretaceous fault blocks with sedimentary depositions that could have covered large parts of the coast areas (Osmundsen et al., 2010), and thus be onshore analogues to the main offshore basins. The reason that these structures and paleo-relief are preserved on land, can be due to the fast Cenozoic isostatic uplift (Faleide et al., 2008). The uplift was followed by coast erosion, land-shelf drainage and sedimentation that have followed specific directions ever since the Jurassic-Cretaceous time.

Pressure-temperature (P-T) studies of faults in western Troms shows that the faults were formed at a depth of around 10 km depth, and the metamorphic conditions were greenschist facies (Indrevær et al., 2014). Minerals from circulated fluids then sealed these faults during the fast isostatic uplift of the crust. Transfer-faults with NW-SE trend (such as the Senja Fracture Zone, Fugløya Transfer Zone and the sub-parallel Trollfjord-Komagelv Fault Zone) segmented the margin and caused a stepwise geometry of the faults and the related basins along the margin (Fig. 1.1). Radiometric dating of fault rocks in western Troms show dominant Carboniferous-Permian ages (Davids et al., 2013), but corresponding faults further southwest in Lofoten-Vesterålen show Jurassic-Cretaceous and Tertiary ages (Hendriks et al., 2010). This means that the rift axis moved successively further westward over time and that the youngest faults are situated further west. Notably important, this suggests that Paleozoic, e.g. Caboniferous-Permian basins and boundary normal faults may exist farther north and east. The present thesis attempts to test if similar faults and associated fractures may exist onshore in western Finnmark.

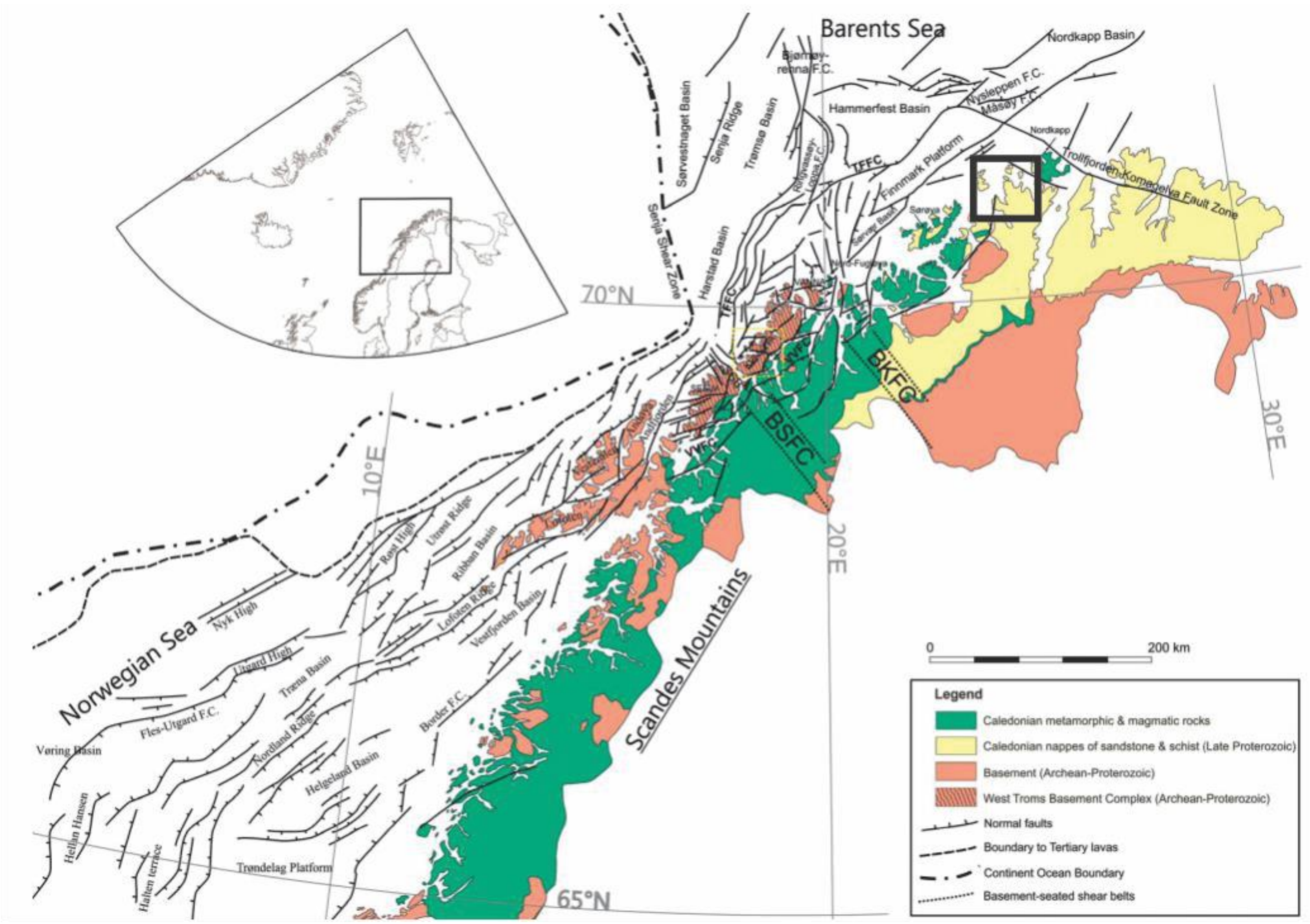

Fig. 1.1 Regional onshore-offshore tectonic map of the Mid-Norwegian to the SW Barents Sea margin. The study area is outlined in the black box. From Indrevær et al. (2014)

The network of onshore brittle faults in coastal areas in Finnmark is yet to be investigated, but some analysis based on satellite images and field studies have been done (Gabrielsen & Ramberg, 1979; Lippard & Roberts, 1987a; Townsend, 1987; Olesen et al., 1990; Gabrielsen et al., 2002; Roberts & Lippard, 2005; Indrevær et al., 2013). NE-SW striking faults are traced onshore on Finnmark and along the fjords, such as the Langfjorden -Varsung Fault which is a continuation of the Vestfjorden-Vanna Fault Complex further south (Olesen et al., 1990). Roberts and Lippard (2005) suggested that the Varsung Fault possibly preserve a hidden half-grabenal succesion beneath outer Altafjorden. They also suggested that the fault are offset by the NW-SE striking Kokelv Fault and continues towards the northwestern part of Porsanger peninsula, right outside Havøysund (Fig. 1.2). Townsend (1987) described brittle faults in Porsanger Peninsula, such as the Snefjord-Slatten fault (Passe, 1978) and the Selvika Eiterfjorden fault (Hayes, 1980) (Fig. 1.2). He also inferred the presence of major faults in the fjords such as the Magerøysundet fault between the Porsanger Peninsula and Magerøya, and an E-W fault detected by bathymetry studies by Vorren et al. (1986) that are suggested to be a possible continuation or splay fault by the major Trollfjord Komagelv Fault(Fig. 1.2). Additionally, there is a dominant NW-SW trend series of faults that are parallel with the assumed transfer zones, such as the Fugløya transfer zone (Indrevær et al., 2013), and sub parallel to the Trollfjord-Komagelv fault zone (Siedlecki & Siedlecka, 1967). These trends together with the NE-SW trending faults seem to segment the margin into a regional stepwise pattern (Johansen et al., 1994) especially in the area between Sørøya and Magerøya, where the study area (Porsanger peninsula) is located (Fig. 1.2).

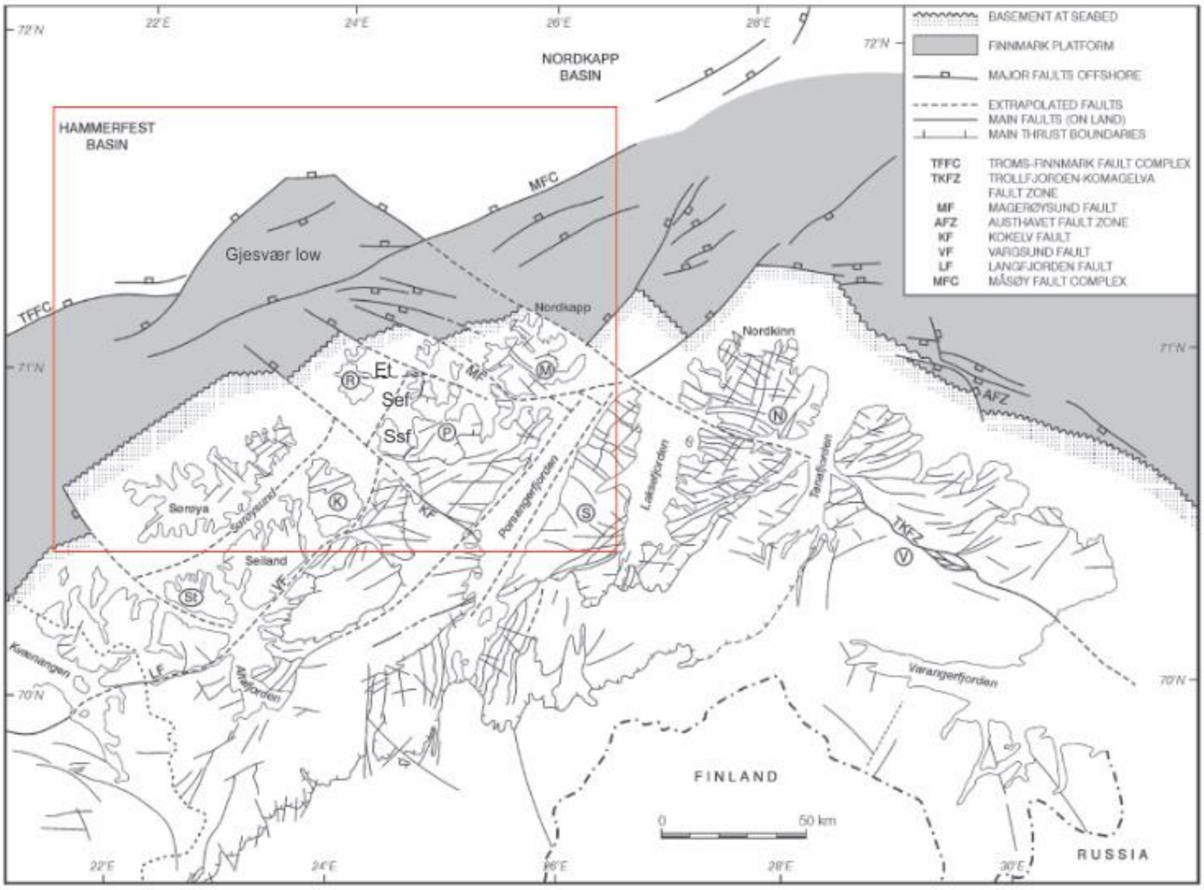

Fig. 1.2 Mapped faults in Finnmark and in the immediate offshore area of the Finnmark Platform. Onshore and offshore study area are framed in red. Modified from Roberts & Lippard (2005). Ssf: Snefjord-Slatten Fault, Sef: Selvika Eiterfjorden Fault K: Kvaløya, M: Magerøya, N, Nordkinn peninsula, P: Porsanger peninsula R: Rolvsøya, S: Sværholt peninsula, St: Stjernøya, V: Varanger peninsula

1.2 Aim and goals

The purpose of this thesis is to analyze the geometry of brittle faults, fracture systems and fault rock onshore in Porsanger Peninsula in western Finnmark, and compare this with faults offshore by using bathymetry data on the shallow shelf along the coast and seismic data on the Finnmark platform and out in the deeper parts of the Barents Sea margin. One of the problems to address is to consider whether the observed onshore faults-fractures are related to Palaeozoic (Devonian-Carboniferous) basin formation with a NE-SW trend parallel with the Troms-Finnmark Fault Complex and Nordkapp/Hammerfest basin trend (Gabrielsen et al., 1990; Johansen et al., 1994; Indrevær et al., 2013) and/or whether they follow a more NW-SE trend parallel to the transfer faults (Senja and Fugløya) farther south in Troms and the major Trollfjord-Komagelv Fault Complex in eastern Finnmark (Roberts et al., 1997; Roberts, 2003; Roberts & Lippard, 2005; Herrevold et al., 2009; Roberts et al., 2011).

Some specific goals were defined in advance to achieve the main objetives.

1. Map and analyse brittle faults and fractures in the Caledonian bedrock in selected localitites in Porsanger peninsula in Finnmark. The goal is to describe and analyze faults geometry, orientation and kinemtaics as a basis for dynamic analysis. Aerial images (www.norgeibilder) and Digital Terrain Models DEM (www.Norgei3D) are used as a tool for mapping.
2. Studies of bathymetry data between Sørøya and Magerøya (25x25 high-resolution bathymetry from MAREANO) with emphasis on seperating brittle faults and fracture sets in the bedrock, and discuss and compare them with orientations of brittle structures onshore.
3. Seismic interpretation of selected 2D seismic lines from the Finnmark Platform (Statoil). The purpose is to interpret Palaeozoic-Mezosoic faults and possible basins to correlate them with tectonic elements on the shelf and coastal areas onshore between Sørøya and Magerøya.
4. Thin section and SEM analysis of fault rocks. The purpose is to document brittle fault rocks, describe and analyze kinematics and mineral asseblages to impove our understanding of the faults and if possibly, its P-T conditions during formation and further development.
5. Propose a tectonic model for onshore-offshore correlation of brittle faults and bathymetry in western Finnmark, which comprising studies of both the Troms-Finnmark Fault Complex/Måsøy Fault Complex trend (NE-SW) and Trollfjord-Komagelv fault trend (NW-SE).

1.3 Regional geology

The bedrock in Finnmark and northern Troms consist of Precambrian basement overlying by Caledonian thrust nappes that were placed onto the Baltic shield (Corfu et al., 2014). This thrusting was a result of closure of the former Iapetus Ocean during the Scandinavian Caledonian Orogeny that took place from Late Ordovicium to Early Devonian (Roberts and Gee 1985). In Finnmark, these events resulted in characteristic nappes (Allochtons) referred to as Lower, Middle (Kalak-Nappes Complex), Upper (Magerøya/Vaddas Nappes) and Uppermost Allochtons (Lyngen Nappes Complex) (Roberts & Gee, 1985). The Lower and Middle Allochtons are shelf and continental rise succsessions derived from the Baltica margin, whereas the Upper Allochtons are mainly composed of exotic terrains made up of ophiolites, island arc successions and intraoceanic sedimentary deposits origin (Gale & Roberts, 1974; Gee, 1975.; Gee & Sturt, 1985; Stephens & Gee, 1985). The Upper Allochton is found on Magerøya, Porsanger Peninsula, Sørøya and Lyngenfjorden referred as the Magerøy/Vaddas Nappe. Fossils discoveries from Magerøya show Late Ordovicium to Silurian age og the Magerøy Nappe (Binns & Gayer, 1980). The Uppermost Allochton is not present in Finnmark, it is found only on the eastern side of Lyngenfjorden in northern Troms and further south (Lyngen ophiolite).

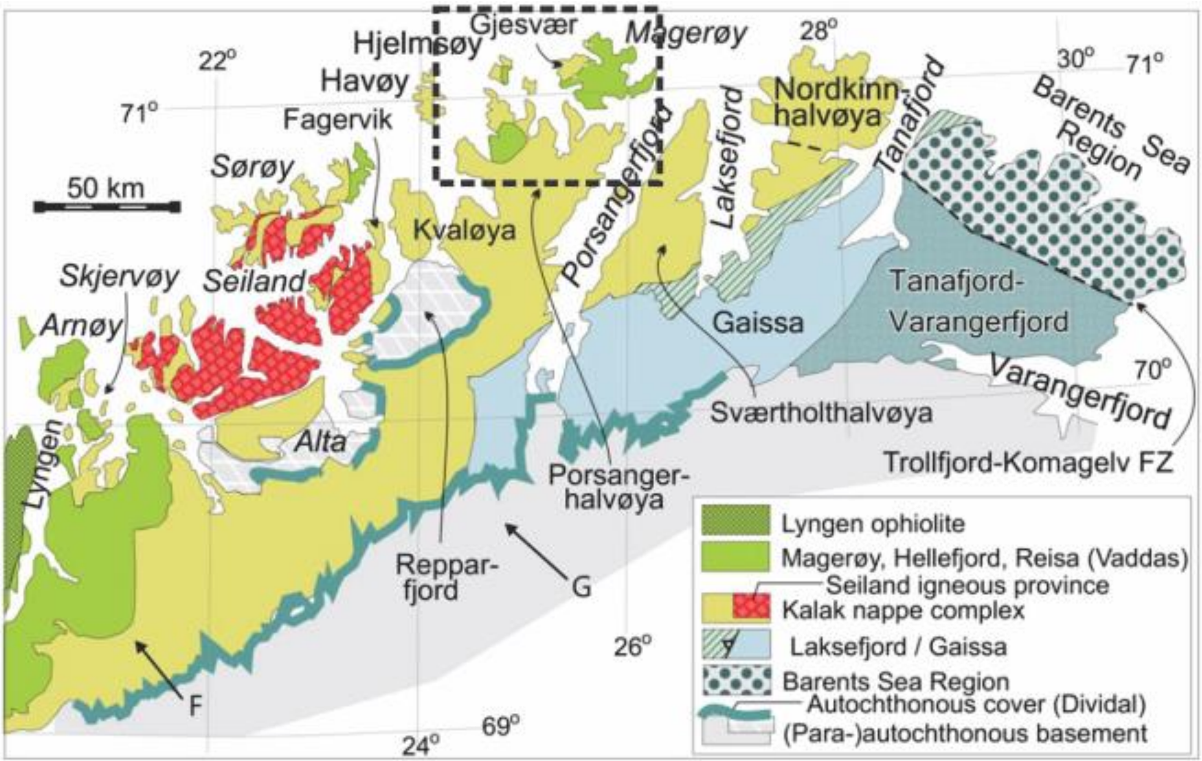

Fig. 1.3 Tectonic map of the Scandinavian Caledonides in western Troms and Finnmark (adapted from Gee et al. 1985). The studied area is framed and are shown in more detail in fig. 4. From Corfu et al. (2014)

1.4 Study area: Porsanger Peninsula

Porsanger peninsula consists of Precambrian paragneiss/orthogneiss complex, metasedimentary rocks of the Kalak Nappe Complex and magmatic intrusions of both pre-Caledonian and Caledonian age. The Caledonian nappes have a general flat lying and weak NW – dipping foliation/schistocity and striking to the NE-SW. Regional correlation of the individual nappes has been proposed and discussed by several authors with only partial agreements (Gayer et al., 1985; Ramsay et al., 1985; Kirkland et al., 2005, 2006).Three different nappes in the northwestern Porsanger peninsula district were identified by (Ramsay et al., 1985) and correlated with the regional important Neoproterpzoic Sørøya succession in western Finnmark established by Ramsay (1971). Based on geochronological, geochemical and structural grounds, some of the correlated units in Porsanger Peninsula have now been excluded to belonging to the upper part of the Sørøya succesion (Kirkland et al., 2005, 2006; Slagstad et al., 2006), described in chapter 1.4.2. Today, the sequence is interpreted to comprise several separate nappes with meta-sedimentary rocks of different Neoproterozoic age, and 980-600 Ma felsic and mafic plutonic intrusions (Kirkland et al., 2006; Davis et al., 2011).

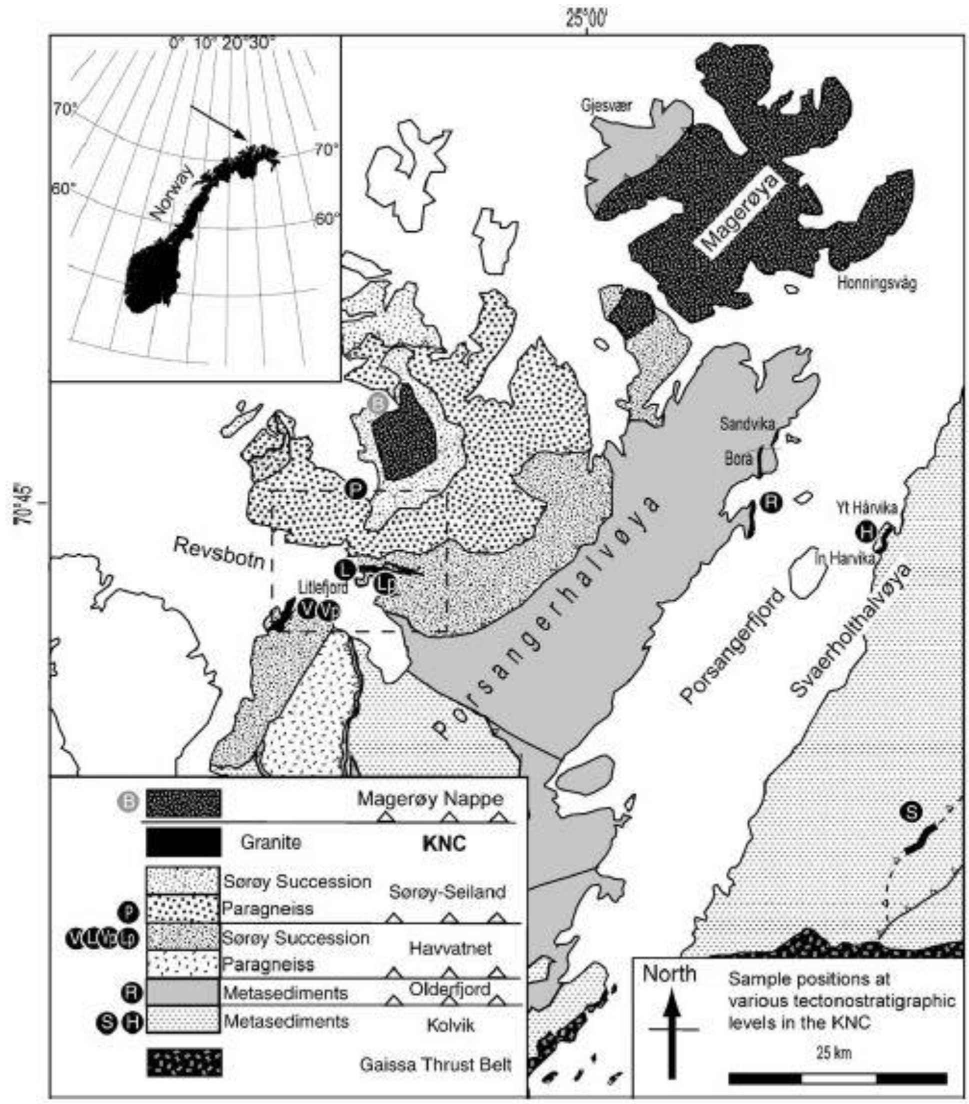

Fig. 1.4 Bed rock geological map of Porsanger Peninsula and Magerøya. L: Lillefjord Granite, LP: Lillefjord Pegmatite, R: Repvåg Granite, B: Bakfjord Granite From Kirkland et al. (2006)

1.4.1 The Precambrian Basement Complex

The Precambrian Basement Complex in Porsanger peninsula is dominated by paragneisses mostly of pelitic origin (augen-gneiss and schist) and lesser amount of orthogneisses comprises mainly of granodioritic, tonalitic gneisses, banded or laminated gneiss and schist (Ramsay & Sturt, 1977) The ortho-/paragneiss basement in the nappe sequence has a complex pre-Caledonian history with variable metamorphic grades (Sturt et al., 1978; Sturt et al., 1981; Ramsay et al., 1985) The pre-Caledonian fabric is still preserved and is seen as strongly deformed ductile shear zones (mylonitized in some areas) of gneiss/schist (Ramsay & Sturt, 1977). In Selvika and Skjarvodden, the paragneisses contain k-feldspar porphyroclasts with elliptical form that appears as isolated augen. More locally in Skjarvodden, large pink heavily fractured garnet porphyroblasts ranging from 2-10 cm in size and are surrounded by strongly deformed mica-rich matrix. These characteristic features are typical for the Eidvågeid basement rock sequence (paragneiss), also found in Kvaløya and Hammerfest. The pink colour of the garnet porphyroblasts are due to higher pyrope contents (Rice, 1990) The Eidevåg paragneiss were migmatized at 680-710 Ma (Kirkland et al., 2006). The gneisses in the area show a varied deformation with an increased fabric development close to the boundary thrusts in the Havøysund and Snefjord area (Ramsay et al., 1985).

1.4.2 Metasedimentary rocks in the Kalak Nappe Complex

The Kalak Nappe Complex is a large sequence with several thrust sheets consisting mainly of clastic meta-sedimentary rocks of Neoproterozoic (1030-710 Ma) age (Ramsay, 1971) and with lesser amounts of Neoproterozoic (570-560 Ma) intrusive rocks belonging to the Seiland Igneous province (Ramsay et al., 1985; Roberts, 2003; Roberts et al., 2003; Roberts et al., 2006; Davis et al., 2011; Corfu et al., 2014). The meta-sediments are generally metamorphosed under amphibolite facies during the formation of the Caledonian orogeny (Roberts, 1998).

In the western part of Porsanger peninsula, rocks in the Kalak Nappe Complex have a general flat lying to weak NW-dipping foliation, and the most dominant metasedimentary rock type is a grey-white, well-banded meta-sandstone/ meta-psammite that varies with feldsphatic, quartzite and pelitic horizons that have been referred as the lowermost unit in the Sørøya sequence (Klubben Group) by Ramsay et al (1985). He also referred the rusty, yellow weathering mica schist observed in the Myrford area to be a part of the Storelv Group. Lesser amount of meta-carbonate/marmor east of Lillefjord have been referred as part of the Falkenes /Åfjord formation (Roberts, 1998). These correlations were later been excluded by Kirkland et al. (2006) and the Kalak Nappe Complex is now referred as the Kolvik Olderfjord, Havvatnet and Sørøy-Seiland Group (Fig. 1.4). The Uppermost sequence in the study area has been described as the uppermost Kalak Nappe Complex and correlated as the lower part of the Hellefjord Group from the Sørøya sequence (Ramsay et al., 1985), which is a thick package comprising of quartzite, psammite, pelites, and schist of turbidite origin (Roberts, 1968). This have later been reassigned by Kirkland et al. (2005) to be part of the Magerøy nappe since it only show Scandian deformation suggesting Silurian age. The eastern part of Porsanger are more tectonic effected causing repetition of the units which make it more challenging to recognize the different formation and correlate it with the Sørøya succesion (Roberts, 1998).

1.4.3 Pre-, syn- and post-Caledonian intrusives

Igneous intrusions are locally abundant, generally parallel to the foliation and mainly felsic (Ramsay et al., 1985), and they become progressively younger upwards within the Kalak Nappe Complex (Kirkland et al., 2006). Intrusions of granitic and granidioritic dykes/bodies are seen south in Porsanger peninsula close to Snefjord and Lillefjord study areas, while gabbroic/amphibolite rocks intrude the area close to Selvika. Segragation of quartz and high concentration of large dark red garnets (ranging from 2-6 cm in size) are seen in the mafic dykes. The presence of granitic intrusions in Bakfjorden have also been described and dated by (Kirkland et al., 2005), showing age og 438 ± 2 Ma (Early Silurian). Coarse granitic E-W oriented pegmatite veins is also present in Lillefjord and have been dated by Kirkland et al. (2006) with zircon, and yield an age of 826 ± 5 Ma. The Lillefjord granite has been described as a strongly-foliated adamellite and dated by Daly et al. (1991) by U-Pb zircon giving age of 804 ± 19 Ma (pre-Caledonian), event termed as Porsanger Orogeny (Kirkland et al., 2006). On the eastern side of Porsanger peninsula, a N-S trending granite (referred to as Repvåg granite) show an intrusion age of 981 ± 7 Ma (Kirkland et al., 2006).

Previous absolute dating of several dolerite dykes in Finnmark (further northeast of the study area) has yielded various ages, including Neoproterozoic, Caledonian, Devonian and Carboniferous ages (Beckinsale et al., 1975; Lippard & Prestvik, 1997; Guise & Roberts, 2002; Rice et al., 2004; Kirkland et al., 2006) In particular, an onshore NW-SE trending dolerite dyke on Magerøya was dated using the K-Ar illite method, suggesting Permo-Carboniferous age (Roberts et al., 1991) and thus coincides with the post-Caledonian rifting event with extensional faulting in the adjacent areas offshore of the Finnmark Platform. Newer and more precise age determination with $^{40}Ar/^{39}Ar$ age determinations resulted in Early Carboniferous age (Lippard & Prestvik, 1997). K-Ar illite age determination were also conducted on a WNW-ESE trending dyke on the Digermul peninsula (eastern Finnmark) indicating Late Carboniferous age (Beckinsale et al., 1975). NE-SW trending dolerite dykes on Varanger peninsula were K-Ar dated and gave Late Devonian- Early Carboniferous ages (Beckinsale et al., 1975). $^{40}Ar/^{39}Ar$ analysis peformed by Guise and Roberts (2002) gave a more accurate age determinations to be Late Devonian. Tholeiitic geochemical composition of three suites of dolerite dykes in eastern Finnmark with WNW-ESE trend, NE-SW and N-S trend, do support continental margin rifting and crustal extenison during lates Devonian to possibly Permian times (Rice et al., 2004)

In western Troms (southwest of the study area), several ENE-WSW trending faults and dykes onshore have been dated by the $^{40}Ar/^{39}Ar$ method, yielding Early Carboniferous ages (Hendriks et al., 2010; Kullerud et al., 2011; Davids et al., 2013). Dating of onshore fault gouge in Troms by Davids et al. (2013) showed that faulting there may have started in the Late Devonian in the innermost faults (Laksvatn fault), and continued until Late Devonian-Early Carboniferous on Andøya in coastal areas of Vesterålen. A similar Carboniferous age was obtained for a major coastal fault zone in Vannøya (Vannareid-Burøysund fault) by Davids et al (2013), whereas a much younger, Cretaceous age was given for a major reactivated normal fault (Kvenklubben fault) in Vargsundet near Hammerfest in Finnmark (Torgersen et al., 2015).

1.5 Post-Caledonian brittle faults

The post-Caledonian rift-evolution of the northern Norwegian continental margin and in the SW Barents Sea started after the orogenic collapse of the Scandinavian Caledonides in the Devonian and has lasted for more than 300 million years (Davids et al., 2013). There has been recognized four major phases of extensional evolution/rifting, starting with crustal subsidence in the Carboniferous and Permo-Triassic phases, followed by the main rifting and crustal extension event in the Late Jurassic-Early Cretaceous, and ending with an inversion phase in the Late Cretaceous-Early Tertiary time (Faleide et al., 1984; Gabrielsen et al., 1990; Faleide et al., 1993; Gabrielsen et al., 1997; Dorè et al., 1999; Roberts & Lippard, 2005). A brief review of the Barents Sea margin offshore western Finnmark, including main provinces, basins and ridges, boundary faults, sedimentary deposits in offshore basins are presented in the following section, followed by the margin evolution.

1.5.1 Main provinces and margin architecture

The main provinces in the offshore study area in southern Barent Sea consist of the Finnmark Platform, Gjesvær low, Hammerfest Basin and Nordkapp Basin (Gabrielsen et al., 1990; Smelror et al., 2009) shown in Fig. 1.1. The Finnmark Platform is bounded by the Norwegian mainland to the south, the Ringvassøy-Loppa Fault Complex to the west, and by Troms-Finnmark/Måsøy Fault Complex to the north (Fig. 1.2) (Larssen et al., 2002). The platform has been stable since the Late Palaeozoic and the boundary of Early Carboniferous clastics and Late Carboniferous to Permian carbonates is interpreted as the transition from a pre-platform to a platform development (Gabrielsen et al., 1990).

Gjesvær low is located further seawards on the Finnmark Platform and was first described as a separate structural element by Johansen et al. (1994). Gravity anomaly data revealed density variations in Gjesvær low that has been interpreted as Caledonian rocks and prominent tilted reflections recognized on seismic has been suggested to be Caledonian thrusts (Johansen et al., 1994). Gjesvær low is suggested to be a Carboniferous basin, with possibly older Paleozoic deposits (Johansen et al., 1994; Gernigon et al., 2014).

The western part of the Barents Sea consist of a series of narrow basins with NE-SW to E-W trend such as the major Hammerfest Basin that are delineated from the Finnmark Platform in the study area. The Hammerfest Basin is characterized by mainly E-W to NE-SW trending boundary and internal faults evolved during the main rifting event in late mid to Late Jurassic and into the Cretaceous time (Faleide et al., 1993; Dorè et al., 1999). Smaller basins on the Finnmark Platform have been described, such as Sørvær Basin that where first recognized by Olesen (1997) with gravity anomaly data (Olesen et al., 1997; Olesen et al., 2010). Other shallow half-graben basins on the platform delineated by NE-SW and E-W trending faults have been identified with seismic and bathymetry studies by (Roberts et al., 2011), and suggested to be of Carboniferous and possibly Devonian age (Roberts et al., 2011).

1.5.2 Basin-bounding faults and major onshore-offshore systems

Major basin-bounding faults in the adjacent offshore areas include the Troms-Finnmark Fault Complex and Måsøy Fault Complex. The Troms-Finnmark Fault Complex is a major fault structure offshore with NNE-SSW and NE-SW trend and dip to the NW that run parallel to the coastline of Troms and Finnmark counties (Gabrielsen et al., 1990) which delineates the Harstad basin in the southern part and Tromsø basin to the north. Further north, the Troms-Finnmark Fault Complex delineates the Hammerfest basin from the Finnmark Platform. These trends are also seen onshore/offshore in Lofoten-Vesterålen and Western Troms where they bound a major basement horst alligned from Lofoten Ridge northward via Senja, Kvaløya and Ringvassøya, to Island of Vanna (Olesen et al., 1997; Indrevær et al., 2013). These trends also form a characterized rombic pattern that is parallel with Ribbe-, Harstad- and Tromsø basins (Bergh et al., 2007; Eig et al., 2008; Hansen et al., 2009) (Fig. 1.1). The fault complex makes up a zigzag regional trend with alternating NNE-SSW and more ENE-WSW trending faults further north, and these are generally normal faults characterized by listric geometry. The northeastern part of the fault complex is described as a series of faults arranged in an en èchelon pattern with minor faults on the platform (Gabrielsen et al., 1990) The Måsøya Fault Complex delineates the western segment of the Nordkapp basin and the Finnmark Platform, and is dominated by NE-SW extensional faults arranged in an echelon fashion and having mainly dip-slip movement (Gabrielsen et al., 1990).

The Trollfjord-Komagelv Fault Zone is a major strike-slip onshore-offshore fault system with WNW-ESE orientation (Fig. 1.1 and Fig. 1.2). The fault zone is traced south of the Nordkinn Peninsula, and onshore through Varanger Peninsula and further southeast at the northern side of Kola Peninsula in Russia. The fault was considered to be initiated as a major strike-slip fault in the Neoproterozoic (Siedlecki & Siedlecka, 1967), that became later on reactivated during the Caledonian orogeny as well as in post-Caledonian times (Rice et al., 1989b; Karpuz et al., 1993). The main argument for a strike-slip origin was the juxtaposition of the Neoproterozoic mostly marine Barents Sea Group at the northern part of the Varanger peninsula against the continental clastic Tanafjord-Varangerfjord Group to the south by dextral movement along the Trollfjord-Komagelv Fault Zone (Roberts, 1972; Rice & Gayer, 1989). Several sub-parallel faults located offshore with WNW-ESE striking trends such as the Magerøysundet Fault southwest of Magerøya (Gabrielsen & Farsæth 1989) are suggested to be a continuation of the Trollfjord-Komagelv Fault Zone. It is also suggested to have been active as a Caledonian transfer fault system (Rice & Gayer, 1989) and also reactivated in the Carboniferous, affecting portions of the Nordkapp basin in areas between the NE-SW Troms-Finnmark Fault Complex and Måsøy-fault Complex (Gabrielsen, 1984; Gabrielsen & Færseth, 1989).

1.5.3 Offshore Sedimentary deposits

The deposition of sedimentary strata on the Finnmark Platform (Fig. 1.5) initiated in the Late Devonian-Carboniferous (Bugge et al., 1995), and such strata are comparable with similar aged deposits found on Svalbard and Bjørnøya (Dallmann, 1999) for example four major Upper Paleozoic depositional units: the Billefjorden Group, Gipsdalen Group, Bjarmeland Group and the Tempelfjorden Group (Larssen et al., 2002). The thickness of this whole sedimentary succession on the Finnmark platform is about 6 km, and the basin infills on the margin outside western Finnmark and the Troms-Finnmark Fault Complex include Carboniferous-Permian strata and sediments deposited during Triassic, Jurassic and Early Cretaceous time (Smelror et al., 2009). Paleogene deposits are only found in a few basin in the Barents Sea, such as the Hammerfest and Bjørnøya Basins. The Late Paleozoic (Carboniferous) units that are present on the platform will be focused on and briefly described below.

Early Carboniferous (Vishean) deposits are identified by shallow drilling and exploration wells on the Finnmark Platform and comprises mostly of fluvial and lacustrine sandstones, siltstones and coal beds (Worsley, 2008). These formations are referred to as the Soldogg, Tettegras and Blærerot formations belonging to the Billefjorden Group (Larssen et al., 2002). These deposits lie directly on the basement rocks just off the coast of Finnmark and further offshore where they are identified by wells down to 2,5 km depth (Bugge et al., 1995). A distinct major unconformity between the Billefjorden Group and the overlying Gipsdalen Group is recognized from well 7128/4-1 and 7128/6-1 on the Finnmark Platform and associated with a change from warm humid to more arid conditions (Larssen et al., 2002). The Gipsdalen Group represents three formations (Ugle, Falk and Ørn Formation) deposited during Mid Carboniferous (Bashkirian) -Early Permian. The group consists mainly of red-colored continental siliciclastics, but dry climate conditions in Late Carboniferous- Early Permian resulted in calcerous and dolomite deposits (Falk- and Ørn Formation). The lowermost unit is referred as the Ugle Formation and is only locally developed on the Finnmark Platform in isolated half-grabens (Worsley et al., 2001; Larssen et al., 2002). Evaporites were also deposited during this period, especially in the Nordkapp Basin where large salt diapirs affected the basin, started to move in Early Triassic and has since then penetrated through the overlain sediments (Smelror et al., 2009) The Bjarmeland Group represents three formations (Ulv, Polarrev and Isbjørn) and consist of carbonate buildups formed during the Early Permian. The group has been identified on the Loppa High and on the Bjarmeland and Finnmark platform (Larssen et al., 2002). The Tempelfjorden Group is of Late Permian age and represents two formations (Røye and Ørret Formation) that are mainly chert and chert-rich limestone, while coarser sliliciclastic influx from the nearby Baltic Shield are present in the Hammerfest Basin (Larssen et al., 2002).

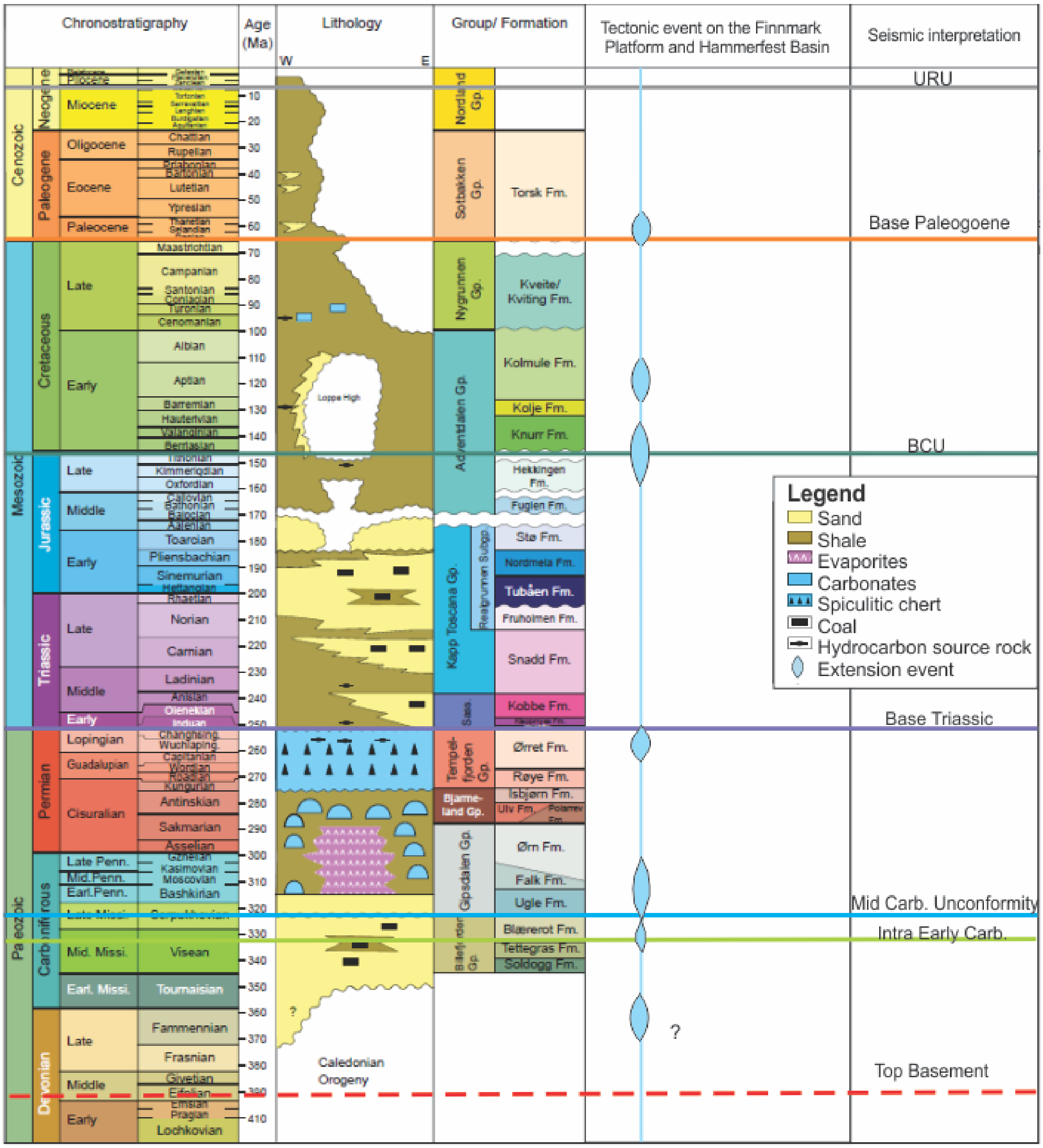

Fig. 1.5 Stratigraphic overview of the lithostratigrapic units in the offshore study area. The blue markers indicate rifting episodes. The seismic horizons used in the seismic interpretation are marked with color code and show the represented age and formation. Figure provided by Statoil.

1.5.4 Margin evolution

The SW Barents Sea margin have a complex tectonic history and undergone mutliple periods of rifting during the regional lithospheric extension since the post-Caledonian orogenic collapse (Devonian times), until breakup in early Cenozoic time (Faleide et al., 2008). In the earliest events (Late Devonian-Carboniferous), several rift-basins developed on the Barents shelf with N-S (Tromsø and Harstad basin) and NE-SW (Hammerfest and Nordkapp basin) oriented structural trends (Gabrielsen et al., 1990). Seismic and stratigraphic studies on the Finnmark platform and in the offshore basins show that Carboniferous and possibly Late Devonian strata rest directly on top of the basement and rift geometry is recognized in the Carboniferous and Permian sequences (Bugge et al., 1995; Gudlaugsson et al., 1998; Larssen et al., 2002). The Nordkapp Basin developed in Late Devonian-Early Carboniferous time (Smelror et al., 2009), while the Hammerfest Basin developed during the Mid to Late Jurassic and into the Cretaceous, at the time when Troms-Finnmark Fault Complex had the most significant active displacement (downfaulting) (Gabrielsen et al., 1990; Faleide et al., 1993; Dorè et al., 1999).

The main boundary fault trends of offshore basins on the Barents Sea margin are believed to follow old Precambrian and/or Caledonian zones of weakness, and the NE-SW trending thrust zones from the Caledonian orogen are thought to be the most likely candidates for rift reactivation in the Devonian-Carboniferous (Smelror et al., 2009). Activity along the major basin-bounding Troms-Finnmark Fault Complex can, however, also be traced into the pre-cambrian sequence (Berglund, Augustson, Færseth, & Ramberg-Moe, 1986), and several episodes of post-Caledonian reactivations are suggested to have taken place until Eocene (Gabrielsen et al., 1990). Some workers proposed sinistral movement in Mid Jurassic (Rønnevik & Jacobsen, 1984) and sinistral strike-slip reactivation in Late Cretaceous to Early Tertiary (Ziegler, 1989) along the northeastern part of the fault complex. The Måsøy Fault Complex has been suggested to have initiated in the Carboniferous, but Mezosoic and Cenozoic tectonic activity are indicated as well (Gabrielsen, 1990).

The major NW-SE trending Trollfjord-Komagelv Fault Zone is an old structure of Neoproterozoic age and has been tectonically active in several stages, starting in Vardenian to Early Ordovician time as a strike-slip fault (Roberts, 1972; Johnson et al., 1978; Kjøde et al., 1978; Lippard & Roberts, 1987b) and later being reactivated as an extentional fault in the Late Devonian - Early Carboniferous (Beckinsale et al., 1975) and in Late Jurassic- Early Cretaceous time (Gabrielsen & Færseth, 1989).

Transform margin development of the western Barents Sea-Svalbard margin occurred in the Late Cretaceous-Palaeocene (Faleide et al., 2008). The western margin of the Barents Shelf was located along a transform/strike-slip transfer zone, referred as the Senja transfer zone and the Hornsund Fault Zone that extend along the western coast of Bjørnøya and Spitsbergen southwards to Senja on mainland Troms, where development of pull-apart basins (such as the Sørvestnaget basin) along N-S trending lineament occurred (Faleide et al., 1993; Knutsen & Larsen, 1997; Breivik et al., 1998; Indrevær et al., 2013), while the basin further east (Hammerfest and Nordkapp basin) were controlled by the NE-SW Troms-Finnmark Fault Complex and Måsøy Fault Complex along the main Jurassic-Cretaceous rift axis (Smelror et al., 2009). Final litospheric breakup and ocean-floor development occurred near the Paleocene-Eocene transition (55-54 Ma) south of the Barents Sea transform margin, and the passive margin to the southwest and northeast of the transform evolved in response to subsidence and sediment loading during the further development of the Norwegian-Greenland Sea (Faleide et al., 2008).

1.6 Methods

1.6.1 Fieldwork

Onshore observations are based on fieldwork carried out in June and July 2015 covering 7 main localities in the Porsanger Peninsula and outcrops in Magerøya. Areas for field studies were selected using high-resolution aerial photographs (from norgei3d.no) looking for regions with well-exposed surfaces and lineaments along the coastal areas that could be correlated with the structures offshore. The methods applied in the field for mapping brittle fractures where strike/dip measurements with a Silva Compass. Fault surfaces, fractures and slickensides where measured.

The program Orient (version 3.0.2) by Vollmer, 2015 is a spherical projection and orientation data analysis software that were used to present the kinematic data and the different fracture sets in the area. Fracture surfaces, contours of the poles and slip-linear plots were made. The excel spreadsheet by Hansen, 2012 where used to convert strike, dip and plunge measurements to strike, dip, trend and to show the fault kinematics where the sense of slip is known.

1.6.2 Digital Elevation Models (DEM)/ bathymetry data

Digital elevation models (DEM) and aerial photographs (Vitual Globe from norgei3d.no) were used to map and locate brittle faults and fracture systems in the field. The high-resolution photos make it possible to observe lineaments, escarpments and depressions in the topography that may represent faults and fractures. It is important to not misinterpret these structures, since they can also represent eroded surfaces, lithological boundaries and fabric in the rock etc. However by using field observations to confirm that structures seen on the DEM are in fact faults/fractures then the DEM can be used to give a better understanding of the areal extent of the fracture system. Combining and building on the field data provides a scientifically excepted method for mapping the structures further over larger areas.

For onshore-offshore correlation, the new 25x25 high resolution bathymetry data from Norges kartverk (MAREANO) shows the structural trends more clearly and was used to interpret the faults offshore on the shallow shelf. Not all areas have that high resolution (25x25), some have 50x50, and some data are lacking in specific areas, such as Snefjord. The GIS software, Global Mapper was used for interpreting faults on the shallow shelf. Analytical tools, such as vertical profile and 3D view were used to get a visualization of the terrain and a cross-sectional perspective of the shape and height of the escarpment/lineaments to help determine if the lineaments are faults. A better quality of the interpretation was achieved when the field data was combined with field data. The lack of seismic result in some uncertainty in the interpreted structural lineaments from the bathymetric data.

Corel Draw X5 was used to draw the major structures and their strike/dip and kinematic data (when possible). The lithological boundaries, foliation, fault gouge, cataclasites and the locality of the sampled fault rocks were also marked.

1.6.3 Optical microscope and Scanning Electron Microscope (SEM)

Fault rock samples were collected in the field, thin-sectioned and analyzed under an optical microscope. The mineral assemblages, textures and structures can provide information about the deformation history and temperature and pressure conditions during the formation of the fault rock. The purpose of thin section analysis was to document the presence of brittle fault rocks, to classify them, identify possible growing metamorphic minerals that can tell about the P-T conditions and to see if the fault rocks had undergone several generations of movement. The fault-rock classification of Braathen et al. (2004) is used. The cohesive/incohesive classifaction is neglected and the classification is build on the cataclastic matrix content of the fault rocks.

Several fault rocks had very fine-grain matrix and it was not possible to identify the mineral contents by using an optical microscope. The SEM gives good quality and high-resolution images with magnification range of 15-30 000x, and show different brightness levels that represent different compositions (heavy minerals are brightest). The SEM were used to analyze the chemical compostion of the fine-grain material in the cataclasites and see if there is any new growing secondary minerals that can give information about the pressure and temperature conditions (P-T conditions) and metamorphism during the formation of the fault rock. The samples were examined with EDS (Energy-dispersive X ray Spectroscopy). Two different SEM instrument at UiT were used; SEM tabletop and Zeiss Merlin SEM. The thin sections were coated with carbon to improve the image.

Abbreviation of mineral names used in the description: quartz (qtz), plagioclase (pl), Alkalie-feldspar (Afs) biotite (bt), muscovite (ms), titanite (tnt), zircon (zr), laumontite (lmt), epidote (ep).

1.6.4 Magnetic anomaly data

The new improved resolution of aeromagnetic anomaly data in Finnmark and the Southwestern Barents Sea where compiled with the bathymetric data by using the GIS software Global Mapper to see if high-anomalies lineaments corresponds to the interpreted faults and/or map blind dykes (possibly fault related) with same trends as the lineaments seen on DEM/bathymetry. The survey used for this study is the Offshore BASAR survey (cover SWBS and to the coastline of Troms-Finnmark) that are compiled with the onshore FRAS survey that covers Finnmark provided by NGU (Gernigon et al., 2014) The magnetic anomaly data have been used to map brittle faults in Porsanger peninsula and the adjacent coastal areas and islands. The magmatic rocks appear with a high positive magnetic anomaly (red colour). It is important to note that different geological bodies/features can have the same magnetic response (Mussett & Khan, 2000). Foliation/bedding of the meta-sedimentary rocks in western Finnmark show high anomaly due to the high magnetic content (Olesen et al., 1990) and these positive anomalies appear as straight linemaents, similar as the margnetic dykes.

1.6.5 Seismic data

Dataset

The seismic data sets used in this investigation is the BSS01 survey (2D) collected by TGS, and is one of the closest available to the Finnmark Platform outside the onshore study area. The dataset covers the Gjesvær low and eastern parts of the Hammerfest Basin including the Troms-Finnmark Fault Complex and Måsøy Fault Complex. The seismic data has a NNW-SSE, ENE-WSW grid with a line spacing that are mainly 4 km, some of the cross-lines (ENE-WSW direction) have a spacing up to almost 10 km. The major deep-seated faults were mapped to see the extend, geometry and orientation of the faults. The key seismic profiles consist of four 2D lines, three with NNW-SSE orientation and one with ENE-WSW orientation that tie the seismic interpretation.

- BSS01 – 103 (Seismic section 1)
- BSS01 – 112 (Seismic section 2)
- BSS01 – 122 (Seismic section 3)
- BSS01 – 204 (Seismic section 4)

The 2D survey have been processed to zero-phase signal. The seismic lines are not depth converted and are shown in two-way travel time (TWT). Description of fault throws and thickness of the seismic units will therefore be described in time. The seismic data have been provided by Schlumberger and NTNU.

Well correlation

There are no direct tie wells in the offshore study area. Therefore, the seismic stratigraphy in this study is built on Statoil´s regional interpretation on the Finnmark Platform that is based on four exploration wells and seven IKU shallow cores (see Table 1). The locations of the wells is shown in fig. 3.6.

All wells have penetrated basement rocks, except 7120/12-4 (an exploration well) and 7126/6U-1 (an IKU well). One well, 7120/12-2 that is located on the northern side of Troms-Finnmark Fault complex penetrated banded gneissic basement. The other wells penetrated quartzite basement; consisting of sand, silt and mud rocks that possibly belonging to the Barents Sea Group of late Precambrian age that are present onshore in northeast Finnmark.

The IKU wells were drilled on a sub crop of the Upper Paleozoic age and penetrate the Billefjorden, Gipsdalen, Bjarmeland and Tempelfjorden Groups, including the Sassendalen Group of Early to Mid Triassic age. The exploration wells 7128/4-2 and 7128/6-1 (Fig. 1.6) show the same stratigraphy, but the Kapp Toscana group of Late Triassic and Early-Mid Jurassic age is also included. The Adventsdalen Group of Late Jurassic and Early Cretaceous age is also represented in the wells. The seismic units seen in these wells thin out to the south and west of the Finnmark Platform.The Early Mesozoic sequence shows almost complete stratigraphy in well 7120/12-4 and 7124/4-1. The Mid to Late Mesozoic sequence in wells 7128/4-1 and 7128/6-1 show several erosion unconformities. The Upper Kapp Toscana Group and the whole Adventsdalen Group are eroded or not deposited in well 7120/12-4.

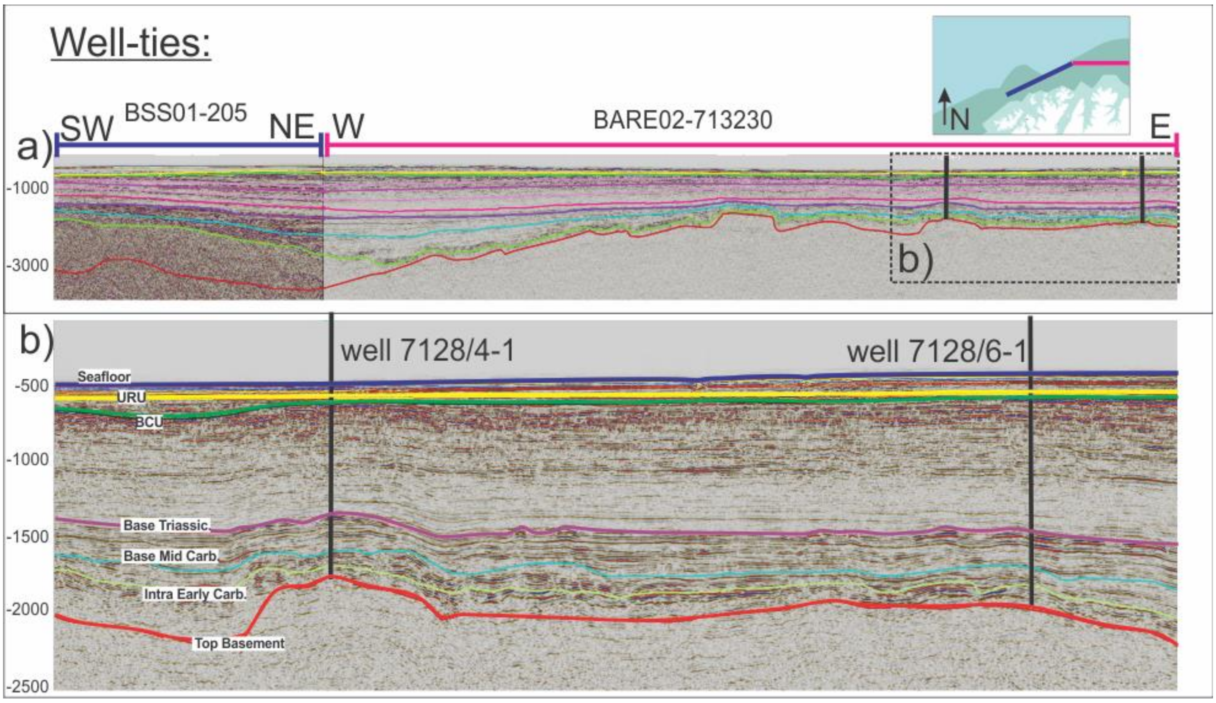

Fig. 1.6 a) Well ties for BSS01 seimsic survey used in this study. Wells 7128/4-1 and 7128/6-1, tied in via seismic line BARE02-713230 and BSS01-205. Modified from Henningsen and Forthun (2016). The location of the wells are shown in Fig. 3.6 (See chapter 3.1).

Well name	**Oldest penetrated rock**	**Formation/Age**
7120/12-2	Gneiss	Basement/ Undefined age
7120/12-4	Sandstone	Ugle FM/ Late Carboniferous
7128/4-1	Quartzite (metasediments)	Basement/ Late Precambrian
7128/6-1	Quartzite (metasediments)	Basement/ Late Precambrian
7126/6-U-1		
7127/10-U-2	Quartzite (metasediments)	Basement/ Late Precambrian
7127/10-U-3	Quartzite (metasediments)	Basement/ Late Precambrian
7128/9-U-1	Quartzite (metasediments)	Basement/ Late Precambrian
7128/12-U-1	Quartzite (metasediments)	Basement/ Late Precambrian
7129/10-U1	Quartzite (metasediments)	Basement/ Late Precambrian
7129/10-U-2	Quartzite (metasediments)	Basement/ Late Precambrian

Table 1 The four exploration wells and IKU shallow wells used for correlation and interpretation of the seismic stratigraphy in the study area.

Interpretation

The seismic interpretation work has been conducted using Petrel 2014 software from Schlumberger. Techniques for mapping the seismic stratigraphy was done by using the the four major groups of systematic reflections defined by (Veeken, 2007):

- Sedimentary reflections (bedding planes)
- Unconformities (discontinuities in the geological record)
- Artefacts (multiples, diffraction etc.)
- Non-sedimentary reflections (faults, fluid contacts etc.)

Interpretation of the different seismic units are done by describing the specific reflection characteristics such as reflection geometry, reflection termination (onlap, downlap, toplap etc.) and reflection configuration (parallel, sub-parallel, divergent layering etc.).

Steeply dipping fault surfaces are normally attenuated in the seismic processing (Veeken, 2007) and characterized as narrow, tabular zones with poor reflections. The resolution of the 2D seismic data limits the ability to recognize small-scales objects (Andreassen, 2009). Steep faults may not be imaged on the 2D data due to the horizontal seismic markers from sedimentation absorbing energy from the nearby objects (Yilmaz, 1987). Seismic imaging of vertical faults are possible using 3D data and applying “timeslice techniques” (Henningsen, Pers. Comm, 2016). It is also important to remember that the kilometer grid spacing in the 2D data will cause objects to be spatially aliased when their size is less than the spacing of the grid (Cartwright & Huuse, 2005), for example small stepping faults will look continuous due to the large line spacing.

1.7 Definitions and terms

Some of the geological definitions and terminology that has been used in this study will be presented in alphabetical order.

Term	**Description**
Accomodation zone	Area of deformation that transfers strain or displacement between two overlapping faults that need not to have been active at the same time (Peacock & Parfitt, 2002)
Antithetic fault	A subsidary fault with opposite dip direction and opposite shear sense than the main fault (Twiss & M., 2007).
Cataclasite	Fault rock that form in shallow crust where brittle deformation dominates (T & M) Cataclastic rock containing 50-90 % matrix (Braathen et al. 2004)
Chloritization	Alteration process of any mafic mineral to chlorite (Winter, 2010)
Conjugate faults	Faults that are accompanied by two sets of small-scale shear fractures at an angle of approximately 60° to each other with opposite sense of shear (Twiss & M., 2007).
Damage Zone	Is the outer zone of a fault consisting of the associated fracture system (Caine et al. 1996; Vevik Ganerød et al. 2008)
Fault core	Is the inner zone of the fault consisting of the fault rock (Caine et al. 1996; Vevik Ganerød et al. 2008)
Fault gouge	Fine-grained and clay-rich non-cohesive fault product formed in place by crushing and chemical alteration of the host rock (Fossen, 2010)
Fault rock	Rock that are commonly formed through strain concentration within a tabular or planar zone that experiences shear stress (Braathen et al., 2004)
Flower structure	Strike-slip duplex that are either extenional (negative flower structure) or contracional (positive flower structure) seen in cross-section (Twiss & M., 2007).
Fractures	Surface discontinuities formed in response to external or internal stresses acting on the fractured object (Fossen, 2010) Mode I – Extensional joint, when the relative motion during propagation is perpendicular to the fracture walls. Mode II – Shear fracture, when the relative motion during propagation is parallel to the surface

	Mode III – Hybrid fracture, when sliding motion is parallel to the fracture edge (Twiss & M., 2007).
Graben	Oppositely dipping normal faults that accommodate lateral extension (Fossen, 2010)
Joint	Extenional fractures that show very small displacement normal to their surface and no, or little displacement parallel to their surface (Twiss & M., 2007)
Lineaments	Linear or curvilinear feature which is believed to represent the trace of intersection between a planar or subplanar structural inhomogeneity (such as fault) and the surface of the Earth. Fracture lineamemt= a zone of fracture representing a stress-induced zone of weakness in the bedrock (O´Leary et al., 1976; Gabrielsen and Braathen, 2014)
Lower ramp branch	When two fault segments link together in the lower part of the ramp (Crider, 2001)
Proto-cataclasite	Cataclastic rock containing 0-50 % matrix (Braathen et al. 2004)
Pull-apart basin	Fault bends where local extension occur (releasing bend) forms where strike-slip segments overlap and hard-link (connect) during accumulation of slip (Fossen, 2010)
Relay structure	Zones connecting the footwalls and hangingwalls of overlapping normal fault segments (Trudgill & Cartwright, 1994).
Riedel shears	A set of subsidary fractures in brittle fault zones, subdivided into groups (R, R', P and T) according to their shape, shear sense and orientation (Passchier & Trouw, 2005). R-shear represent a low-angle normal fault, P-shear is a synthetic low angle fracture T-shear is extensional fractures R'-shear is an anthitetic reverse fault with high angle to the main fault (Fossen & Gabrielsen, 2005)
Seritization	Alteration process by which felsic minerals (usually feldspar) are hydrated to produce sericite (Winter, 2010)
Slickenfibres	Fibrous grains along a fault surface parallel to the fault and usually parallel to the latest movement along the fault (Passchier & Trouw, 2005)
Slickenside	Exposed fault surface that are commonly smooth, polished surfaces which form in response to shearing on the fault surface

	or in the fault gouge that typically contain strongly oriented linear features parallel to the direction of slip (Twiss & M., 2007).
Splay fault	A set of s maller subsidary faults that brach off from the main fault (Twiss & M., 2007)
Strandflat	A horizontal to gently sloping submarine/subaerial platform in front of higher land/coastal mountains (Nansen, 1922; Klemsdal, 1982)
Strike-slip extensional duplex	A set of horizontally stacked horses bounded on both sides by segments of the main fault that are formed at an extenionsal bend or step-over. The faults that bounding the the horses in the duplex is a combination of strike-slip and normal slip. The duplex is referred as a negative flower structure in cross-section (Woodcock & Fisher, 1986)
Synthetic faults	A subsidary fault that has similar dip direction and the same shear sense as that of the main fault (Twiss & M., 2007)
Transtension	Strike-slip deformation involve simultaneous simple shearing pure shearing (extension orthogonal to the deformation zone). Deformation is typically non-coaxial and involves strain partitioning (Fossen & Tikoff, 1993; Morley et al., 2004)
Transfer fault	Fault that links, is at a high angle to, and transfer displacement between two normal faults (Gibbs, 1984)
Ultra-catclasite	Cataclastic rock containing 90-100 % matrix (Braathen et al. 2004)
Upper ramp branch	When two fault segments link together in the upper topographically end of a ramp (Crider, 2001)

Table 2 Definitions of fault rocks, deformation mechanism and structural terms used in this work.

2 Description of onshore data

2.1 Introduction

The study areas in the Porsanger peninsula and Magerøya have numerous well-exposed outcrops (fresh road cuts and shore sections) where brittle faults and fractures have been studied in map view and cross-section. Fault geometry, mineral fills on fault/fracture surfaces and fault rocks are described from the field. Orientation data and kinematics (slickensides) of various fault-fracture sets were collected. Other kinematic indicators such as offset marker beds, drag folding and subsidary fractures (Riedel fracture geometry) are also described. Along the coast, were the rocks are well exposed, possible cross-cutting and timing relations are described. Fault surface lineation (slickensides) and mineral coated fractures are generally lacking in the coastal areas due to wash-out by the sea, however, numerous slickensided surfaces were seen in the fresh road cuts were most of the measurement were taken.

The description of the onshore fault-fracture sets and their geometry is made by integrating several data sources (see below) from the field. These data will be presented systematically, starting with the regional structures in the area (by using satellite and aerial photos), followed by more detailed description of the fault-fracture geometry and specific fault zones. Fault rocks are described in outcrop-scale and a selection of the sampled fault rocks were investigated by thin-sections in micro-scale. Kinematic indicators related to faults and the relative timing constraints between faults and fracture sets shown by cross-cutting relations, are also described.

The different localities (consisting of one or more outcrops) are divided into seven major areas that include fjords, bays and sounds along the western coast of the Porsanger peninsula (marked in fig. 2.1). In addition, Magerøya is included as a separate locality at the end of the chapter. All these areas and their landscape architecture seem to be controlled by the attitude and frequency of major faults and fracture sets (see later discussion chapter 4.1.1), which is also confirmed by fault-fracture orientation data (Fig. 2.1. stereoplots).

The following localities will be described in successive order:

1. Havøysund
2. Myrfjord
3. Selvika
4. Skjarvodden
5. Bakfjorden
6. Snefjord
7. Lillefjord
8. Magerøya

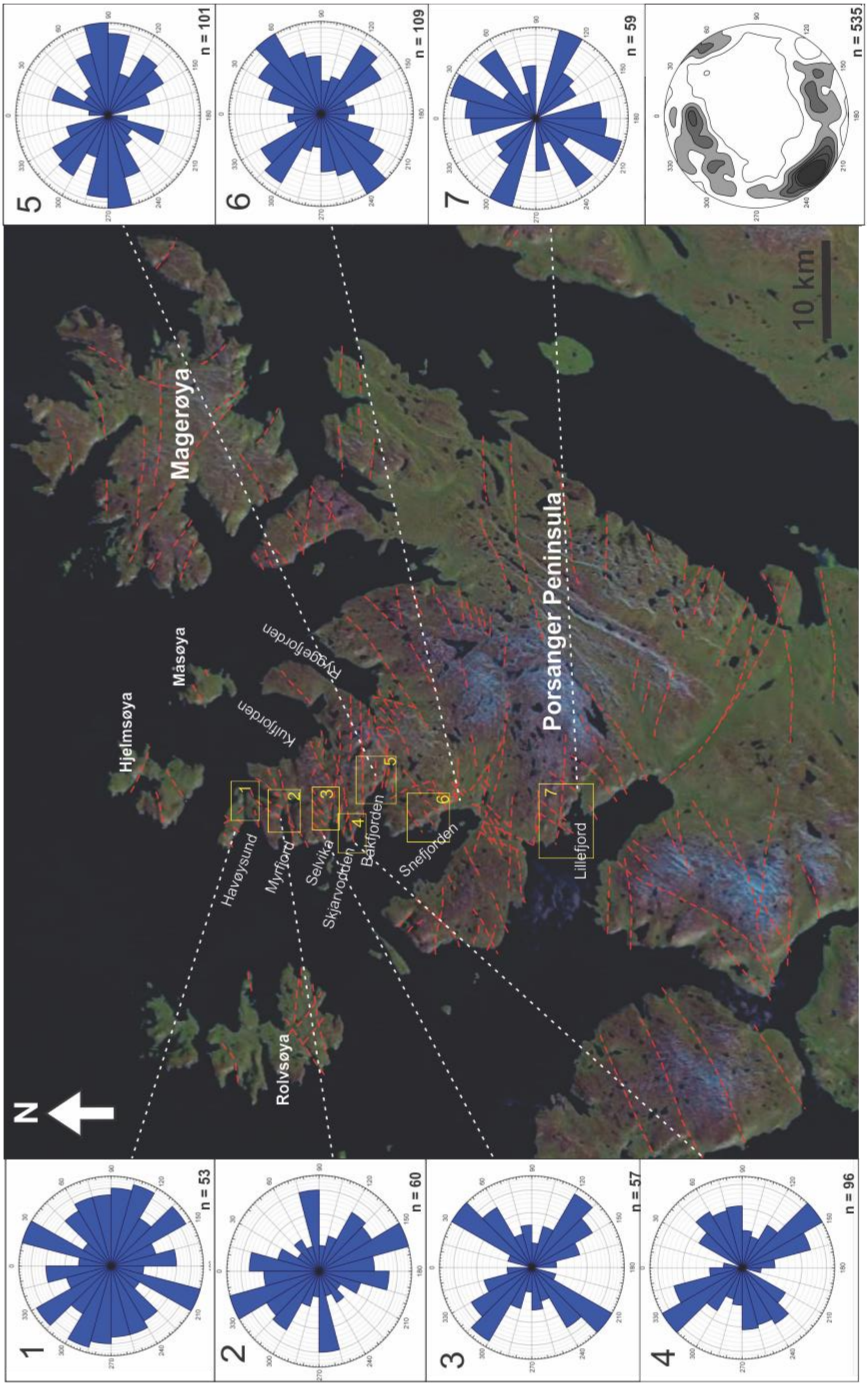

Fig. 2.1 DEM of Porsanger peninsula and onshore data of brittle faults and fractures (marked in red). Contour plot shows the main trends of all the measured fractures in the area and are NW-SE dipping NE and NE-SW dipping NW and NE. The rose diagrams show the frequency of the different fault-fracture trends for the different localitites. For more detailed stereoplots for every locality, see chapters 2.3 and 2.9.

2.2 Regional trends

DEM data and aerial/satellite photos (from norgei3D) were used to identify regional lineament trends and their geometry and to see if they can be linked to the trends and geometry of the observed and measurred fault-fractures in outcrop-scale (see chapter 2.3-2.9).

The region shows a complex pattern of lineaments expressed as steep escarpments that are clearly identifiable on aerial photographs. Especially the northwestern part of the Porsanger Peninsula, distinct brittle faults and fractures along with landscape lineaments seem to link with the brittle structures. The regional map pattern (Fig. 1.1) is dominant by three major trends of lineaments: 1) NW-SE 2) NE-SW 3) E-W. The most dominant of these three trends is the NW-SE trend (Fig. 2.1.). Field measurements of the fault - fracture surface orientations in the study area show that the dominant NW-SE trending fault-fractures are steeply dipping mainly NE while the NE-SW trending fault- fractures dip mainly NW (Fig. 2.1). These fracture sets are part of a regional pattern seen along the entire coast of northern Norway (western Troms, Lofoten and Vesterålen and further north in Finnmark) that form a rhombic shaped lineament pattern of the landscape (Eig et al., 2008). The topographic lineaments are both planar and curved and the surrounded islands, such as Rolvsøya, Hjelmsøya and Måsøya (Fig. 1.1), seem to be dominated by the same trends as the Porsanger peninsula.

The first and second lineament sets are arranged parallel with narrow fjords and bays that are defined by linear NE-SW trends and subordinate NW-SE trends (Fig. 2.1) for example Myrfjord, Selvika and Bakfjorden. These topographic trends largely overlap with visible brittle fault-fracture trends, suggesting structural control on the landscape. In map view, the NE-SW and NW-SE lineaments are predominantly straight and define a zigzag pattern. The third lineament set is arranged parallel with straight and narrow E-W striking sounds such as Havøysundet, and the straight E-W lineaments that define the topography between Havøysund and Selvika. The separateion and/or interaction of the different fault-fracture trends appears to segment the margin (see later discussion). Fig. 2.3 show a large E-W trending lineament with several NW-SE lineaments that seem to curve away from the main lineament, and form a similar horsetail splay in the area between Selvika and Skjarvodden.

The area between Havøysund and Myrfjord has a set of parallel NW-SE striking lineaments that define fjords/bays and steep escarpments that seem to be delineated and bounded by E-W striking lineaments. Some of the parallel NE-SW lineaments appear as curved lineaments and bend sigmoidally into the E-W striking planar lineaments (Fig. 2.2a). An E-W trending escarpment in Havøysund varies in height, which forms a gentle slope terrace of the topography, similar to and oblique-ramp geometry (Fig. 2.2b) (Crider, 2001). The area between Selvika (locality 3) and Skjarvodden (locality 4) has a large rhombic shaped valley defined by

ENE-WSW and NW-SE trending lineaments (Fig. 2.3). This valley has abundant NW-SE and ENE-WSW lineaments that form a set of smaller rhombic/sigmoidal patterns (Fig. 2.3a). Typically, the ENE-WSW trending lineaments change orientation along strike through the peninsula. On the eastern side, the lineaments are NE-SW oriented and curve into an E-W orientation on the western side of the peninsula (Fig. 2.3Fig. 2.3).

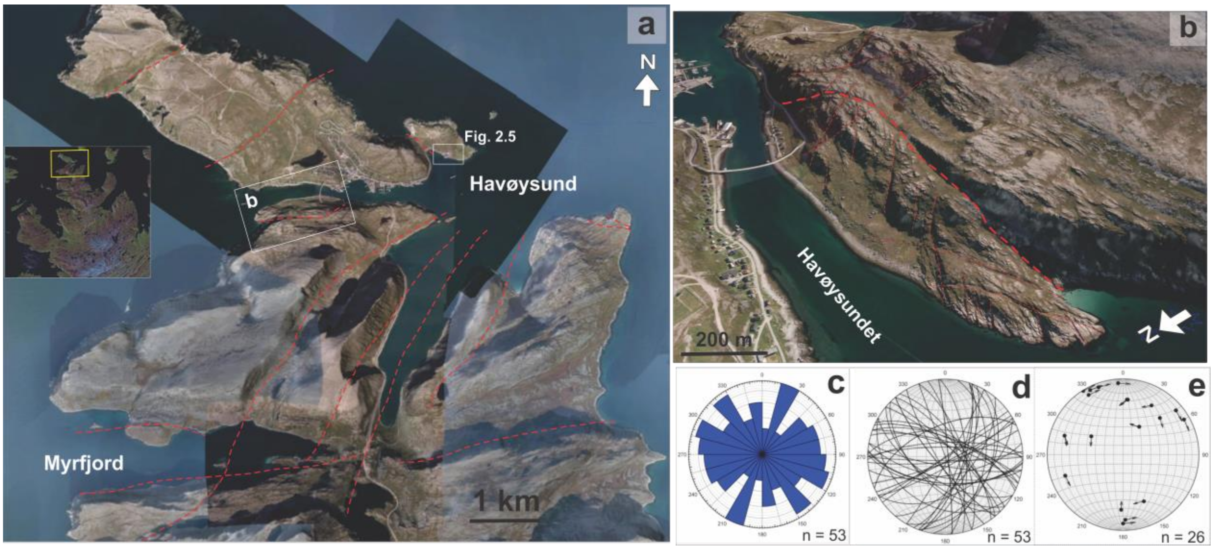

Fig. 2.2 a) Aerial image of Havøysund and Myrfjord showing two dominant trends with lineaments: NE-SW and E-W. b) E-W striking fault linkage structure parallel with Havøysundet. The fault has changing displacement laterally and increasing displacement westwards. Note that the E-W striking fault curves into a NE trend. c) Rose diagram show the frequency of the measured faults and fractures in the area. b) Stereoplot show strike and dip orientations of the fault and fractures. d) Slip-linear plot show poles to planes (marked as black dot) with directions of slip-linears for the hanging wall (marked with black arrow).

On the eastern side of The Porsanger peninsula, the fjords and bays change to a dominant NE-SW trend, such as along Ryggefjorden and Kulfjorden (Fig. 2.1).These large NE-SW lineaments trends can be traced through the Porsanger peninsula and seem to bend into a more E-W orientation (Fig. 2.3). This coincides with the distinct E-W lineaments that defines fjords and valleys on the northwestern side of the Porsanger peninsula. A good example can be seen in Bakfjorden (locality 5), (Fig. 2.3), where E-W trending lineaments dominate. Some of the parallel E-W lineaments bend toward each other and form distinct lense-shape geometries (Fig. 2.3b -2). The large E-W lineaments also seem to splay out and bend in a more NW orientation. The NE-SW trending lineaments on the eastern side can be traced on the DEM with a curved geometry towards the north in Ryggefjorden (Fig. 2.3 b). The E-W lineaments together with the NE-SW lineaments form rhombic shape patterns that are quite distinct on the DEM (Fig. 2.3c). Similar geometric patterns are also recognized further south in the Snøfjorden area.

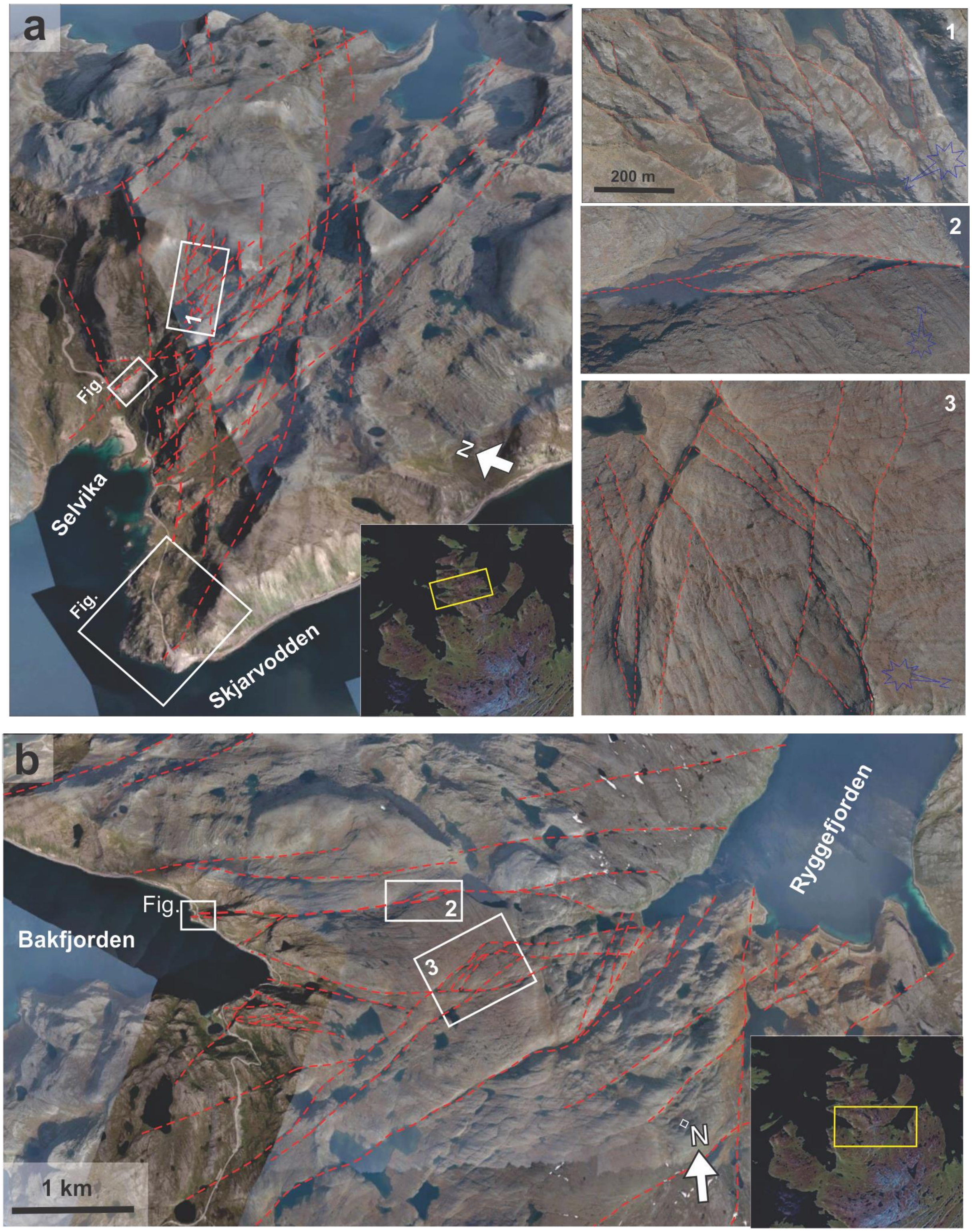

Fig. 2.3 a) Aerial photo of the area between Selvika (locality 3) and Skjarvodden (locality 4) showing rhombic pattern of NW-SE and NE-SW striking lineaments. Notice that the NE-SW lineaments bend into E-W trend westwards. 1) close up of the NE-SW/E-W and NW-SE lineaments that form rhombic geometry b) Aerial photo of Bakfjorden (locality 5) and Ryggefjorden showing the main regional trends of lineaments (marked in red) 2) A distinct lense-shape geometry between to E-W trending lineaments that merge together 3) Close up of a large-scale rhombic pattern made up of NE-SW and E-W trending lineaments.

The eastern side of Snefjorden has abundant ENE-WSW lineaments curving into a more NE-SW trend. South of Snefjord, NNE-SSW oriented lineaments with straight geometry dominating. These two trends together form a rhombic shape pattern (Fig. 2.4a and c). E-W trending lineaments are also quite distinct here and can be traced through the peninsula.

Sigmoidal/lense shape geometry along the E-W lineaments are also recognized south of Snefjord. The lense-shape zone is cut by distinct NNE-SSW lineaments with escarpments dipping NW (Fig. 2.4a and b). These sharp-parallel escarpments are interpreted to be parallel to brittle normal faults. This is supported by a high number of parallel and closely spaced NNE-SSW trending lineaments observed farther east, that may be linked to a major NE-SW fault that cuts through the area.

Lillefjorden is defined as a wedge-shaped E-W trending fjord that comprise E-W trending lineaments in the south and subordinate NW-SE trending lineaments in the north. However, internally, NNE-SSW lineaments dominate the area and have a planar geometry in map view (Fig. 2.21). Smaller WNW-ESE trending lineaments are seen along the northern side of the fjord. In smaller scale, three distinctive lineaments dominate at the shore north of Lillefjord: 1) N-S trend, 2) NW-SE trend and 3) E-W trend.

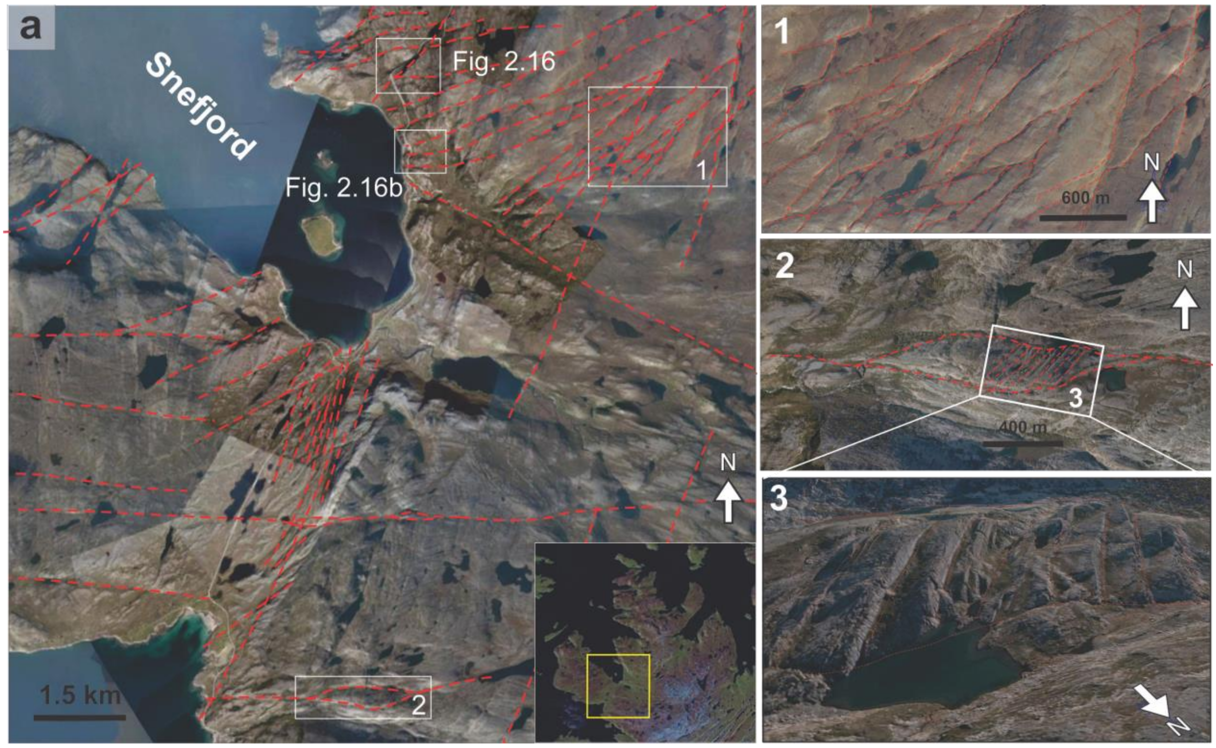

Fig. 2.4 Aerial photo of the Snøfjord area showing the main lineament trends. 1) Rhombic pattern of NNE-SSW lineaments and NE-SW to E-W lineaments. 2) A lense-shaped E-W trending fracture set seem to interact with several NNE-SSW lineaments. 3) close-up view of the NNE-SSW lineaments in the lense-shape structure in fig. 3. Note also a ca. 15 meter high escarpments parallel to the NNE-SSW lineaments. c)

2.3 Havøysund-Myrfjord

Field relations and host rocks characteristics

Havøysund is a small fishing village located at Havøya, an island that is separated from the Porsanger peninsula by a narrow E-W striking sound (Havøysundet). Myrfjord is a narrow E-W trending fjord south of Havøysund. The bedrock in the Havøysund area consists mainly of foliated mica schists and phyllites that are part of the Kalak Nappe Complex (Roberts, 1998) (see chapter 1.3) The foliation in the area are NW-SE oriented and gently dipping (30º) and Caledonian folds are overturned (almost horizontal) with isoclinal geometry. South of Myrfjord is E-W trending thrust boundary that delineates the meta-psammite (Klubben Group) (see chapter 1.3.1) from the para-gneisses (chapter 1.4.1) further south. These bed rocks are heavily affected by mainly steep E-W and NW-SE striking brittle faults and fractures (see chapter 1.5) . Myrfjord (Fig. 2.2) consists of a rusty and yellow, strongly foliated rock (schistosic texture) that predominantly consists of micas, defining an undulating, subhorizontal to gently-dipping attitude. The schist is comformable with a light-grey gneissic unit with dark bands, that could possibly be a sliver of precambrian basement in the Kalak Nappe Complex.

Description of fault and fracture geometries

In outcrop-scale, the faults and fractures in the area are mostly steeply dipping with planar geometry, but there is also faults that changes dip from steep planar to more low angle dipping surfaces. A fluctuating, not completely planar, but more low-angle NE-trending fault with minor offsets is observed in Havøysund (Fig. 2.5). This stepping fault consist of several fractures that branch together as a main fault and splays out into three subsidiary fractures. One way to interpret these geometric associations is that the individual fractures consist of two sets that display an apparent R-P Riedel-shear fracture geometry (Braathen et al., 2009). One set display en echelon geometry and is synthetic fractures with respect to the main fault surface (R-fracture), and the other fractures are also synthetic to the main fault surface, but oriented at a lower-angle (P-fracture geometry).

A large regional E-W striking steep escarpment with variable height is observed on DEM/aerial photo in Havøysund, that bounds a gently NW-dipping surface/terrace (Fig. 2.2b). The depressed area beneath the escarpment with gentle slope, defines a possible tilted surface or oblique-ramp geometry (Crider, 2001). Notably, the slope area is highly fractured and cut by NW-SE and NE-SW fractures. The interpeted E-W trending fault segment has the largest displacement towards the east and decreases in throw westwards, and can further be traced as a curved lineament toward NE in map view (Fig. 2.2b).This bend cut across the topographically higher end of the terrace and seem to link with the parallel E-W escarpment close to the road. The overall structure can be interpreted as a possible, pivotal rotated fault block bounded by oblique-ramp in a fault-linked structure (Larsen, 1988; Gawthorpe & Hurst, 1993).

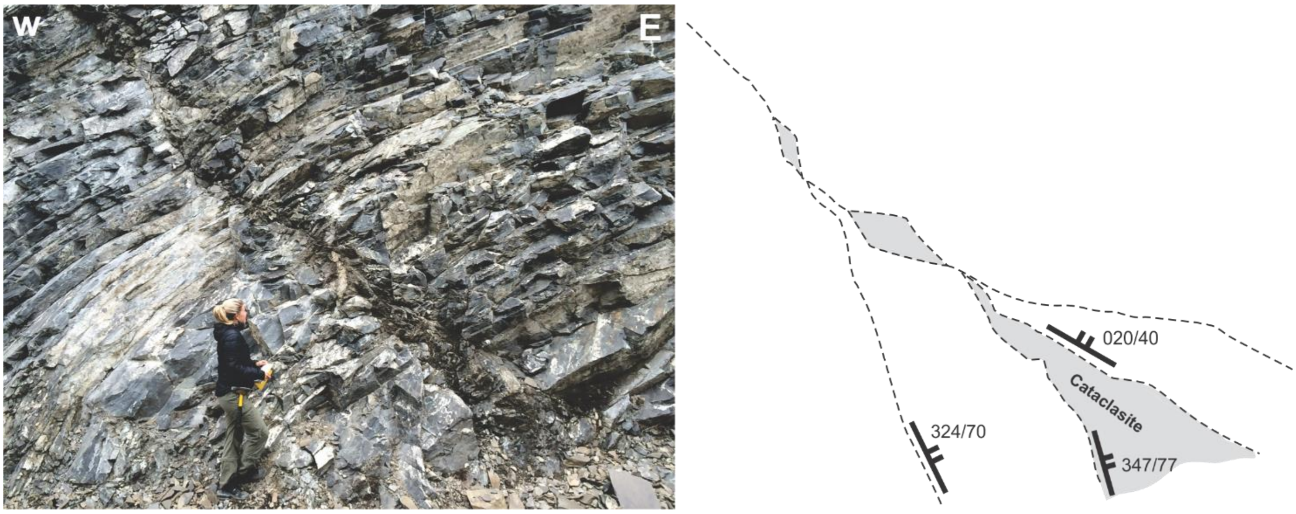

Fig. 2.5: Outcrop of foliated meta-psammites cut by a NE-SW trending low-angle, oblique-stepping fault-fracture system. The main fault trace is narrow in the upper part and split into several faults downsection, defining a horse-tail or fan-shaped fault geometry, with internal cataclasites. The fault core in the lower part of the photo varies in size and appear as rhombic shaped isolated zones with crushed cataclastic material.

Description of kinematic data and fault rocks

The area is dominated by fractures where some had mineral fibre growth along the surface, indicating they represent shear fractures (Mode II of Kulander et al. (1979)). In the road cuts, fiber lineations with epidote were present along the fault surfaces that were well exposed and a few fault rocks were observed. In Havøysund, the NE-SW stepping fault that branches into a main fault surface has three separated areas with crushed material/lenses that seem to contain both consolidated cataclasite and unconsolidated gouge material. These shape of the crushed lenses have rhombic shape that are similar to R- and P- surfaces (Braathen et al., 2009). Indication of movement along the NW striking foliation that are gently dipping (30º) is seen with mineral coating on the surfaces with well developed lineations and steps. Some of the foliation surfaces show several mineralfibres with mainly dipslip movement. Most of the E-W striking faults in Havøysund dipping south (Fig. 2.2d) with dark slickenfibres, show normal dip-slip movement (Fig. 2.2e). Oppositely dipping E-W fractures (dipping north) are observed on the south side of Havøysundet (the narrow sound), but they lack slickenside fibres and thus, cannot be contrained as conjugate sets. There are also several NW-SE trending fractures with mineral coating with no striations, indicating that they possibly represent extensional joints (Mode I).

2.4 Selvika

Field relations and host rocks characteristics

This locality is a road cut Fig. 2.6) close to the inner end of Selvika bay (Fig. 2.1 and Fig. 2.3), where brittle faults and fractures are well exposed. The area consists of paragneisses that are light-grey with banded darker amphibolite units. The banded foliation surfaces are very thin (flattened) and internally irregular, lense-shaped and anastomosing, resembling mylonitic textures, and thus likely represent Caledonian shear zones. The gneiss also comprises thin crenulation cleavage planes mostly composed of muscovite, that cut the flatlying foliation. Mafic intrusions are horizontal, parallel with the foliation and have high concentrations of large garnets. The western side of the road cut is dominated by NW-SE trending brittle faults, whereas the eastern part has more abundant NE-SW trending faults and fractures.

Description of faults and fracture geometry

The road cut is made up of gently E-dipping gneisses cut by networks of NE-SW and NW-SE trending oppositely dipping faults and fractures (Fig. 2.8a). From a distance these oppositely dipping faults in conjunction, form characteristic horst- and graben structures (Fig. 2.6A). An iron-rich oxidized marker unit in the gneisses is cut along one such fault surface and show an offset of ca. 1 meter, down-thrown into the graben Similar offset occurs along W- and E-dipping faults bounding a horst farther east (Fig. 2.6 b), with a somewhat larger displacement along this most easterly located fault. The iron-oxidized unit cannot be traced further west of the road cut, where oppositely dipping fault seem to form another horst structure.

Several NE-SW trending and SE-dipping faults, considered as synthetic since they all dip SE and merge into a major planar SE-dipping fault (Fig. 2.7a) These synthetic faults change dip from steep to more low-angle and thus display a listric geometry. The very thin horizontally laminated and foliated bedrock gneisses show cm-scale displacements along these synthetic fault surfaces, and small gaps are seen between the blocks suggesting internal block rotation along the faults. The areas in between the major fault cores in the road cut is highly fractured.

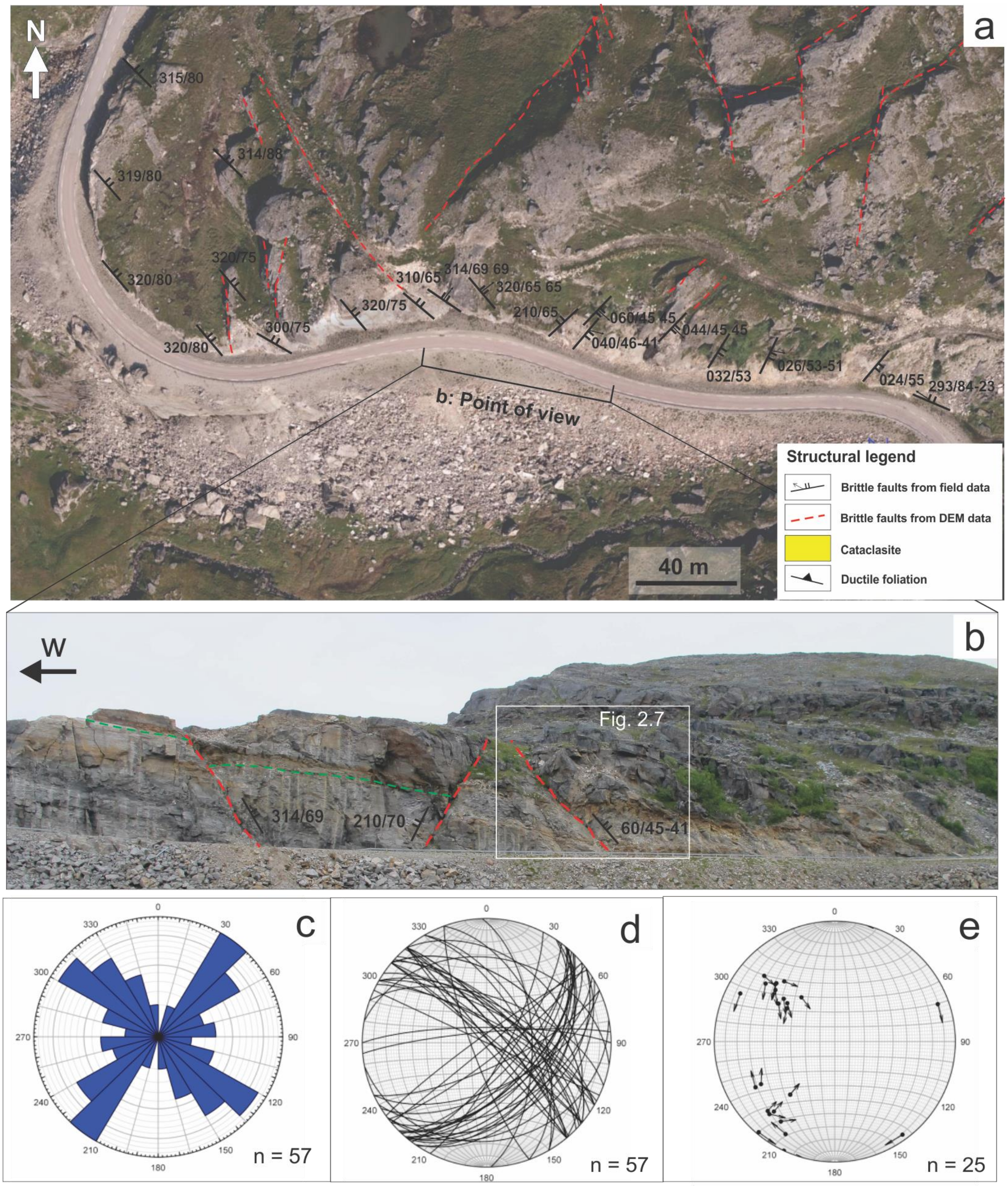

Fig. 2.6 a) Structural map of road cut in Selvika. b) Graben and horst geometries in Selvika. c) Rose diagram show the frequency of the measured fault-fractures in the area d) stereoplot show the NW-SE striking fault dip SE and the NW-SE faults dip NW e) Slip-linear plot show that the NW-SE faults have both dip-slip and oblique-slip movement with dextral and sinistral components. The NE-SW show mainly dip-slip movement.

Description of fault rock and kinematics

Fault rocks are identified on several of the horst-graben bounding faults in Selvika. They are primarily thin incohesive fault gouges with fault surfaces mineralized with chlorite, hematite and quartz. Several fault surfaces display more than one striation trend and some change along the same fault surface with different mineral precipitation (Fig. 2.7c). Most of the fault surfaces with mineral growth also had well developed steps, indicating normal, dip-slip movement on the faults (Fig. 2.7d). Selvika has fractures with a dominant NE-SW and NW-SE trend and dip NW and NE, and some show slickenside fibres that can be used to infer sense-of-shear. The slip-linear plot (Fig. 2.6 e) indicates that the NE-SW striking faults yield dominantly oblique-sinistral, normal, down-to-the-SE movement, and subordinate, both, oblique-sinistral, dextral and dip-slip, down-to-the-NE movement. Small cm-scale offsets of laminated units in the gneisses along listric NE-SW faults, indicate dextral-oblique normal movement.

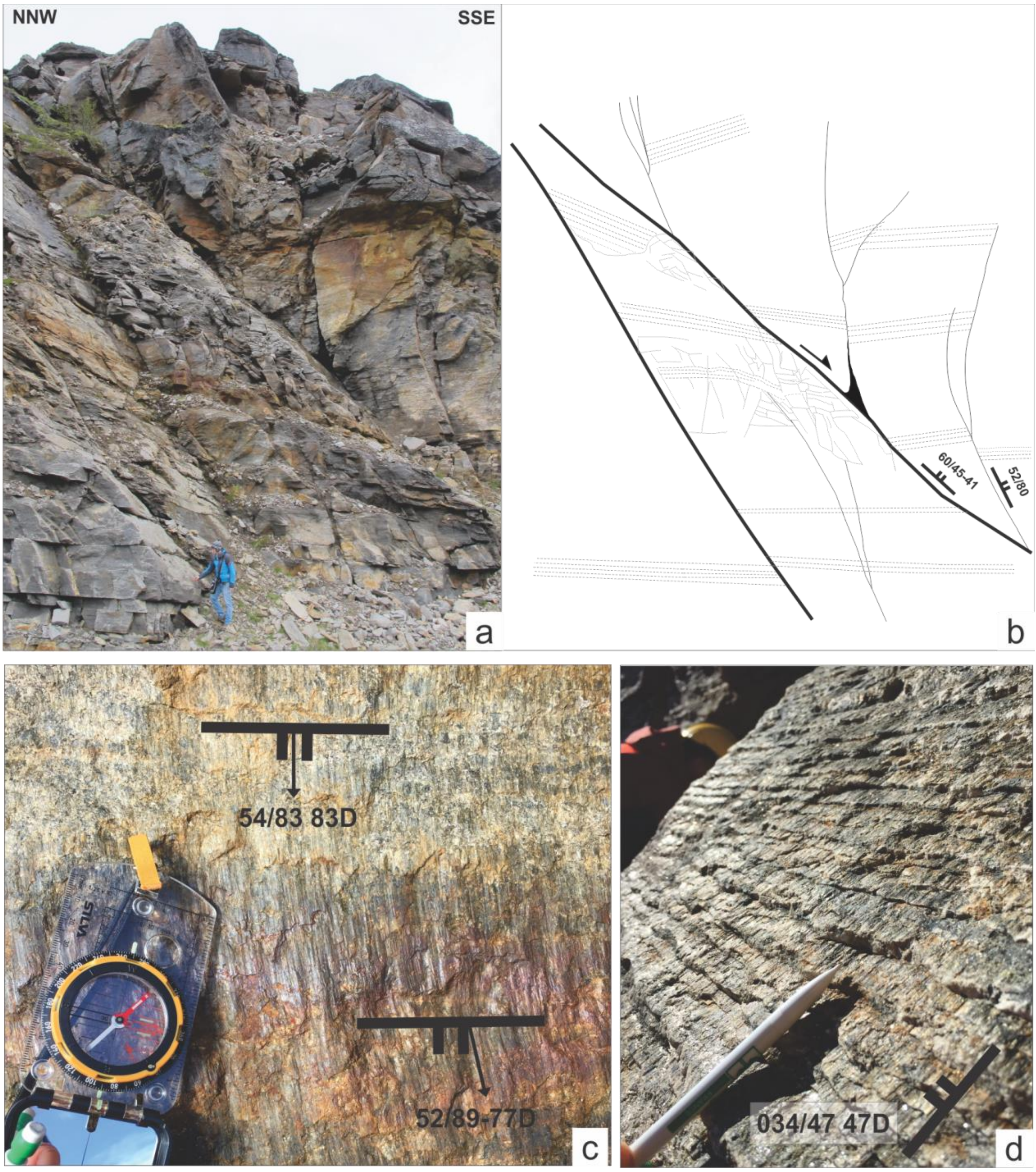

Fig. 2.7 a) Listric NE-SW faults merge into a more planar major NE-SW striking fault. d) Sketch of the picture illustrating the fault geometry and fractures better. c) NE-SW trending and SE-dipping fault with several mineral coatings (quartz,chlorite and hematite) with fiber striations that show mainly normal dip-slip movement. d) Well-developed steps of quartz and chlorite precipitation along a fault surface with slickensides showing normal dip-slip movement.

2.5 Skjarvodden

Field relations and host rocks characteristics

Skjarvodden is a headland located south of Selvika (Fig. 2.1) with well-exposed road-cuttings and shoreline areas that are heavily faulted and fractured. The bedrock in the area consist of Precambrian augen-gneisses, defined as part of the Eidvågeid granulite/migmatite sequence (Rice, 1990), which is characterised by purple garnet porphyroblasts surrounded by a strongly deformed mica-rich matrix. The gneiss has migmatitic portions with larger garnets with dark biotite rims, and K-feldspar porphyroclats are also present. The bedrock is highly fractured and covered with iron-oxidized and mineral coated fault and fracture surfaces.

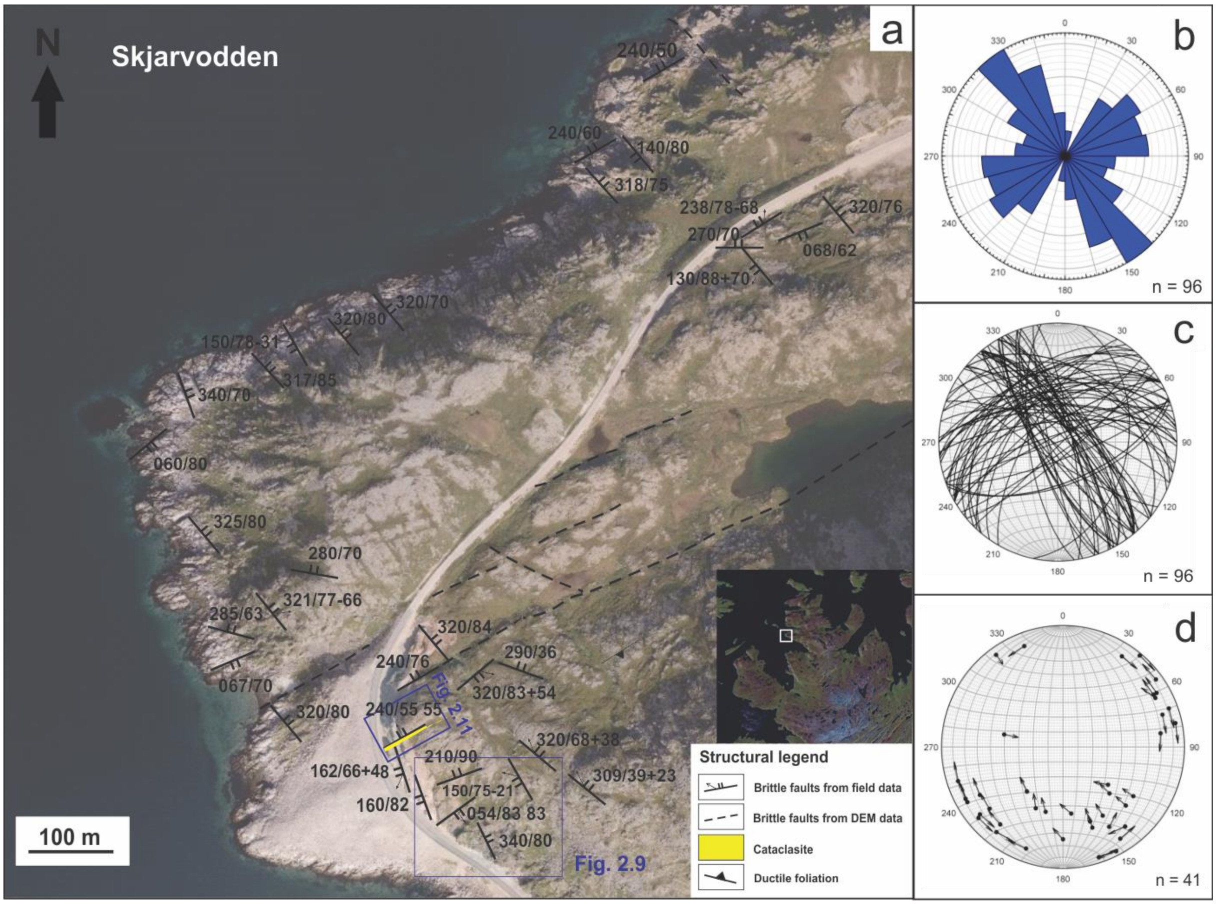

Fig. 2.8 a) Structural map of Skjarvodden. The bedrock in the area consist of paragneiss that are cut by dominantly NNW-SSE and NE-SW to E-W faults and fractures. b) Rose plot show the frequency of the fault-factures in the area c) steroplot show the strike and dip of the measured faults-fractures in the area. d) Slip-linear plot of the sickenside data recorded in the area. The NW-SE striking faults are dominantly oblique slip, with a dominant dextral movement. The NE-SW to E-W faults are dominantly dip-slip normal movement.

Description of fault and fracture geometry

There are two dominant fracture sets in Skjarvodden: ENE-WSW trending fractures dipping NW and NNW-SSW trending fractures that are dipping NW and SE. The ENE-WSW trending fractures follow the major valley, and a high number of fractures with the same trend are seen along the shore. A High frequency of NNW-SSW trending fractures predominate with planar geometry further north in the shore area. These faults are steeply dipping (60^0) to the NNW and display a distinct planar fault geometry (Fig. 2.9a). On the road cut, a high frequency of parallel E-W to ENE-WSW trending faults cut the NNW-SSE fractures and NW-SE faults suggesting that the E-W faults dipping NW is younger that the NNW-SSE and NW-SE faults Fig. 2.9a. In the shore area, NNW-SSE trending faults with opposite dips to the WSW and ENE make up graben-like geometries, and these faults can be interpreted as conjugate fault sets.

Fig. 2.9 a) Several parallel NNW-SSE faults (marked in green) and NW-SE fault (marked in red) with planar geometry are apparently cut by ENE-WSW faults (marked in white).

Description of fault rock

Several fault rocks where observed along the mapped brittle faults at Skjarvodden, mainly in the fresh road cut. The fault rocks are primarily cohesive cataclasites , incohesive gouges and brecciated host rock with surrounding fault surfaces that are mineralized with hematite, quartz, chlorite and possibly epidote.

A fault core of a steep NE-SW trending fault changes from 40 to 15 cm thickness downsection. It consists of clayish gouge material in the lower part and the crushed material gradually increases in size upwards to larger blocks/fragments of the host rock (Fig. 2.10a). Another fault zone ranging from 10-40 cm in width strikes NW-SE and dips steeply to the SE and shows a 10 cm offset of a felsic vein in the foliated gneisses (Fig. 2.10b). The fault core consist of highly fractured host rock lenses ranging from a few cm to ten cm long along with clasts and grey clayish material in between, that are possibly fault gouge. Iron oxidized fault surfaces are common where the surfaces are viewed parallel to the road cut (Fig. 2.9, Fig. 2.10 and Fig. 2.11). Such ENE-WSW trending faults may contain centimeter- wide fault cores with grey clayish material and some fractured fragments of the host rock. The fault surfaces typically display mineral coating of chlorite with well developed slickensides (Fig. 2.9). Two samples were taken along this fault (Fig. 2.11 for location) and the fault rock samples are further described below from thin-sections in micro-scale.

Fig. 2.10 a) Steep NE-SW (243/86 +85) trending fault in Skjarvodden with a fault core that is changing from 40-15 cm and is sub-divided vertically into three zones. The upper zone consists of consolidated brecciated host rocks where most of the clasts are in place. The middle zone consist of smaller crushed clasts that are unconsolidated. The lowermost zone consist of unconsolidated clay material. b) NW-SE trending fault in Skjarvodden displaying a changing fault core from 40-10 cm in width, with internal lenses of highly fractured host rock. Felsic vein (marked in red) show a small offset of 10 cm.

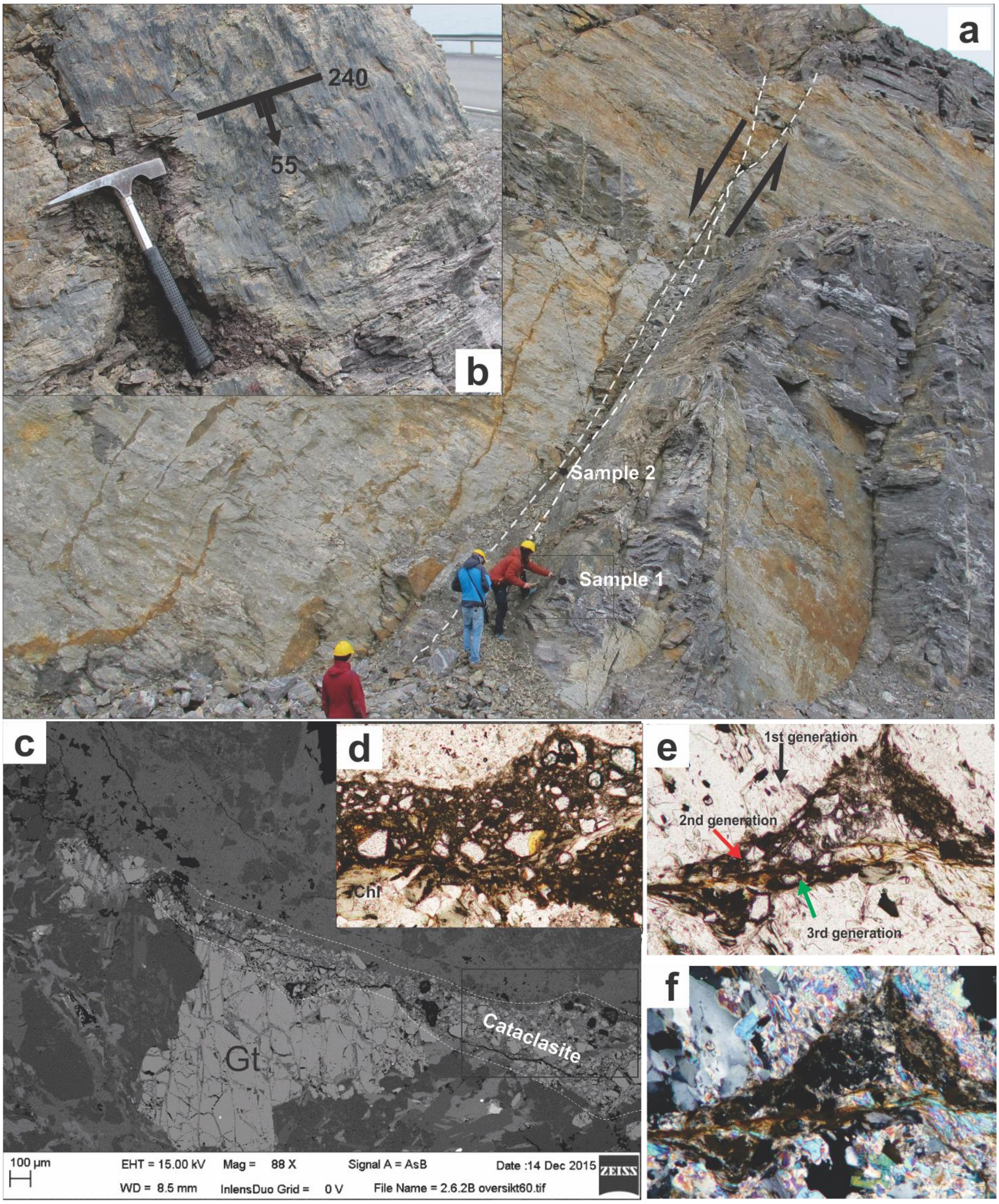

Fig. 2.11 a) Major ENE-WSW striking and NNW-dipping fault surfaces with chlorite precipitation and fibrous slickensides showing dip-slip movement. The samples of fault rocks 2.6.2B and 2.6.3 were taken from this fault, marked as black dots. b) Picture in the upper left corner show the chlorite slickensides and where sample 2:6:2B were taken. c) SEM- BSD image of the fault rock from the ENE-WSW fault zone (sample1) show cataclasite along the grain boundary of a higly fractured garnet. d) Thin-section show two generation of cataclasite. e) microphotographs show three generation of cataclasites f) same picture as c, but in cross-polarized light.

Sample 1 from fault rock in Fig. 2.11 a), is a proto-cataclasite where large grains of the host rock and its fabric are still preserved. Two possible generations of cataclasites are observed along the grain boundaries, especially at the boundary of a large garnet (Fig. 2.11 c and d). This mineral contact reveals micrograins of very fine grain dark matrix with larger and angular fragments that cut through the whole thin section, suggesting formation of the cataclasite by cataclastic flow (Passchier & Trouw, 2005). At a closer look, the cataclasite is cut by a thin iron-rich fracture with less fragments that may represent another generation/stage of brittle faulting (Fig. 2.11d). The host rock garnets have a poikilitic texture containing mineral inclusions of quartz and chlorite grains and several iron-rich fractures cut through the crystal that may be due to the brittle faulting events. Another sample (sample 2) taken from the same fault (Fig. 2.11) show three generations of cataclasites (Fig. 2.11c and d). The fist generation is mica-dominated (sericitation) and are cut by a cataclasite consisting of dark matrix with larger crushed fragments that are mainly garnets. The third generation os a thin ultra-cataclasite (matrix dominated) with iron-precipitation. The cataclastic angular fragments in the fine grain matrix seem to be an older stage of movement, while the iron-rich cataclasite cuts and “overprints” the other catclasite.

Description of kinematic data

Several surface lineations on fault slip surfaces (slickensides) where observed and measured in the field and they display well-developed corrugation steps indicating normal-slip movement and block rotation. Slip-linear plot of slickensida data from faults at Skjarvodden (locality 4) show that the NE-SW trending faults are dominated by normal, dip-slip, down-to-the-SE movement, whereas the NW-SE trending faults show dominant strike-slip dextral, down-to-the-NE movement. By contrast, offset of a felsic vein (Fig. 2.10b) indicates normal sinistral movement along the NE-SE trending fault surface in this outcrop.

2.6 Bakfjorden

Field relations and host rocks characteristics

This locality is in the inner end of Bakfjorden, and data are achieved from along the shore and in a steep E-W trending gully (Fig. 2.12 a and b) The bedrock in the area consists of mainly phyllite, mica schist and meta-sandstone with less amounts of paragneisses (on the eastern side of the fjord). All the bed rocks are cut by E-W trending brittle faults and fractures.

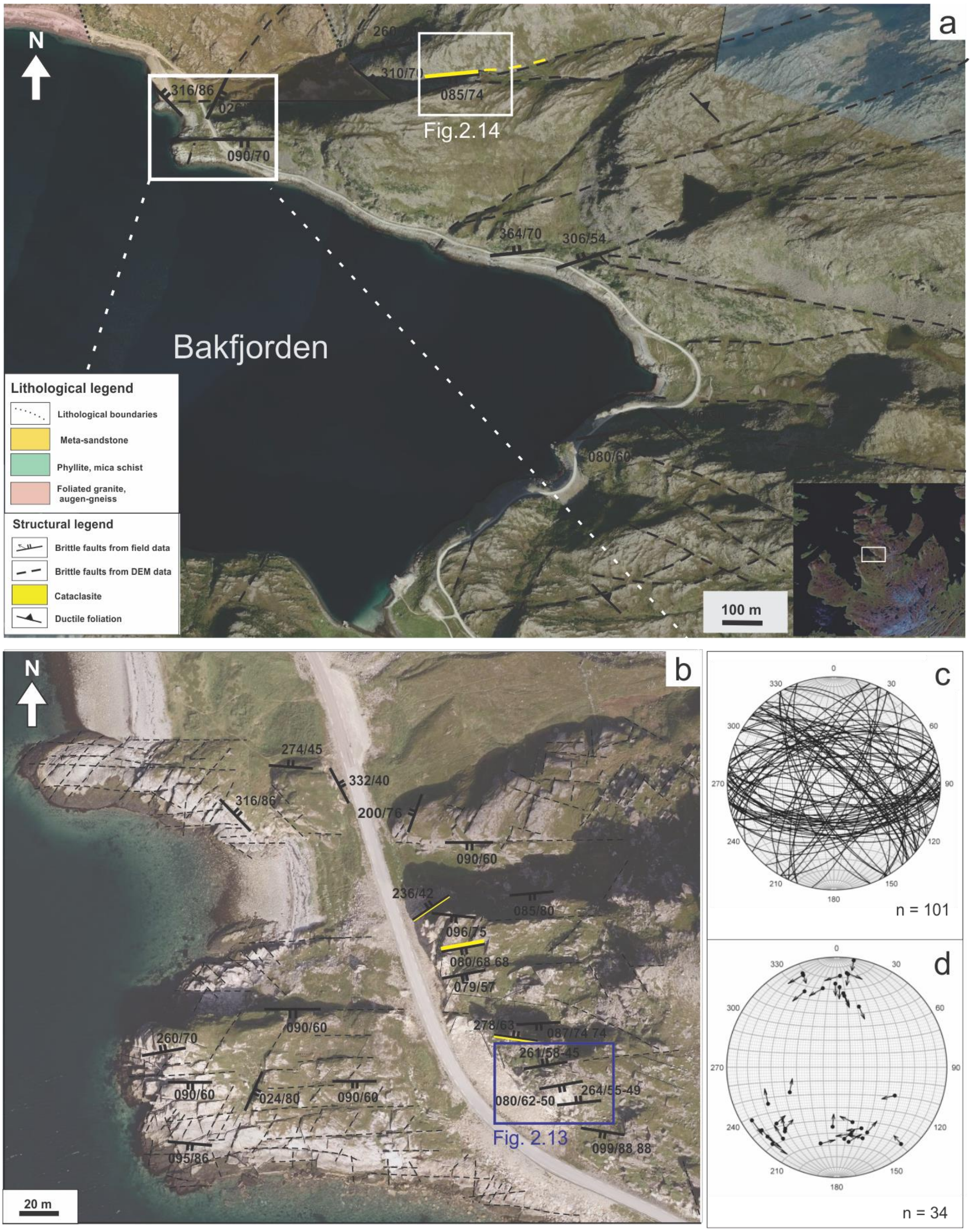

Fig. 2.12 a) Structural and lithological map of Bakfjorden area. The bedrock consist of dominantly phyllite, mica schist and meta-sandstone. The northern part of the fjord also consist of paragneisses. b) Structural map of a road cut and shoreline consisting of phyllite, mica schist and meta-sandstone that are dominantly cut by E-W striking fault and fractures, and less NW-SE and NE-SW fractures. c) Stereoplot show strike and dip of the measured fault and fractures in the area. The E-W striking fractures dip either E or W, the NW-SE striking fractures dip mainly NE and the NE-SW fracture set dip either NW or SE. d) Slip-linear plot show that the E-W striking faults dipping S are mainly dip-slip with oblique sinisitral component. The E-W faults dipping N are mainly oblique sinistral movement. The NW-SE faults show mainly oblique dextral movement.

Description of fault-fracture geometry

The mapped shore area is highly fractured and displays strong planar lineaments seen on the aerial image with a dominant E-W trend and a few lineaments curving from more WNW-ESE trends into the E-W trend (Fig. 2.12 b). There is also a high number of NE-SW trending "en echelon" lineaments that either die out along strike and/or step toward NE and merge up with minor NW-SE trending lineaments. On a smaller scale, E-W striking and oppositely dipping faults in Bakfjorden define meter-scale wide half-graben structures, where the north-dipping fault seem to have the largest offset of a marker unit of strongly foliated mica schist on top of meta-sandstones dipping southwards, thus making a graben with syntethic and antithetic normal faults (Fig. 2.13).

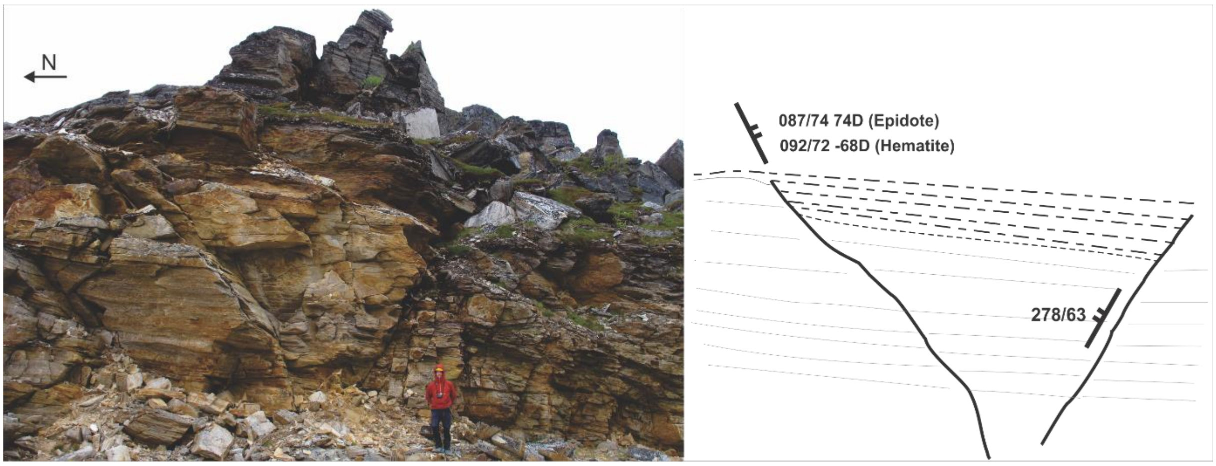

Fig. 2.13 Fig. E-W trending anthitetic-synthetic faults form graben geometry in Bakfjorden. The E-W trending fault dipping south has two different coating of possibly epidote and hemtatite. The green slickenfibres are shown in fig. 2.15b. Sketch of the picture, better illustrating the the fault geometry.

In Bakfjorden, a steep E-W trending gully is shaped by E-W trending faults and fractures dipping alternating to north and south, suggesting they are conjugate fracture sets (Fig. 2.14a). Along one of the fault surfaces, a thin fault core consist of unconsolidated clay-rich gouge material. The south-dipping fault has different alteration products along the fault surface and as well, contain two slickenside striations. One of the striations is made up of white and light-green slickenfibres (possibly epidote) indicating normal dip-slip movement (fig. 2.15b). The other has dark red (hematite) slickenfibres that show normal oblique-sinistral movement which seem to be covered with the epidote slickenfibres, suggesting that the hematite slickenfibres are relatively older.

Fig. 2.14 Steep valley in Bakfjorden shaped by conjugate E-W trending fracture sets (marked in red)). Cataclasitic rock is seen on the surface in the gullie , location is framed and seen in fig. 2.14b. c) E-W trending cataclasite in plan view located a large valley. The cataclasite have sigmoidal shape (marked with white dashed line) cut by several NE-SW striking fractures.

Description of fault rock

The fault rocks found in this area are primarily cohesive cataclasites and incohesive gouges surrounded by fault surfaces coated with chlorite, hematite, quartz and epidote and some minor biotite. Several fault surfaces display mineral growth with lineations (slickensides) and corrugation steps. There are also several fractures with mineral growth, mostly quartz without surface lineations. This was especially true for the areas close the shore where NW-SE fractures are abundant. An E-W trending fault has a 20 cm wide core conisisting of cataclasites, gouge and small fault lenses (Fig. 2.15a). The fault core has unconsolidated gouge material in the middle, ranging in thickness from 4-8 cm. Closest to the footwall, a 4 cm wide consolidated dark green alteration product (chlorite) on the fault surface has well-developed slickensides and steps indicating normal dip-slip movement (fig. 2.15b). The lenses are consolidated host rock fragments that seem to be displaced. Fault rocks is observed in the fault core in the gully, and the fault rocks display sigmoidal lense-shape geometries surrounded by anastomosing fractures filled with quartz (Fig. 2.14c). Some of the fractures have undulating geometry and change strike when merging from E-W to NE-SW trends in the area . The same lense-shape geometries are observed in regional-scale along the same lineament in map view (Fig. 2.4)

Description of kinematic data

Dominating E-W striking faults containing slickensides in the form of slickenfibres that give great indications of the sense of shear/movement of the faults. Several surfaces had well-developed steps that indicate downward movement (Fig. 2.15 b and c). The E-W fault trend dipping south has slickensided surfaces suggesting oblique dextral, normal movement (Fig. 2.12d). The E-W faults dipping north have predominately oblique sinistral, normal movement. NW-SE striking faults have slickensides that indicate oblique sinistral, normal movement with a lower component of sinistral displacement.

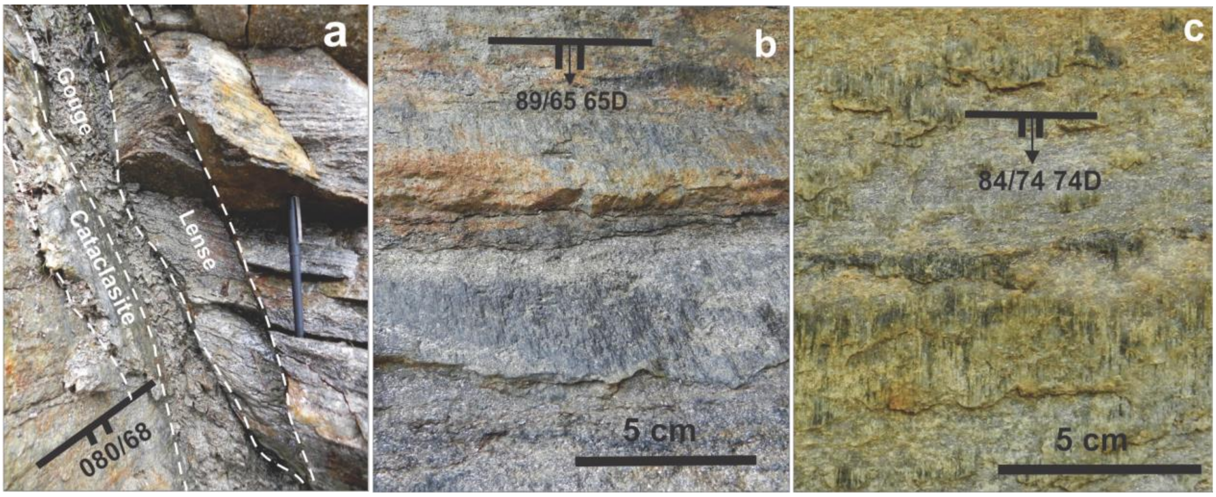

Fig. 2.15 Photos of fault rocks and kinematic indicators in Bakfjorden a) E-W trending fault with a fault core consisting of cataclasite with stiations (fig. a), unconsolidated gouge and a fault lense b) Slickensides on a E-W trending fault surface, possibly chlorite, showing normal dip-slip movement.The fault surface has well developed steps. c) Epidote/chlorite Slickenfibres with steps downward indicating normal dip-slip movement of E-W trending fault.

2.7 Snefjord

Field relations and host rocks characteristics

The mapped localities in Snefjord are two road cuts on the eastern side of the fjord (Fig. 2.4). The bedrock in the area is mainly meta-sedimentary rocks (Klubben psammite group), mica schist and phyllite with a generally flat-lying foliation. The bedrock are primarly cut by NE-SW striking faults and fractures and NW-SE fractures.

Description of fault-fracture geometry

The fault and fractures in the area are mostly steeply dipping with a planar geometry in cross-section view, whereas undulating fault and fractures are more common in map view (Fig. 2.4). Parallel sets of NE-SW trending faults dominate and link with the major lineaments with similar trends in the area. Most of the observed lineaments are narrow SE-dipping faults with slickensides indicating mainly normal dip-slip movement, but NW-SE faults and fractures with slickensides also exist. Two major NE-SW and NW-SE trendin faults are well exposed displaying an orthogonal geometry (Fig. 2.16). Notably, these fault surfaces change dip and dip direction along strike forming a possible conjugate set.

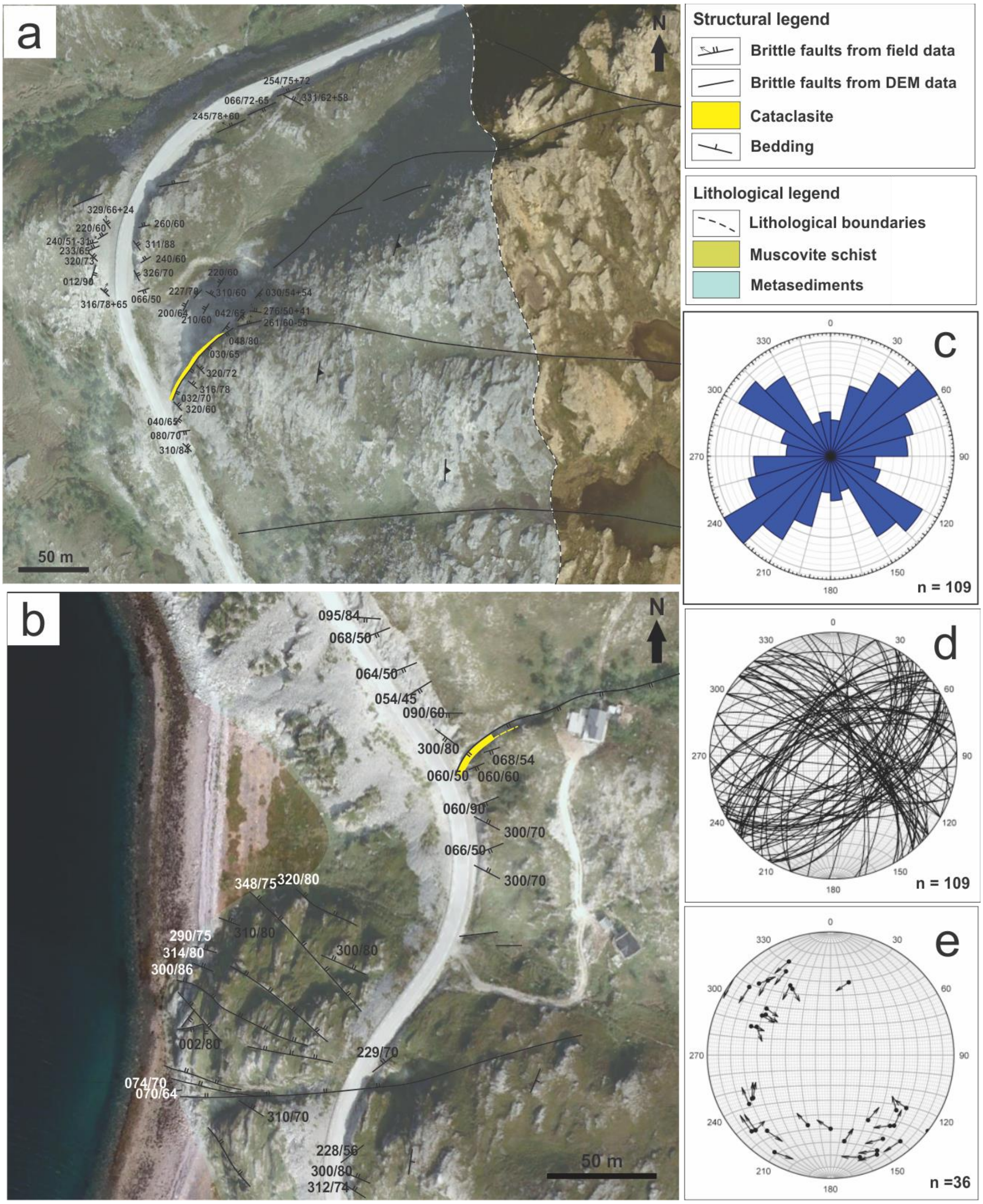

Fig. 2.16 Structural and lithological map of two road cuts on the eastern side of Snefjord. a) Road cut 1 in Snefjord showing a major NE-SW fault (Snøfjord-Slatten Fault) see Fig. 2.18. The bedrock consists of meta-sandstone and mica schist that are cut by NE-SW and NW-SE striking faults and fractures. E-W striking lineament seems to bend into parallelism with the major NE-SW striking fault in outcrop 1 (yellow line). b) Road cut 2 is dominated by meta-sandstone that are dominantly cut by NE-SW faults and fractures and less NW-SE fractures. A major NE-SW fault with a 0,5 m wide fault core consisting of different cataclastic material. See Fig. 2.19. c) Rose diagram of fractures measured in the field from both road cuts. d) Stereplot show strike and dip of the measured fractures from both road cuts. e) slip-linear plot show fault orientation data as poles to planes (black dot) with directions of slip-linears for the hanging-wall (black arrow).

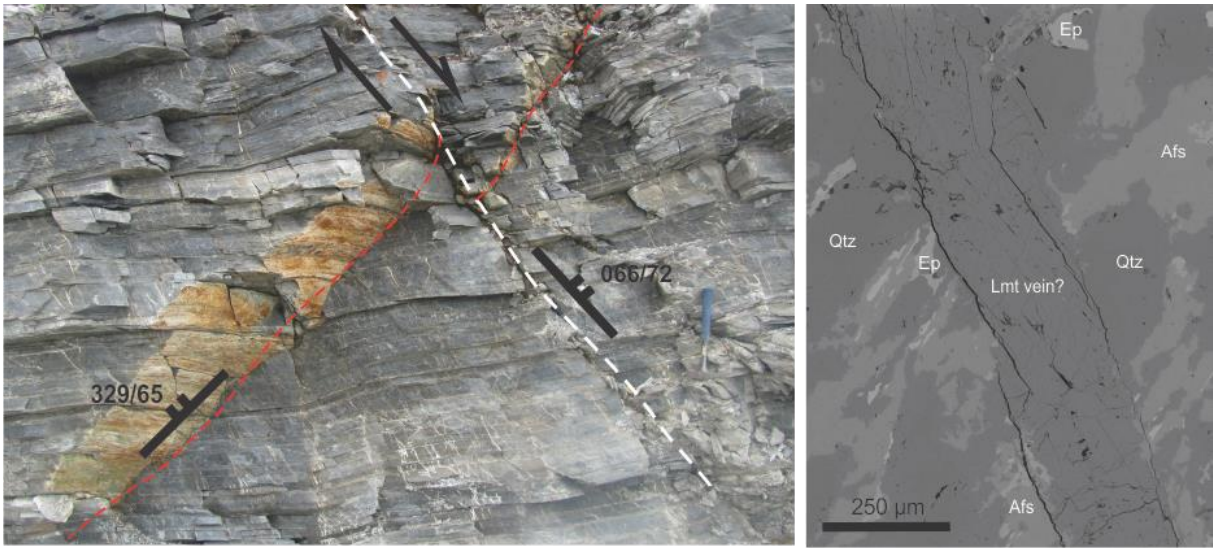

Fig. 2.17: a) Photo showing interaction between a NE-SW trending fault (marked in white) and a NW-SE trending fracture (marked in red). Note that the former is offset ca. 30 cm down-to the SE. High frequency of white small E-W oriented filled fractures with no crystalform, possibly laumontite. Arrow shows normal movement along the NE-SW fault. b) SEM image show the foliated metasandstone are cut by fractures filled with large prismatic crystals with strong cleavage that show no deformation.

Description of fault rock

Along outcrop 1 in Snefjord (Fig. 2.4d), the NE-SW trending Snefjord-Slatten fault defines a high-angle normal fault zone has an up to 2 meter wide fault core consisting of unconsolidated clay (fault gouge) material and highly fractured host rock fragments in the footwall. The fault core consists of two very thin zones of white clay close to the hangingwall and the footwall. The host rock in the hangingwall is coherent and still intact , while the foliation is still preserved in the damage zone but is more steeply dipping than the surrounding host rock (Fig. 2.18a). The displaced and highly crushed material is heavily weathered with different zones of rusty-coloured material that may represent different types of cataclasites and gouge materials. Closest to the footwall, the material consists of coarser clasts that are less crushed and the foliation is better preserved. Two samples were taken in the fault core of the Snefjorden-Slatten fault, one of the unconsolidated material (thin section 3.1-C), and one of the consolidated material that was sampled closest to the hangingwall and oriented (thin section 3.1-S). The unconsolidated cataclasite (3.1-C) consists of iron-rich precipitation (possible hematite) along the shear fracture and in the fine grain matrix that surrounds angular crushed fragments of quartz and feldspar in the fault damage zone (Fig. 2.18 c and d). On the left side of the sheared fault boundary, a host rock fragment has grains that are still preserved and in-situ, but the grain decreases in size closer to the fault core. This indicates that the fault was affected by the movement along the sheared contact resulting in crushed material (cataclasite). Several areas of very fine dark matrix in between grains indicate that fluids were injected and recrystallization occurred. Thin section 3.1-S is oriented and sampled closest to the fault surface. Remnants of magnetite crystals are present and are converted to hematite that explains the precipitation of the red-orange iron oxide found along the fractures and matrix (Fig. 2.18c and d). Fragments of the host rock have preserved fabric (foliation dominated by biotite), but there is very fine matrix found along some of the grain boundaries. The rock fragments are surrounded by crushed material in a very fine grain matrix, with local areas of hematite precipitation.

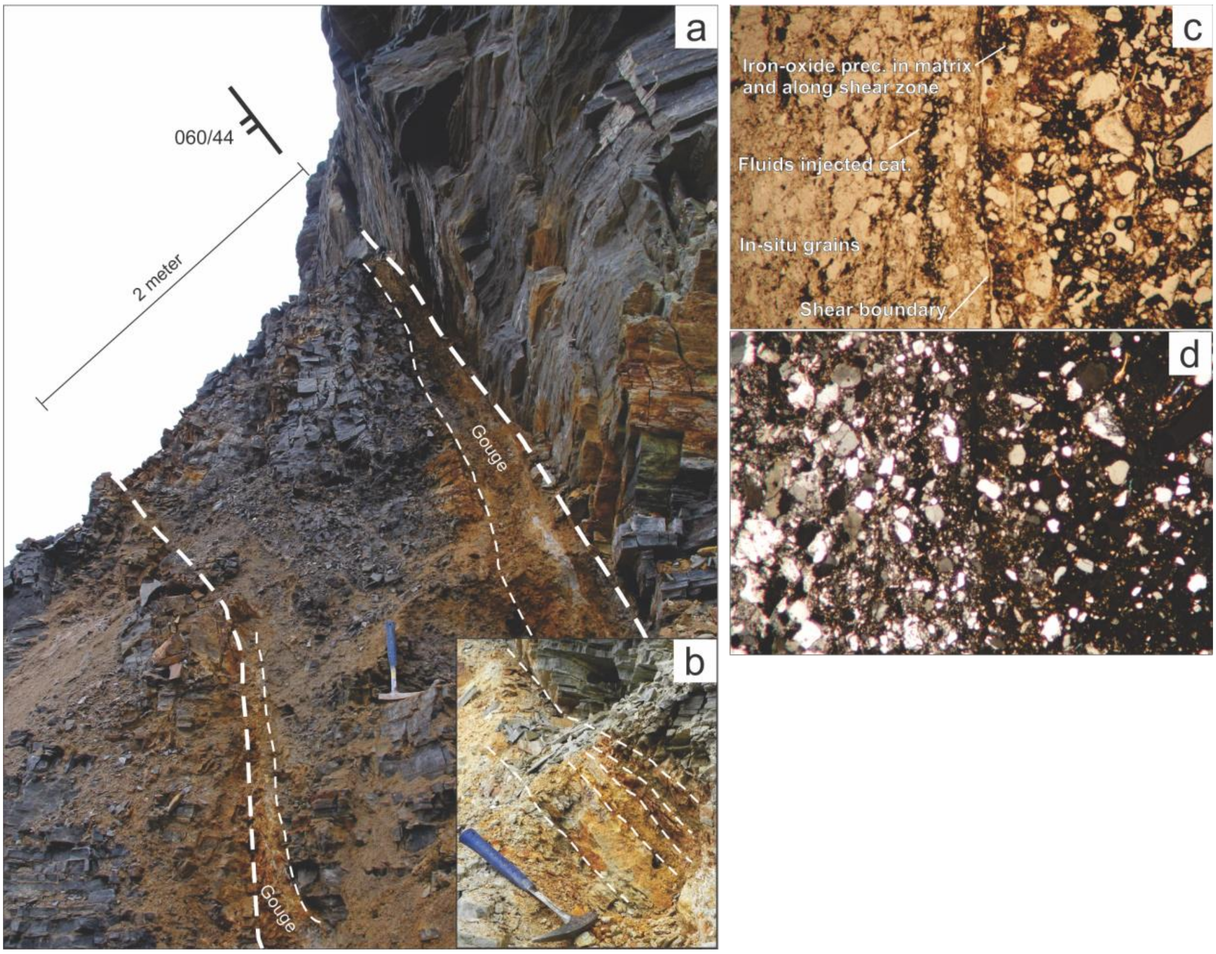

Fig. 2.18a) NE-SW trending steeply NW-dipping fault with two meters wide fault core of clay-rich gouge and cataclasite. B) The fault core consist of cataclasites of different colour and material. White zones of gouge material (clay) are seen on both ends of the core zone. The material in the fault core is crushed and fractured host rock (brecciated host rock). 3:1C and 3:1S were sampled from this fault. c) Fault rock in plane polarized light show iron oxide precipitation along shear boundary and matrix in the cataclasite. The grains in the host rock are more crushed closer to the shear boundary. d) same picture as c, but in cross-polarized light.

In addition to the major NE-SW trending fault in the Snefjord area, NW-SE trending faults are abundant, and these fault surfaces are also coated with green elongated epidote crystals and opaque hematite coating (Fig. 2.17). Small open fractures (extensional joints) are also filled with white mineral that seems to have no crystalform. In optical microscope, the minerals in the veins are colorless (in plane-polarized light), low relief, prismatic crystals and good cleavage, that could possibly indicate minerals belonging to the Zeolite group (Fig. 2.17b). Since it is difficult to distinguish among the different zeolite species based on optical properties (Nesse, 2000), SEM analysis of the vein where taken and result in a zeolite mineral assemblage (O +Si + Al+ Ca) that eliminate the Zeolite species down to Laumontite ($CaAl_2Si_4O_{12}$ $4H_2O$), Heulandite ($CaAl_2Si_7O_{18}$ $6H_2O$), Stilbite ($CaAl_2Si_7O_{18}$ $7H_2O$), Scolecite ($CaAl_2Si_3O_{10}$ $3H_2O$) and Wairakite ($CaAl_2Si_4O_{12}$ $2H_2O$) (Nesse, 2000),

Further south from the Snefjord-Slatten Fault, a NE-SW striking fault in outcrop 2 (fig. 2.5 e) has a 0.6 meter thick fault core that can be subdivided into six different cataclasites/gouge layers based on color and size of the crushed fragments (Fig. 2.19):

Zone 1: Closest to the host rock wall, and is a 10 cm wide zone of cataclasitic material with a weak planar fabric and numerous hydrothermal quartz veins.
Zone 2: A 10 cm wide zone of cataclasite with undulating fractures parallel to the fault.
Zone 3: A 20 cm wide cataclasite with light-colored clay matrix, moderately consolidated with mm-scale clasts.
Zone 4: A 1 cm wide zone consisting of white clay gouge material.
Zone 5: A 20 cm wide cataclasite that is clay-dominated, and less consolidated with cm-clasts (similar as zone 3).
Zone 6: a 2-25 cm cm wide zone of clast-dominated breccia of the host rock material.

Thin-section sampled from zone 1 shows a cataclastic fault rock consisting of multiple micro-fractures and possibly two generations of cataclasitic events are observed (Fig. 2.20a and b). The first generation is an ultra-cataclasite (matrix-dominated) with fine grain matrix and with sub-angular fragments. The second generation of cataclasite is a thin ultra-cataclsite with precipitation of iron-oxide in fractures that cut though the older cataclasite and the larger host rock fragments. The matrix contain two sets of cleavage planes, one parallel to the fault and another oblique to the fault surface, merging into each other, and thus defining a shear-band (S-C) fabric

The thin-section from zone 2 shows that the fault rock is a proto-cataclasite. Micro-faults cut through a foliated porphyroclast with dextral offsets (Fig. 2.20a and b). Along the micro-faults there is precipitation of iron-oxide. The foliated grains (old mylonitic foliation) consist of both chlorite and biotite. A fine dark matrix with larger angular fragments surrounds the porphyroclasts. There are are areas with darker matrix, possibly consisting of more opaque minerals that can represent another generation of cataclasite. A set of micro-fractures parallel to the main fault surface and another set cuts the other with approximately 40º and form a rhombic pattern (Fig. 2.20c and d)

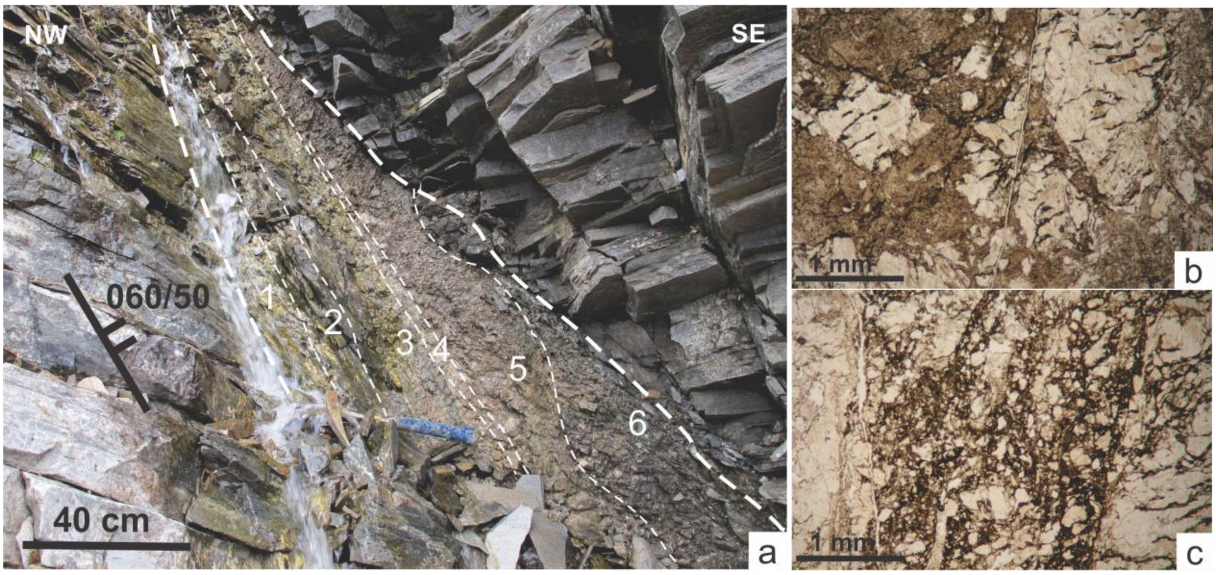

Fig. 2.19 a) NE-SW trending fault zone with fault core subdivided into six different fault products. Fig. 2.5e for location. b) Microphotograph of the sampled fault rock in zone 1 c) Microphotograph of the sampled fault rock in zone 2

Description of kinematic data

Several slickensided fault surfaces were measured both on fault/fractures parallel to the Snefjord-Slåtten fault, and on the NW-SE trending fractures, and cross-cutting relations and micro-scale kinematic data where obtained from these faults. The slip-linear plot (Fig. 2.16e) shows that there is a high number of NW-SE striking faults dipping NE with movement senses varying from strike-slip to normal oblique-dextral.

Fig. 2.17 show cross-cutting relationship of the two dominating fracture sets. A NW-SE trending fault is cut, and displaced by a NE-SW trending fault suggesting that the NE-SW trending fault is younger. Several E-W trending filled veins are also observed, suggesting they represent extensional joints formed by N-S extension. Several offsets were also observed in the oriented fault rock samples. Fig. 2.20a and b show several undulating fractures that cut a porphyroclast with dextral movement. Fig. 2.18 c and d show NE-SW micro-cractures and another set of micro-fractures form together a rhombic pattern. Iron-oxide precipitation are seen along the fractures and in the mylonitic fabric, and crushed cataclastic material in between and along the fractures indicate movement along the fracture sets.

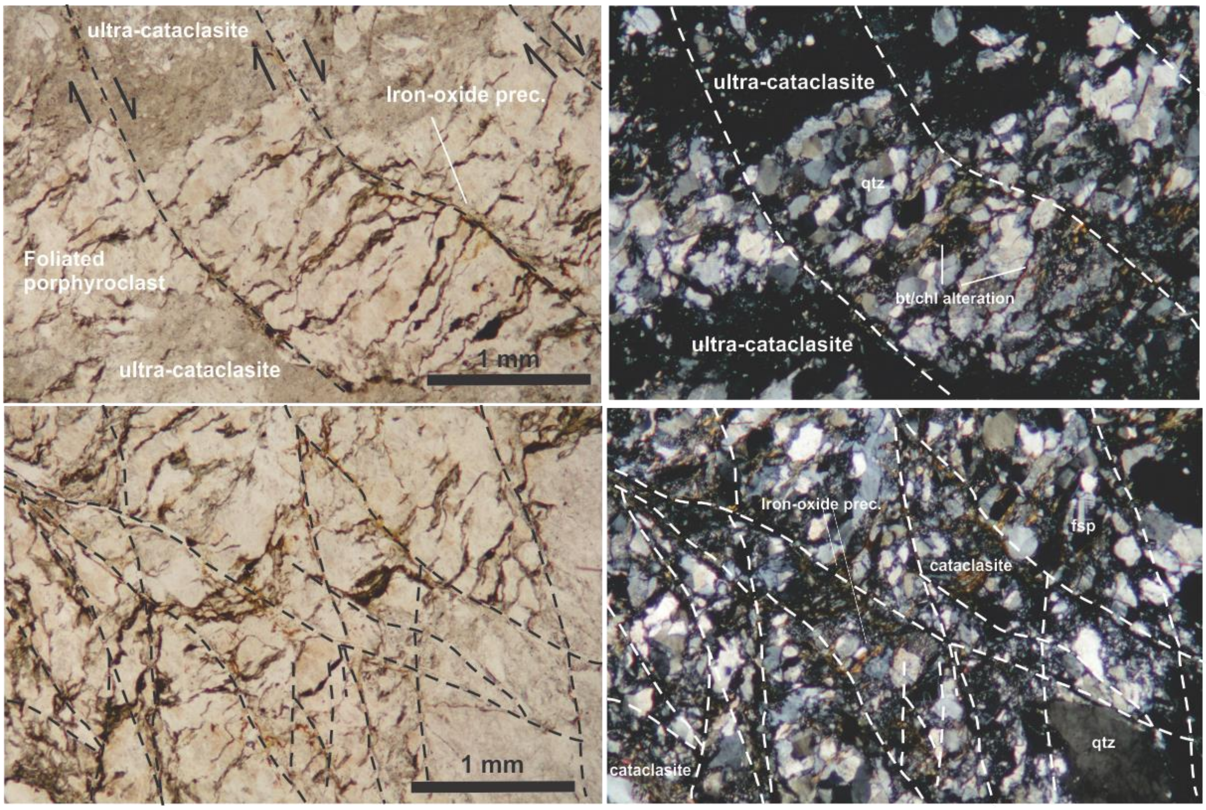

Fig. 2.20 a) Microphotograph show foliated porphyroclast with normal dextral offsets surrounded by matrix-dominated cataclasite b) same picture as a, but in cross-polarized light, c) Microfractures display rhombic pattern and cataclstic material inbetween d) same picture as in c, but in cross-polarized light.

2.8 Lillefjord

Field relations and host rocks characteristics

Lillefjord is the southernmost locality on the northwestern side of the Porsanger Peninsula and the bedrock consists of meta-sedimentary rocks of the Kalak Nappe Complex, including phyllite, mica schist, and a large intruded granite body (Lillefjord granite) (Kirkland et al., 2006). These are cut by straight and parallel NNE-SSW faults. Several small coarse grain pegmatitic dykes (Lillefjord pegmatites) are observed on northern side of the fjord and are mainly cut by NE-SW and NW-SE and E-W striking fractures.

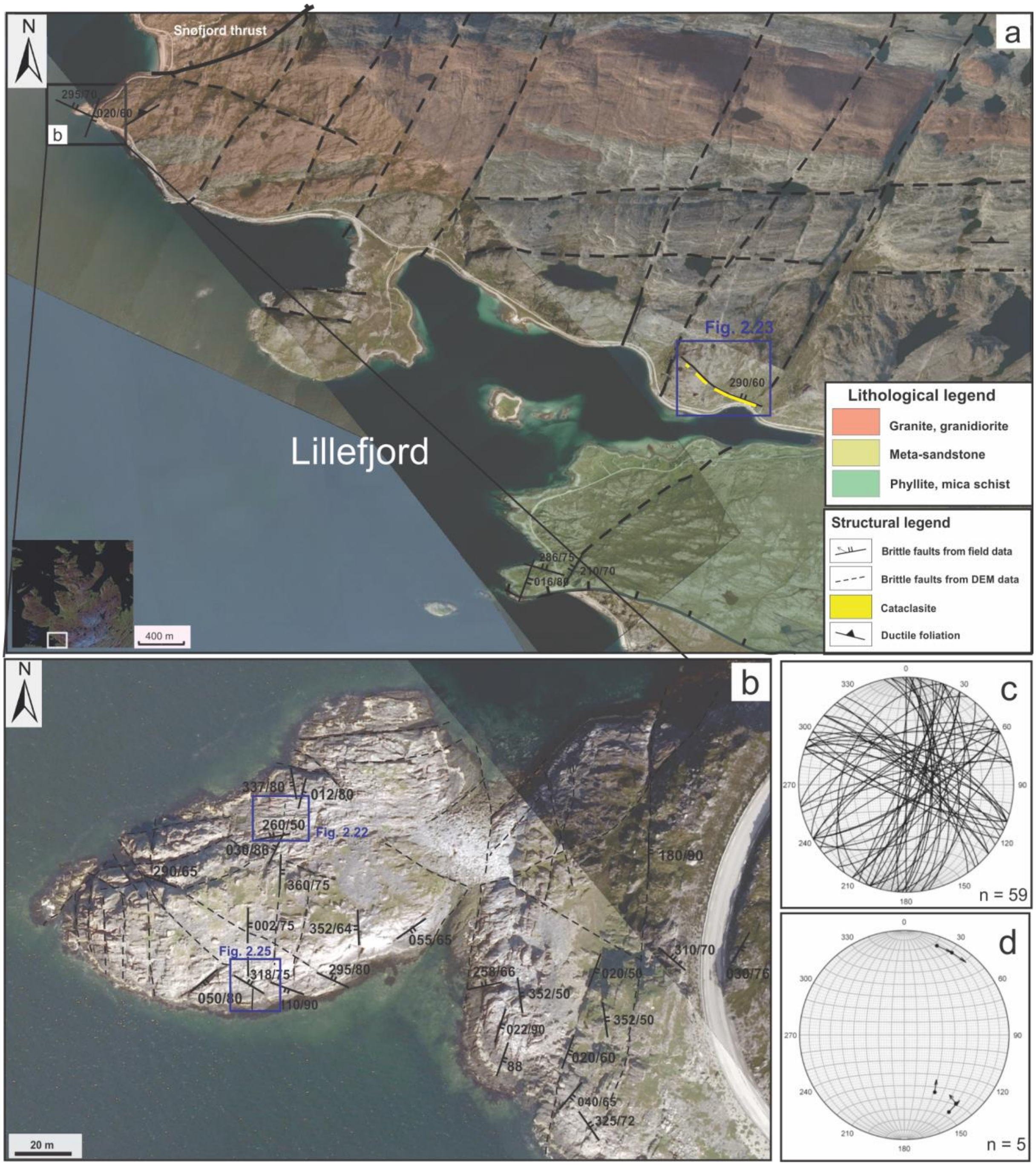

Fig. 2.21 Structural map of Lillefjord (locality 7) a) smaller-scale of a mapped outcrop in Lillefjord showing three main fracture sets (N-S, NW-SE and E-W) b) NW-SE fault cut and displace a N-S trending quartz vein.

Description of fault-fracture geometry

Faults and fractures observed in outcrops at Lillefjord are generally steeply dipping with a planar geometry in cross-section, but low-angle surfaces also exist. In map view the NNE-SSW faults and fractures predominantly display straight geometry and are parallel. NW-SE and E-W trending faults have undulating geometry (Fig. 2.21). A High frequency of N-S fractures is seen along the shore on a small peninsula and they display planar geometry and are steeply dipping (Fig. 2.21). Conjugate fractures are also present (Fig. 2.22), and are subvertical (steeply dipping) with planar geometry. The NNE-SSW and NNW-SSE conjugate fractures cut a distinctive white pegmatite dyke that shows lateral displacement suggesting that these fractures are conjugate strike-slip faults. The NNE-striking fracture are precipitated with quartz and show largest displacement (15 cm) of the pegmatite dyke. The NNW-SSE fracture offsets the dyke with 7 cm.

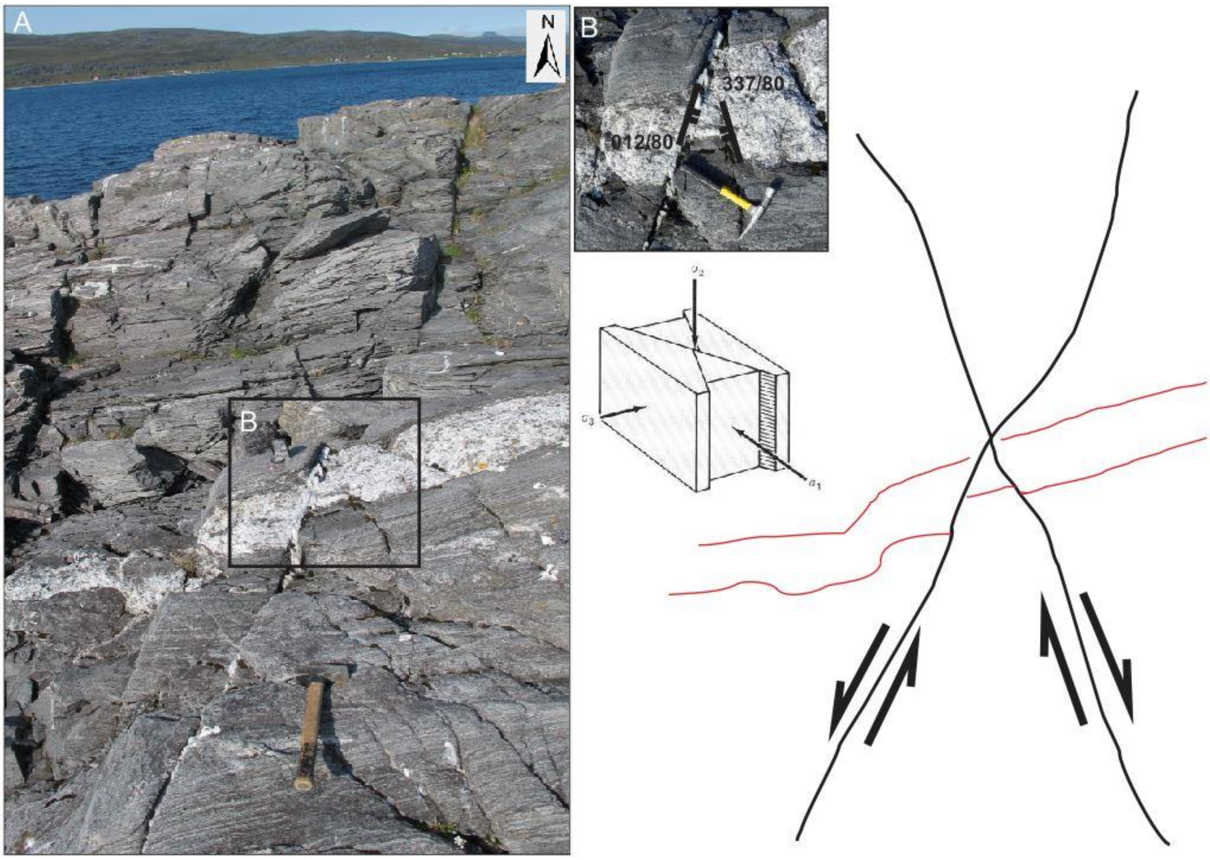

Fig. 2.22 Outcrop along the shore in Lillefjord showing brittle faults, fractures and cross-cutting relationships. A) a subvertical E-W striking pegmatitic dyke is offset sinistrally by a younger NNE-SSW striking fracture, and dextrally by NNW-SSE trending faults. . The NNE-SSW striking fault is precipitated with quartz. See location fig. 12. Sketch of the picture illustrating the fault geoemtry better The pegmatite marked in red and the conjugate strike-slip fault are marked in black. The black arrows show dextral movement on the NNW-SSE striking fault and sinistral movement on the NNE-SSW striking fault. The block diagram show the paleostresses of conjugate strike-slip faults. Maximum stress (sigma 1) axis is oriented N-S.

Description of fault rock

A major WNW-ESE (290/70) trending fault with fault gouge have been traced along the valley in the region (Lillefjorddalen). In cross-section view, minor faults with trends parallel to the valley show offset of marker units in the gneisses and local bending of the ductile foliation into the faults (Fig. 2.23). This suggest: (1) that the brittle fault overlaps with a semi-ductile, drag-folded ductile shear zone in the Caledonian rocks, and/or (2) that the fault was not fully brittle. Using the drag folds as a kinematic indicator alone, would suggest normal down-to-the movement along the fault surface, thus supportive of the second interpretation. Notably, the host rock in the hangingwall is much darker in color than rocks in the footwall suggesting large displacement along the fault. In the fault core, a large block with mylonitic fabric parallel with the fault surface is present. The host rocks has a different foliation than the rotated and displaced lense in the fault core. The fault core also consists of cataclastic material and unconsolidated fine-grained material that are possibly gouged. Samples from this fault core (3.4) show a foliated ultra-cataclasite. Several generations of cataclasite can be identified and show evidence of structures that are formed in both ductile and brittle regimes, thus confirming observations seen in outcrop-scale, such as the foliation-drag folding along the fault surface (Fig. 2.23). In between parallel quartz veins, a dark cataclastic zone of very fine grain matrix with crushed angular fragments has the same orientation as the fault surface. One type of matrix in the cataclasites is pale green in plane-polarized light and may be chlorite-rich, but the grains are to fine to identify. When applying SEM analysis, this cataclasite shows three different fine-grain matrix components with different color, based on the heavy-metal contents (the lightest color indicates highest content of iron-rich minerals). The most dominant matrix is chlorite-rich, second is a mica-rich matrix (sericite) and the third and less dominant is a phosphate-rich matrix. Several clasts show sigmoidal structures (sigma clasts and fish structures) with dextral shear movement.

Three sets of fractures are observed in the thin-sections of this fault rock cataclasite (Figs. 2.21 and 2.22), and they are described relative to the slip-surface of the fault, applying the Riedel shear terminology (Fossen & Gabrielsen, 2005) (See chapter 1.7 for defenition).

1) En echelon arrays that are synthetic fractures to the main fault surface, defined as R-shears (Fossen & Gabrielsen, 2005).
2) Synthetic shears with lower angles than the R-Shears, defined as P-shears (Fossen & Gabrielsen, 2005).
3) Extensional fractures filled with quartz, defined as T-shears (Fossen & Gabrielsen, 2005). (Fig. 2.24).

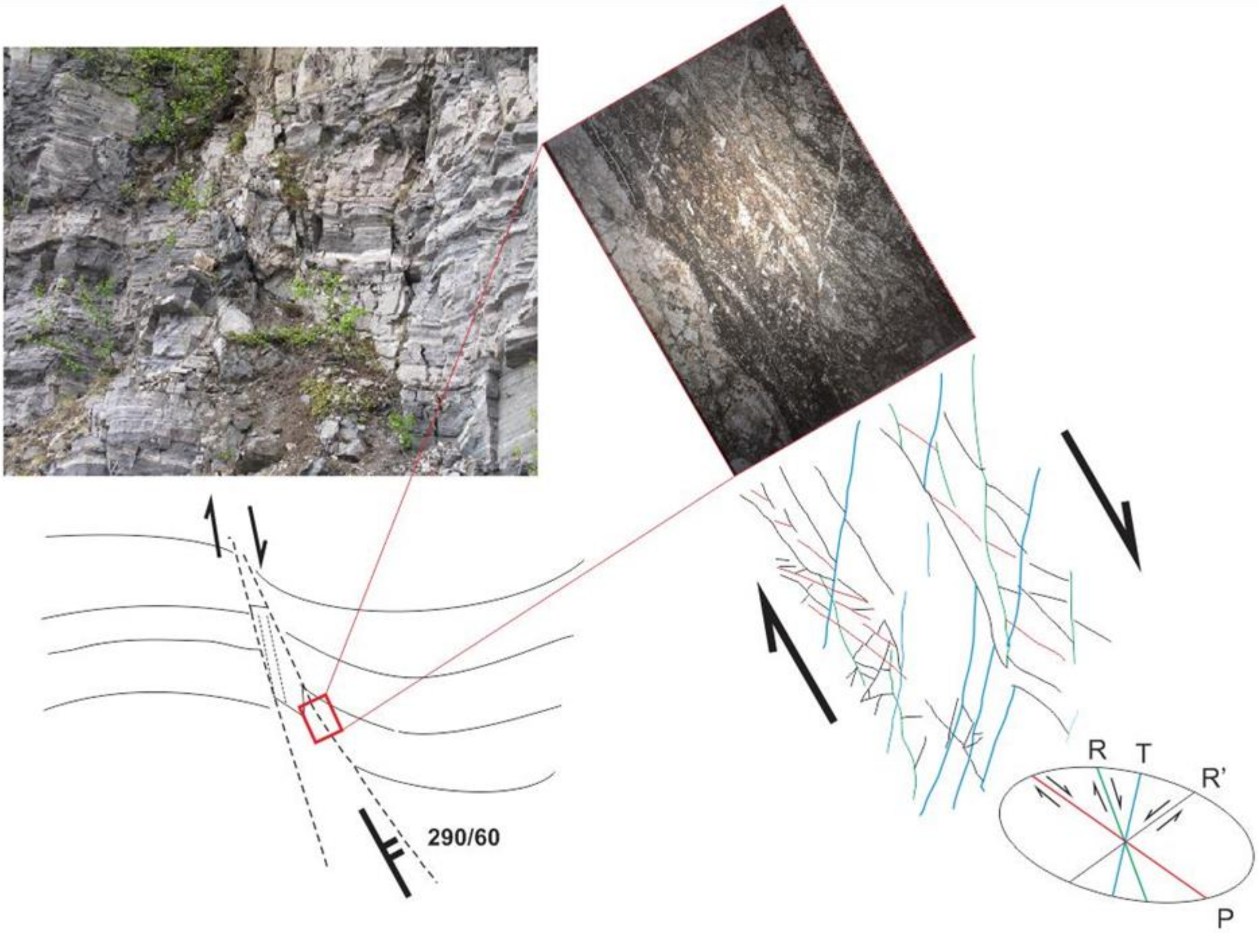

Fig. 2.23 WNW-ESE striking fault in Lillefjord show drag-folding along the fault surface. Sketch below to show the geometry better and the location of sample 3.4 (framed in red). The thin-section indicate several shear fractures that are interpreted as riedel shears (R-fractures, P-fractures and T-fractures).

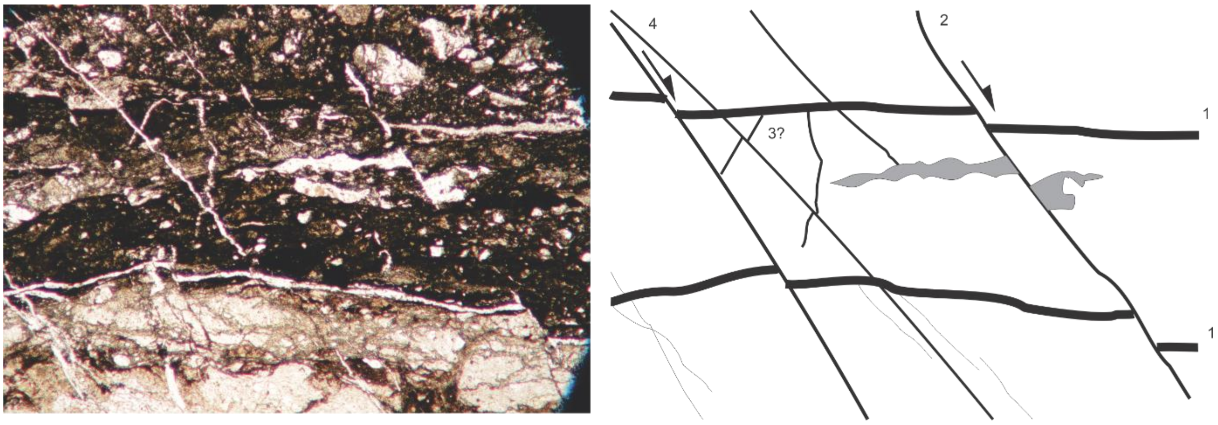

Fig. 2.24 show fault rock from WNW-ESE fault in Lillefjorden. Cross-cutting relations show four different stages of extentional quartz veins.

Description of kinematics and relative age

Several kinematic indicators where observed adjecent to brittle faults and fractures in Lillefjord, but very few slickensides were gathered compared to in the other localities (Fig. 2.21d). The movement of the main slip surface of the fault in Fig. 2.23 have been determined by possible semi-ductile drag-folding in addition to internal brittle fault-block rotations, and kinematic data of potential Riedel shear structures. Drag folding/rotation of layering blocks was observed along the WNW-ESE fault (Fig. 2.23). Kinematics in micro-scale from thin-section analysis showed subsidiary fractures interpreted as Riedel-shears (Rutter et al., 1986; Dresden, 1991).The subsidiary shear fractures (R, R´, P, Y and T) orientation relative to the slip surface can also be used to determine the overall sense of slip within a large brittle fault-slip- system. Cross-cutting relationship and offset marker units in the gneisses were also observed in the area and give relative age of the faults and sense of shear.

The slip-linear plot (Fig. 2.21d) shows NW-SE striking faults with strike-slip dextral movement and NE-SW striking faults dipping NW with normal dip-slip and oblique-sinistral movement. Some of the faults appear to have a ductile component due to the foliation drags along WNW-ESE fault indicating dextral shear (Fig. 2.23).

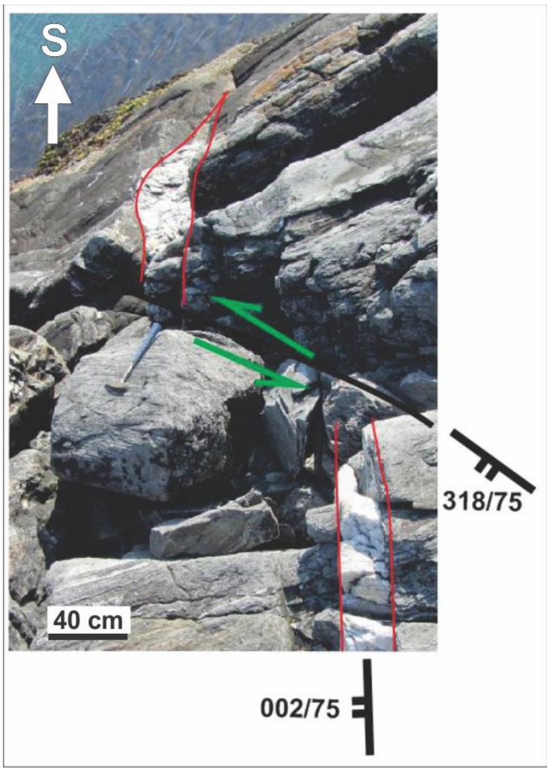

Fig. 2.25 A N-S striking felsic vein are cut and displaced laterally (1 meter) by a NW-SE fault and show sinsitral movement.

Vein offsets was seen in both outcrop-scale and micro-scale. In the shore area north of Lillefjord (Fig. 2.22b), cross-cutting relations demonstrate that NNE-SSW and NNW-SSE trending, inferred strike-slip conjugate faults, cut an E-W trending pegmatitic dyke that show lateral displacement, suggesting maximum stress (sigma 1) axis oriented N-S (Fig. 2.22) The NNE-striking fracture is coated with quartz and traced further south where it is sinistrally offset by a NW-SE trending fault (Fig. 2.25) This suggests that the NNE-SSW trending fault is older than the NW-SE trending fault. The anastomosing pattern of brittle faults seen in thin-section (Fig. 2.23) is interpreted to be formed by the interaction of R- and P-shears. Then a quartz vein parallel with R- and P-shear is cutting through, and sigmoidal clasts with same orientation show dextral movement. A set of antithetic quartz veins (T-shear) cuts in a later stage. This third fault generation cut the cataclasite that have the same orientation as the WNW-ESE fault surface and form half-graben structures with dextral offset (Fig. 2.24).

2.9 Magerøya

Field relations and host rock characteristics

The main study area is Porsanger peninsula but during the fieldwork, a few outcrops on the western side of Magerøya (Figure 2.26) was visited and some observations of fault geometry, fault rocks and kinematics are included for comparision. The island contains mostly of rocks belonging to the Magerøy Nappe underlyin by the Gjesvær Migmatite Complex that have been assigned to the Kalak Nappe Complex (Ramsay & Sturt, 1976; Andersen, 1981).

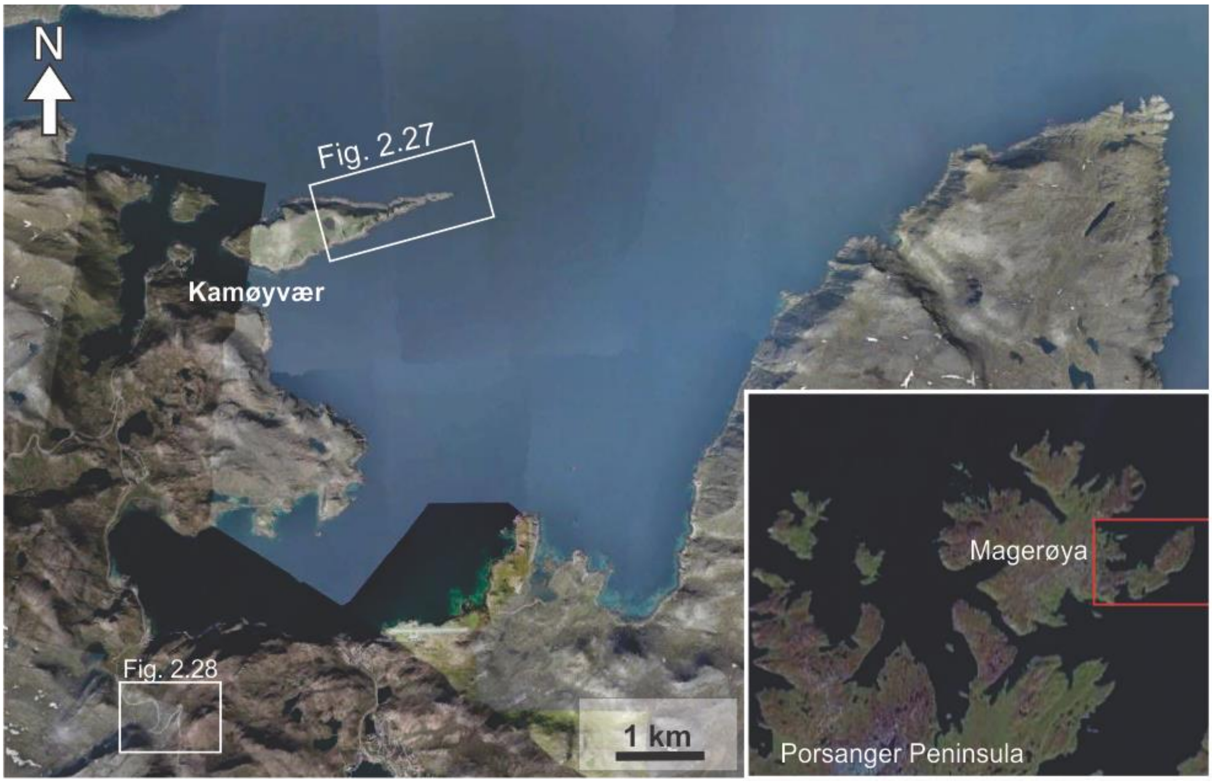

Figure 2.26 Aerial photo of the western side of Magerøya, showing the visited areas (framed in white).

Description of fault-fracture geometry

Close to Skarvåg in Magerøya, are two set of lineaments observed on aerial images and during fieldwork (Fig. 2.27). The lineaments are characterized by planar geometry in both cross-section and in map view and N-S lineaments define the topography as sharp individual blocks dipping west with domino geometry. The NW-SE lineaments dipping NE. In cross-section, these to lineaments trends appear as synthetic-anthitethic faults that form graben geometries. A distinctive light colour bed (Fig. 2.27) seems to be cut and displaced along the N-S lineament suggesting normal faulting.

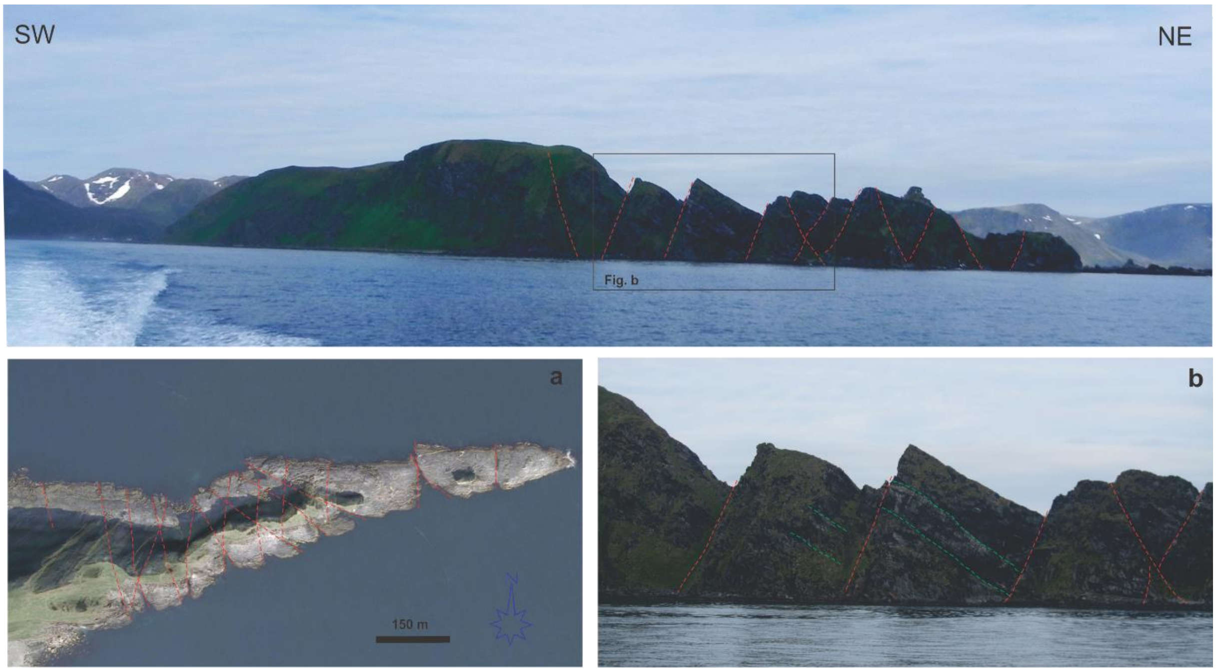

Fig. 2.27 N-S and NW-SE striking lineaments dipping towards W and NE in Magerøya. a) Aerial photo show the orientations of the lineaments in map view. b) Possible bed-marker (marked in green) show displacement along the NNE-SSW lineaments.

Fault rock and kinematics

A 0,5 wide NW-SE fault core consist of cataclasite precipitated with white minerals inbetween the crushed clasts. In thin section, the fault rock consist of crushed material with fractures filled with quartz, calcite and with similar to the zeolite minerals (laumontite) that where observed in fractures in Snefjord (Fig. 2.17). These minerals have strong cleavage, low birefringence and colourless in plane–polarized light and with elongated crystals to the orthogonal veins indicating precipitation and growing in opening extensional fractures. The veins in which the laumontite precipitated seem to be affected by further cataclastic deformation, indicating a late syn- and post laumontite metamorphic facies stage of cataclastic fracturation.

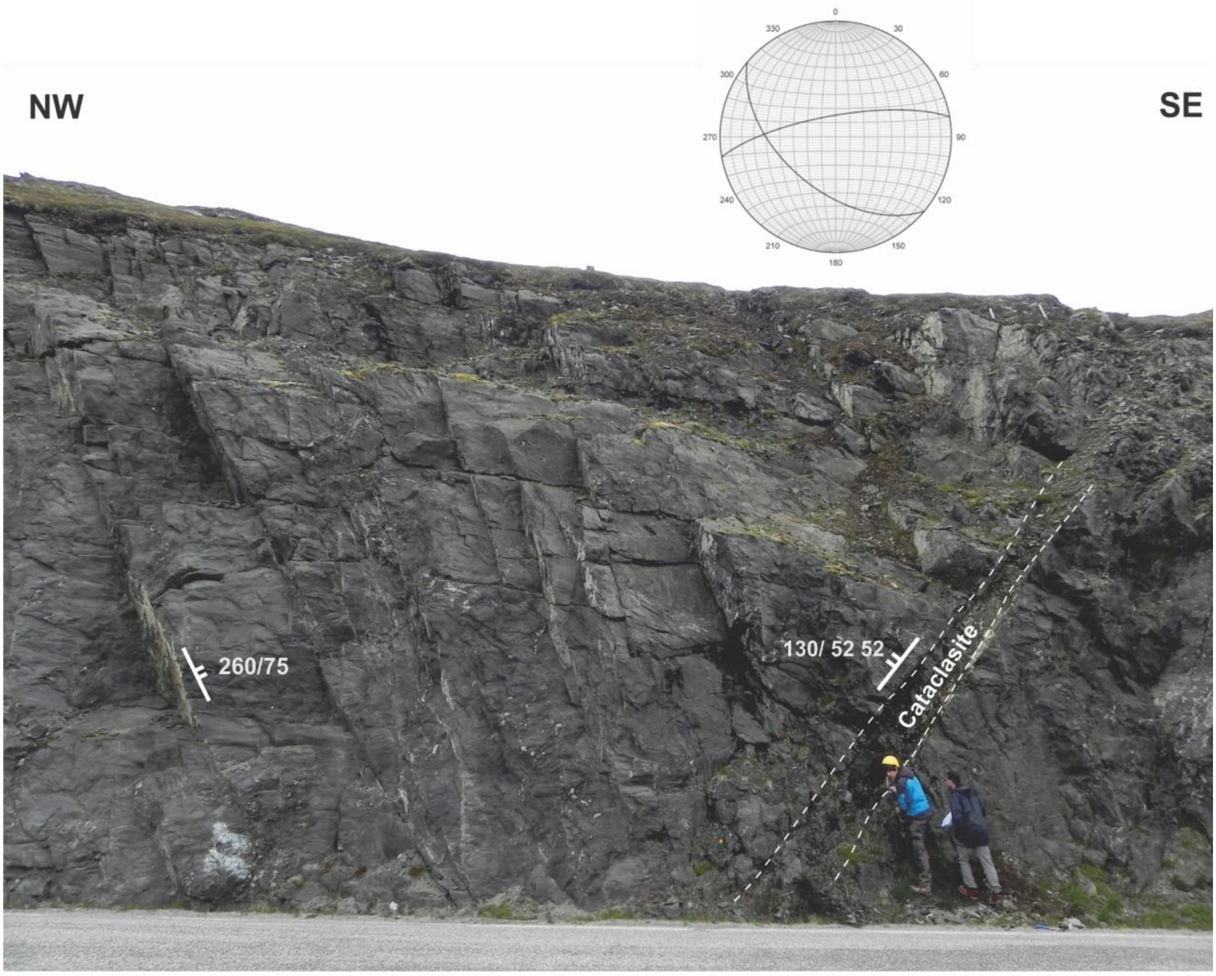

Fig. 2.28 show graben geometry in Magerøya defined by E-W fractures that terminates towards a NW-SE trending fault with a 0,5 m wide fault core consisting of cataclasites and gouge material that are rich in quartz, zeolite (laumontite) and calcite.

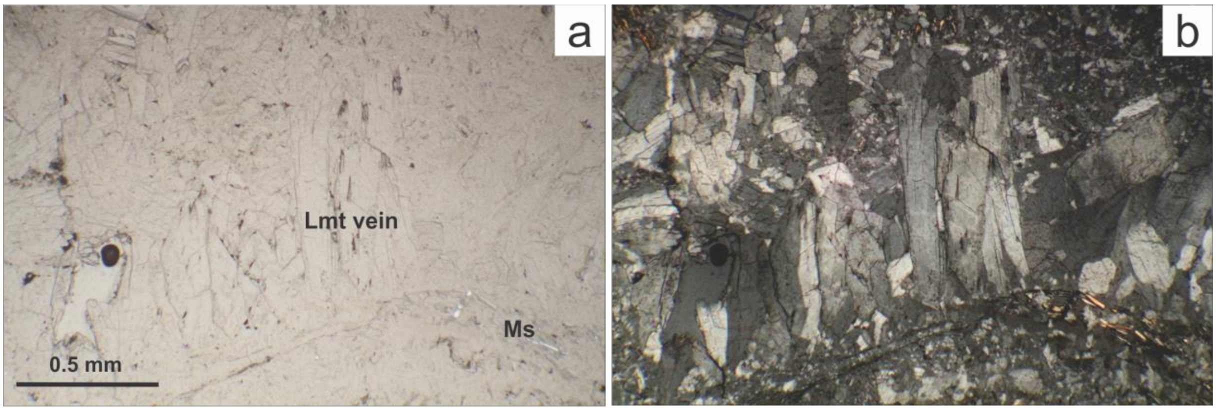

Fig. 2.29 Late laumontite growth in opening fracture in cataclasite from Magerøya. a) Plane-polarized light b) Cross.polarized light,

3 Description of offshore data

3.1 Bathymetry

3.1.1 Introduction

The shallow seafloor of western Finnmark has been studied by using the new high-resolution bathymetry data (Mareano) in order to correlate the structural lineaments observed in outcrops onshore and the lineaments interpreted from DEM (aerial photos). Vorren et al. (1986) has described the inner shelf area outside Porsanger peninsula and Rolvsøya as a strandflat that are cut by 200-300 meter deep throughs. The strandflat is a flat foreland in front of higher land/coastal mountains (Nansen, 1922), and has an irregular terrain with a thin cover of loose material (Klemsdal, 1982). The structural elements seen on the strandflat, are easier to interpret because of the thin cover of sediments. It is important to separate the seafloor morphology structures from the structural elements. The 3D window and profile tool in Global Mapper software were used to see the steepnes and shape of the escarpments to help identify the faults.

3.1.2 General seafloor geomorphology

The faults-fractures mapped from the bathymetry data (Fig. 3.1) are identified as straight to undulating/curved lineaments that generally show a sharp and significant drop/depression at the shallow ocean floor. Some of the lineaments seen at the bathymetry data are much smoother than the sharp escarpments that are interpreted as faults. These smooth and parallel features are most likely glacial lineations from ice flowing that eroded the surface. These appear on land, in fjords, but also further away from land in deeper troughs. At Magerøya, streamlines follows the ductile foliation that has a NE-SW trend seen in the fjords (southwest and east). The streamlines are both seen parallel and oblique to the fjords. At the Sværholt peninsula, the foliation has a NE-SW trend while the streamlines has an opposite flow direction (NW trend). At Porsanger peninsula, the foliation are more flat lying and dipping to the west. Some of the interpreted streamlines do not follow any of the fracture sets or foliation. Close to Lillefjorden, the ice flowing towards SW out in the fjord. Further north, the flowlines have a NW direction towards Snefjord. Northwest of Havøysund there is several parallel soft structures that are diverting northwards, dominantly bending to the west where a large old glacial deposit are present. Three large and wide throughs in mainly NNW-SSE orientation are seen between Magerøya and Sørøya. These throughs are around 2 km wide and with escarpment around 200 meter high (on the highest). Three large wedge-shaped deposits are seen at the end of these throughs. These deposits are suggested to be fan/deltas described as Rolvsøy, Hjelmsøya and Måsøy deltas by Vorren et al. (1986).

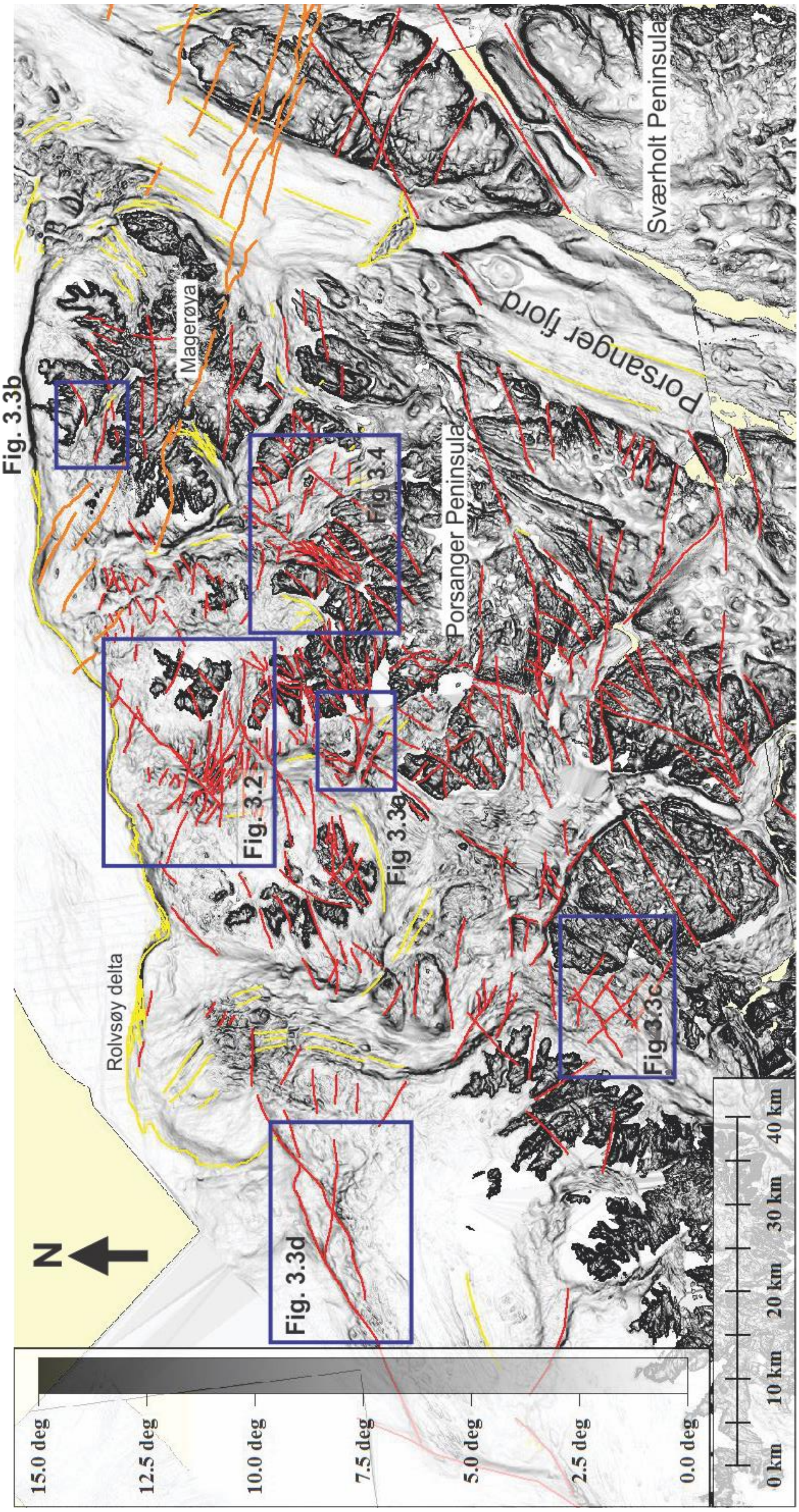

Fig. 3.1 Interpeted faults from bathymetry and DEM (red) dykes from magnetic anomaly data (orange) and glacial features (yellow). The aeromagnetic anomaly map is shown in fig. 3.5. Blue boxes show locations for fig. 3.2, 3.3 and 3.4

3.1.3 Brittle fault-fractures

The two major sets of lineaments observed onshore were also observed on the strandflat: i) NE-SW ii) NW-SE. In map view, rhombohedral shaped patterns are made up by these two dominant trends. The lineaments continuous and cut through the rhombic shaped blocks and there is no apparent displacement between these two trends. The lineaments in the area is dominantly straight and display en echelon geometries, left-stepping patterns, but there is also lineaments that has curved geometry. Right outside Skjarvodden (locality 3), E-W trending lineaments appear with a curved geometry and show deflection towards northwest and merge into NW-SE trending lineament (Fig. 3.3a). High frequency of distinct straight NW-SE striking lineaments that are seen west of Hjelmsøya (Fig. 3.2). These lineaments is made up by distinct escarpments with a height around 100 meters and are interpreted as brittle faults. The vertical profile (Fig. 2.2) of the NW-SE lineaments seems to have opposite dipping fault surfaces that form graben geometry. These tightly spaced lineaments terminates toward a NE-SW trending lineaments that are an eroded through where Hjelmsøya delta is located further north suggesting that the glacial lineations of ice flow following the faults in this area. Lineaments with same trend can be traced between Havøya (north of Havøysund and Hjelmsøya. The high increase in frequency of NW-SE lineaments may support that there is a major NW-SE fault in the area, since the frequency usually increases towards a major fault, this is also seen onshore. A large trough are cut by 200-300 meter deep throughs with NE-SW trends and left-stepping patterns toward northeast. These throughs are seen on the strandflats outside Havøysund and Hjelmsøya (Fig. 3.2).

Southwest for Rolvsøy delta, two major ENE-WSW striking lineaments are parallel and link together and form relay geometry (Fig. 3.3d). These faults are cut by several NW-SE striking lineaments that is charcaterized by a curved geometry with deflection towards NE-SW. These curved lineaments are also recognized onshore at Rolvsøya as distinctive escarpment with a height of 100 meter cut through the island. Lineaments that cross-cut each other and show displacement is also observed on the bathymetry data. A lithological boundary that can be seen clearly onshore at Magerøya, is cut and displaced sinistrally 1 km by a WNW-ESE striking lineament seen on the ocean floor of Tufjorden on the northwestern side of Magerøya (Fig. 3.3b). Parallel lineaments with NW-SE and NE-SW orientations has also been observed that are almost perepndicular to each other and form large squares (chessboard patterns). One straight NW-SE striking lineament are cut with minor sinistral displacement around 500 meter by a NNE-SSW striking lineament observed on the ocean floor between Sørøya and Hammerfest (Fig. 3.3c), suggesting that the NNE-SSW faults are youngest. However, the other parallel NW-SE striking lineaments that are cut by the same NNE-SSW faults do not show any clear displacement.

NW-SE WNW-ESE oriented lineaments are observed with undulating lineaments and small associated lense-shaped patterns resembling duplexes (outline on Fig. 3.4) The high-resolution bathymetry data in Ryggefjorden, northeastern part of Porsanger peninsula (Fig. 3.4) show a set of distinctive and complex pattern of lineaments. A major NE-SW striking lineaments separate the fjord in two lensoid structural elements. The northern lense-shape segment (segment 1) has oblique NNE-SSW striking lineaments cutting through and seems to be extensional fault blocks with overall en echelon geometry. 3D view in Global Mapper yield information about the topography and the lineaments define blocks with domino-geometry that seems to be down-thrown to the southeast. The southern lense-shape segment (segment 2) are characterized by a number of smaller tightly spaced NW-SE lineaments that seems to have an interconnection with the major NE-SW boundary faults where they seems to terminate. In Kobberfjorden (Fig. 3.4), straight NW-SE trending lineaments appear with right-stepping pattern towards the NW.

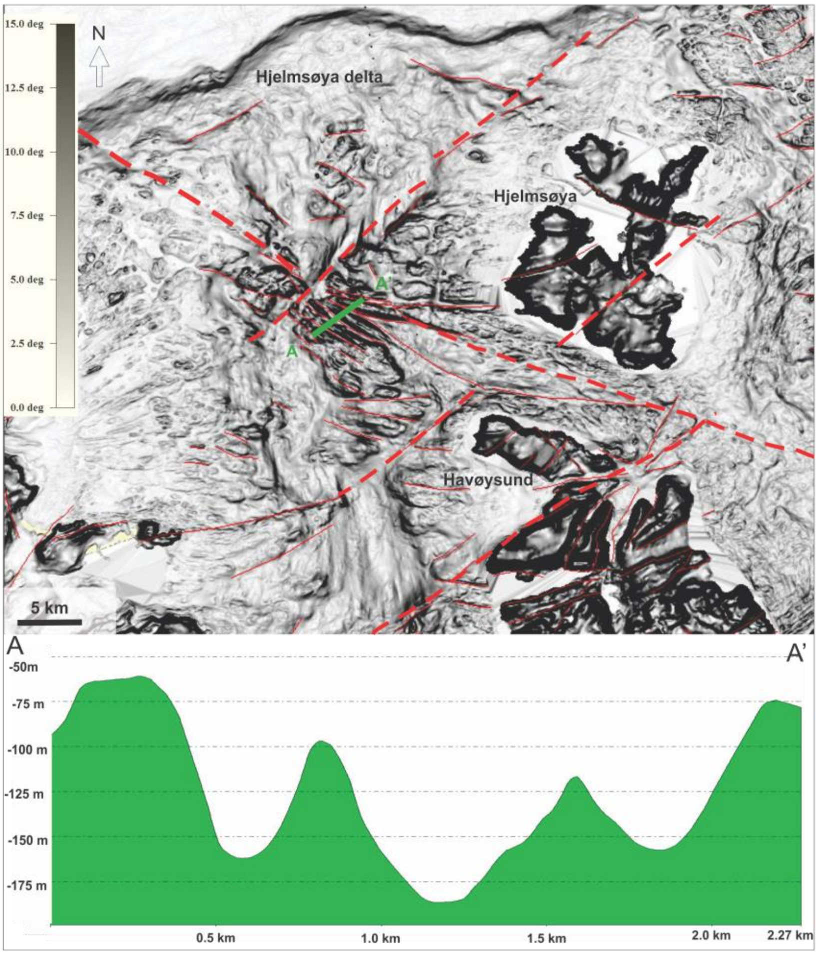

Fig. 3.2 High frequecy of straight, parallel NW-SE striking lineaments cut by major NE-SW striking lineaments. E-W striking lineaments together with the NW-SE lineaments form a rombhic pattern. Green line A-A' represent vertical profile over the NW-SE lineaments. The interpreted fault are marked in red. The lineaments interpreted as major faults are dashed in red.

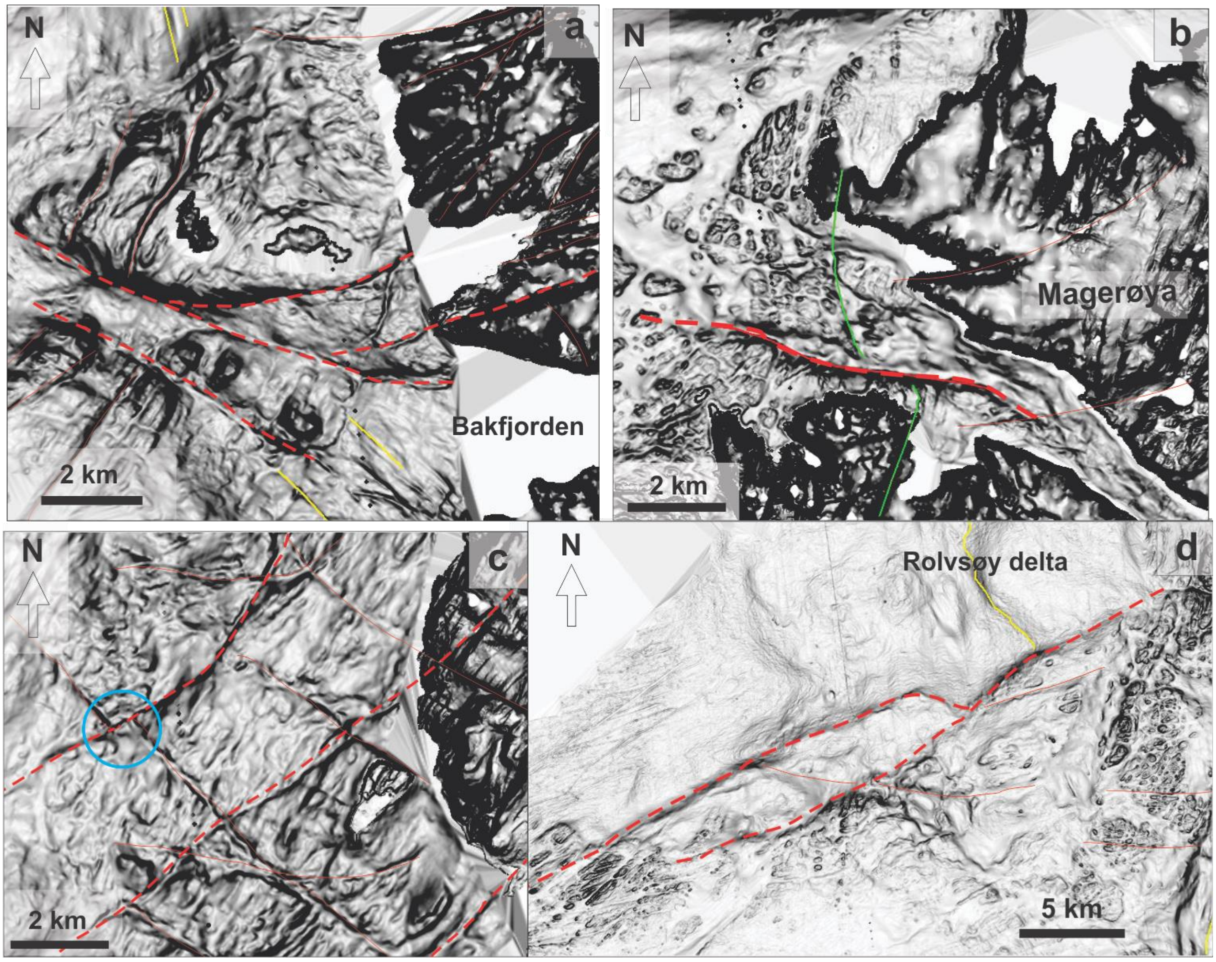

Fig. 3.3 a) NE-SW linemanet with curved geometry with deflection towards northwest. b) Bathymetry data in Tufjorden located northwest at Magerøya, show a lithological boundary that are cut and displaced 1 Km by a WNW-ESE striking fault. c) NE-SW faults cut through NW-SE striking lineaments where a minor sinistral displacement is obseerved, area marked in the blue circle. d) NE-SW striking lineaments define a relay structure. The interpreted faults are marked in red, lithological boundary marked in green, glacial features marked in yellow.

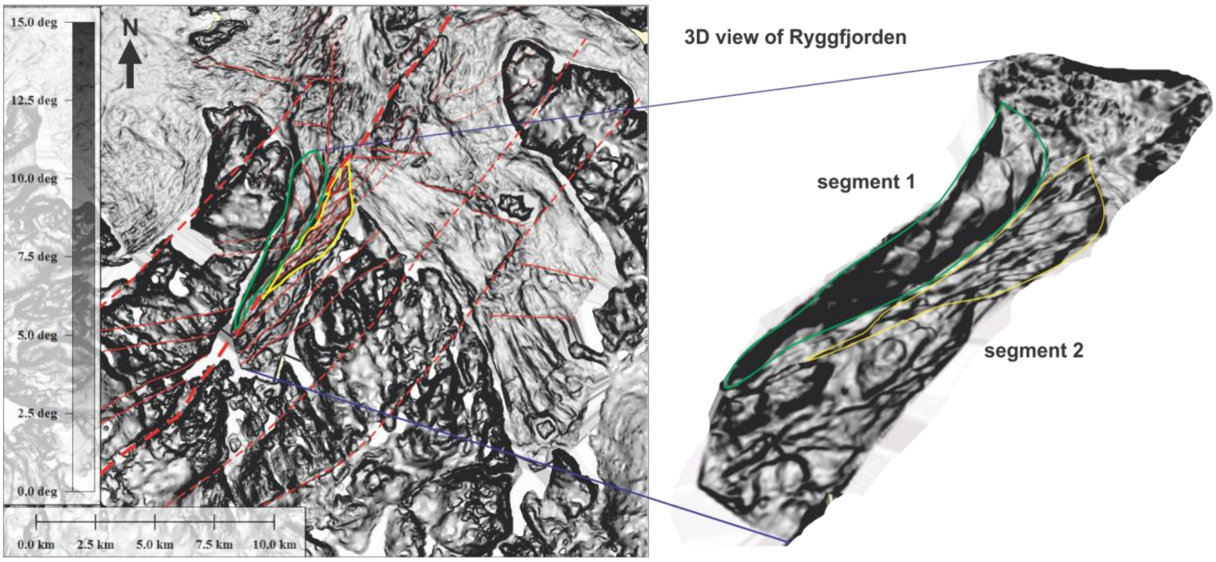

Fig. 3.4 Ryggfjorden display complex geometry of lineaments. Major NE-SW lineaments (dashed in red) can be traced onshore and offshore. The major NE-SW linemaent in Ryggfjorden separate two lense-shaped segment that display different geometry. Segment 1 (marked in green) is cut by E-W trending lineaments that seems to continue onshore. Segment 2 (marked in yellow). Notice the right-stepping pattern of straight NW-SE trending lineaments in Kobbefjorden.

3.1.4 Magnetic anomaly data

The aeromagnetic anomaly map (Fig. 3.5) were used to link the magnetic anomalies to the intepreted structures from DEM/bathymetry and seismic data and to strenghten intepretation in areas where the crystalline basement is covered by sediments on the shelf and onshore. The magnetic data show two trends of high positive anomalies i) WNW-ESE ii) NE-SW. These trends seems to corresponds to the dominating fault and fracture trends. The WNW-ESE trends are seen as distinctive linear positive anomalies northeast of Porsanger peninsula. These anomalies stretching from Nordkinn Peninsula, Sværholt Peninsula and through Magerøya as segmented lineaments with left-stepping geometry. Several lineaments on the bathymetry and onshore show the same trend but not all corresponds to the high-anomalies that are seen on the magnetic data suggesting that not all fault segments have intrusions of mafic dykes.

The NE-SW trends are more spread out. One NE-SW set crossing the WNW-ESE trends and is suggested to be iron-rich bedding that result in these straight and narrow positive anomalies (Olesen et al., 1990). Three other distinct NE-SW anomalies are seen southwest of Posanger Peninsula and seems to correspond to escarpments/lineaments interpeted as faults from the bathymetry.

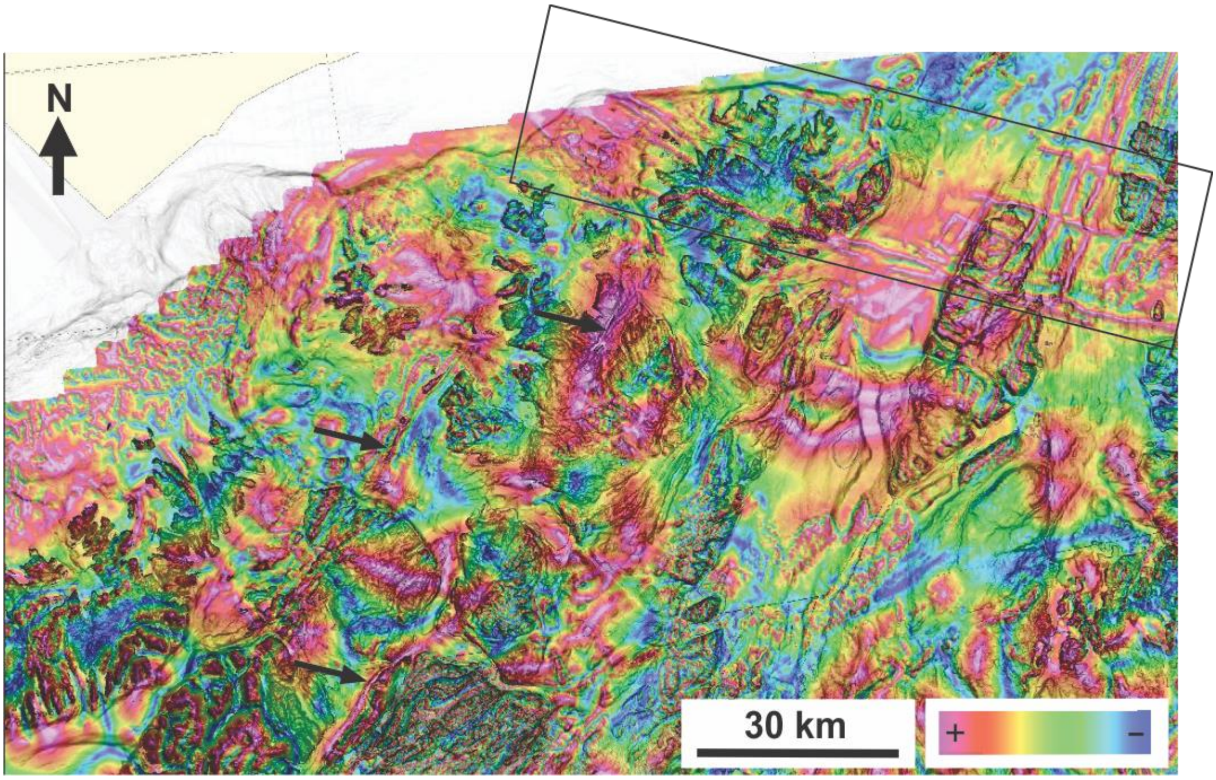

Fig. 3.5 Tilt-derivate map of aeromagnetic data show high corresponds of NW-SE lineaments onshore and offshore (Sværholt peninsula and Magerøya) left-stepping towards southwest on Magerøya (marked in black box). High positive anomalies with NE-SW trend correlates with intepreted faults on the bathymetry (marked with black arrows)

3.2 Seismic data

3.2.1 Introduction

This chapter presents the seismic interpretations of the analyzed seismic dataset on the Finnmark Platform, from the Gjesvær low and parts of the Hammerfest Basin. The main goal was to identify brittle faults in the Caledonian basement rocks (see chapter 1.3), to explore their relationship to known offshore basins (chapter 1.4), and to see if they can be related to the onshore structures observed in the Porsanger Peninsula. The faults mapped from seismic data cannot be directly linked with the faults and fractures mapped on the shallow shelf and onshore, due to the gap between the bathymetry data and the 2D seismic lines (Fig. 3.6). However, by inferring the trends and their possible link with adjacent structures it is possible to conclude reasonably well that the faults and fractures sets seen onshore is associated with the basin-bounded faults and the major fault complexes offshore that display similar trends and geometry.

The seismic data (described in chapter 1.6.7) was interpreted and used to generate the structure-contour map of the intra Early-Carboniferous horizon (see chapter 3.3.2.), shown in Fig.

3.8. Once the entire data set was mapped, four representative lines from BSS01- survey were interpreted and described (the four seismic lines are identified on Fig. 3.6).

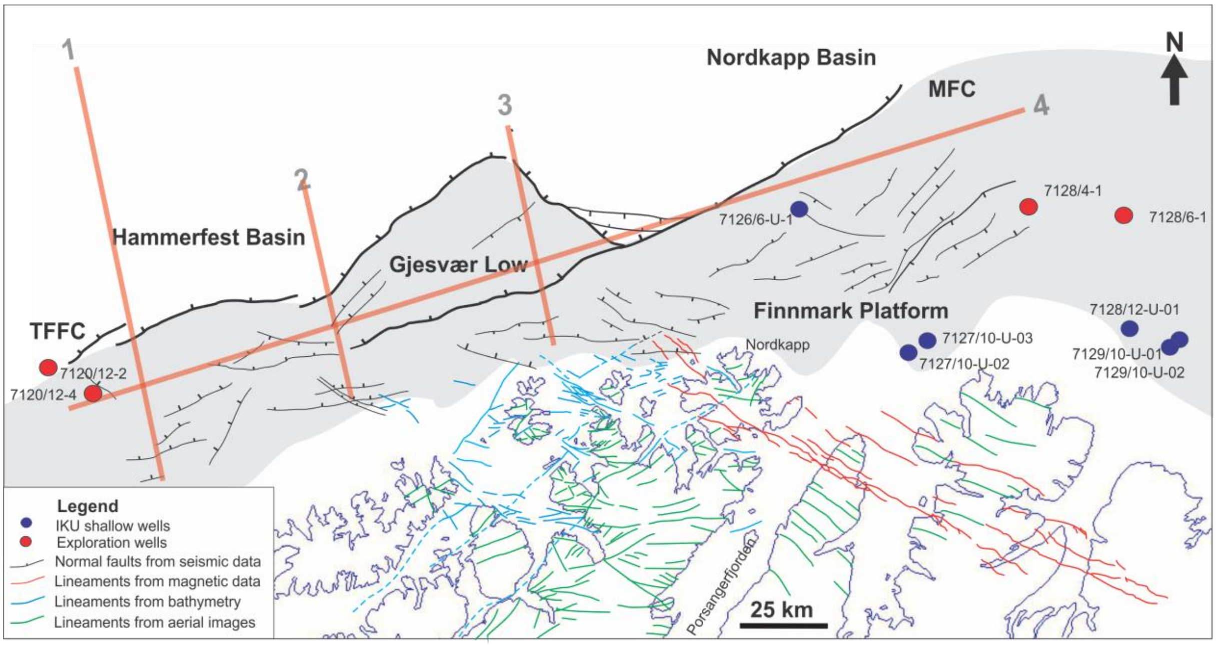

Fig. 3.6 Simplified structural map of the interpreted structural trends onshore in Western Finnmark and offshore on the Finnmark Platform and in the deeper parts of the South western Barents Sea, based on fieldwork and DEM (green), bathymetry(blue), magnetic data(red) and seismic interpretation (black). The red lines show the location of the seismic profiles. The blue areas represent small Carboniferous basins. Wells used for calicration of seismic data to define the seismic stratigraphy are marked in circles. The locality of the seismic sections(1-4 are marked in red and numbered. Abbrevation: TFFC: Troms-Finnmark-Fault Complex and MFC: Måsøya Fault Complex

3.2.2 Seismic stratigraphy

The seismic stratigraphy in the study area is based on the regional interpretation by statoil that include several wells described in chapter 1.5.6, see Table 1. The description of the various interpreted horizons of Upper Paleozoic age is based on the lithostratigraphic nomenclature defined by Larssen et al. (2002). The Mesozoic section is based on description by Worsly et. al. 1988. and Dallmann,1999. Seven key horizons are interpreted and described below, starting from the lowermost horizon.

Top Basement horizon

In wells 7128/4-1 and 7128/6-1 the Top Basement consists of quartzites that probably form impedance between the basement and overlying lightly consolidated sediments of Upper Paleozoic age. Well 7120/12-2 was drilled into the basement just north of The Troms-Finnmark Fault Complex and based on the Completion log from the well, the basement rocks is described as banded gneiss. (T. Henningsen pers. Com). The interpretation of the Top Basement is therefore based on well correlation from the wells on the Finnmark Platform and an overall assessment of how the interpretation of the Top Basement must be on the seismic section. It is difficult to specify where the boundary between quartzite and gneissic basement areas are on the platform based on the seismic data. The interpreted Top Basement is dashed to reflect the uncertainty in interpretation in those areas where the seismic quality is poor. This is especially true for seismic data below -4000 ms (TWT) where it is challenging to trace the Top Basement. On the Finnmark Platform, the Top Basement is generally traced as an irregular unconformity, dipping gently towards NNW (Fig. 3.7). The reflection patterns above the unconformity display wedge-shaped prism with strong seismic signal and continuous reflection representing younger sediments (Fig. 3.7). Below the unconformity, the reflection patterns are diffuse/chaotic to transparent and represent the basement rocks.

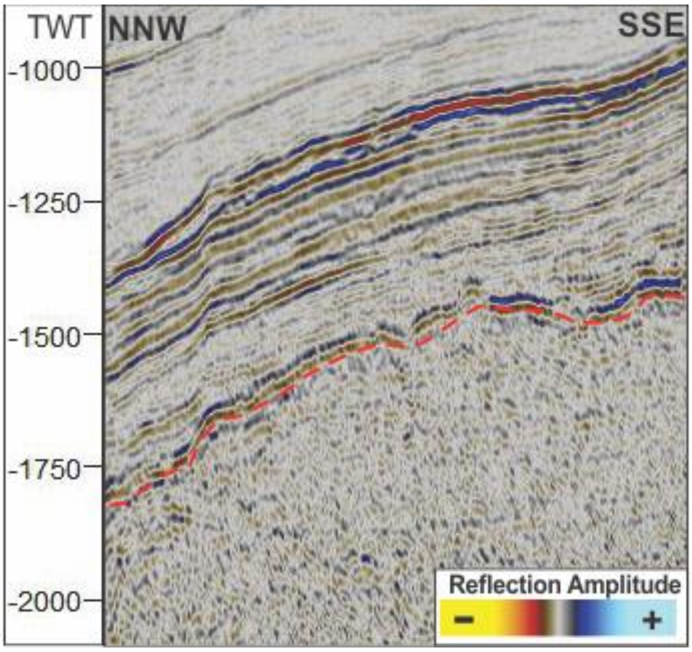

Fig. 3.7 show the boundary between the basement and the sediments on the Finnmark Platform (from BSS01-129 seismic line). Top Basement (marked in red) is an irregular unconformity dipping seawards. The sediments display more continuous and stronger reflection, while the crystalline basement rocks display diffuse/chaotic reflection.

Intra Early Carboniferous (Visèan) horizon

This horizon represent the base of an unconformably overlying siliciclastic sequence that consists of coal beds, referred to as the Tettegras formation. This formation is correlated to be part of the Billefjorden Group seen onshore on Svalbard and Bjørnøya (Dallmann, 1999) and is defined in the seismic sections as the interval from 2358 m to 2202 m in well 7128/6-1 (Larssen et al., 2002). The unconformity has generally a changing seismic signature that is mostly strong with several short low amplitude and discontinuous reflections. The variation in amplitude and characteristic (seismic discontinuity) seen in the seismic signature is thought to be due to variation of organic material content (coal) (Larssen et al., 2002). Lateral variations in thickness of the Early Carboniferous units occur on the Finnmark Platform due to infill of local half-grabens suggesting active rifting during deposition as a result from Visèan-Serpukhovian rifting (Larssen et al., 2002). The formation thickness varies from 292.5 meter in well 7128/4-1 and thickening to 650-700 meter in the half-graben where the IKU wells drilled around 210 meter of the unit without fully penetrating the entire formation (Larssen et al., 2002).

Mid Carboniferous (Bashkirian) horizon

The Mid-Carboniferous horizon is interpreted to define the approximate base of the Ugle formation (Larssen et al., 2002) that is an unconformity representing a transgressive siliciclastic sandstone unit formed by a tectonic period of uplift (The deposition change to continental sandstones). The horizon is generally characterized by a changing seismic signature that cannot be followed continuously throughout the area, while the overlying sequence is characterized by occasionally strong and continuous reflections. However, in areas where the reflection is discontinuous, it has a weak seismic signal and difficult to map. The Mid-Carboniferous formation is correlated to be part of the Gipsdalen Group that are exposed onshore on Svalbard (Dallmann, 1999). The formation is only locally developed on the Finnmark Platform, and is found in isolated half-grabens and was deposited during the active rifting in the Late Serpukhovian to Bashkirian (Worsley et al., 2001; Larssen et al., 2002).

Base Triassic horizon

The horizon defines the base of the Triassic sequence which is made up of alternating sandstones, siltstones and shales (Bugge et al., 1995). The seismic character of this reflection is represented with a very high amplitude and continuity, likely due to the underlying Permian units that consist of mixed carbonates and silica dominated sedimentary rocks (cherts). The overlying Triassic sequence comprises a series of clinoforms that mostly downlap onto the base Triassic horizon itself. The sequence is referred to as the Klappmyss/Havert formation belonging to the Sassendalen Group (Dallmann, 1999).

Base Cretaceous Unconformity (BCU)

This seismic horizon defines the Base Cretaceous Unconformity that represent a major change in the depositional environment in the Jurassic/Cretaceous from shale dominated deposits to fine clastic sediments (Worsley, 2008). The seismic character of this reflection is represented with a strong amplitude and continuity that are mapped in the interval from -1500-500 ms (TWT). The Base Cretaceous Unconformity is not present on the Finnmark Platform, but is traced in the Hammerfest Basin and in the Gjesvær low. In the Hammerfest basin, the Cretaceous sedimentary units make up a wedge shaped unit that is gently dipping and thins out to the northwest (Fig. 3.9).

Base Paleogene horizon

The horizon defines the near base of the Torsk Formation that is an unconformity below the Cretaceous and Paleocene boundary (Dalland et al., 1988). The horizon is characterized by a strong, continuous reflection coefficient that can easily be identified in the Hammerfest Basin and terminates towards the Troms-Finnmark Fault Complex. The horizon is also present in Gjesvær low, and gently dipping seawards (Fig. 3.9).

The Upper Regional Unconformity (URU)

The Upper Regional Unconformity is generally characterized by a strong seismic signal with high continuity that is located around -500 ms (TWT). The URU is an angular unconformity representing the erosional base for several glacial depositions that are seen as flat-lying sedimentary units (Andreassen et al., 2008) Parts of this reflection is disturbed by truncated clinoforms of the underlying sequence (Torsk Formation). The quaternary sequence, which overlies the URU is thickening in some areas on the Finnmark Platform due to large submarine deltas.

Key horizons	Properties	Color Code
Top Basement	Generally strong continous reflection separating overlying stratified reflections from underlying diffuse/chaotic reflections	
Intra Early Carboniferous	Semi-continuous reflection with changing amplitude. in the east: separating overlying strong seismic facies from a facies with weak seismic signal. in the west: strong reflection overlying by stratified reflection that lap onto the horizon.	
Base Mid Carboniferous	Semi-continuous reflection with generally strong amplitude separating overlying continuous unit from a more discontiuous unit	
Base Triassic	Strong continous reflection separating overlying stratified units with low amplitude from underlying stratified unit with high amplitude	
BCU	Strong continous reflection	
Base Paleogene	Strong continous reflection	
URU	Strong continous reflection separating flat-lying stratified unit from underlying truncated units	

Table 3 Summary and description of the mapped key horizon in this study

These seven stratigraphic horizons described above (Table 3) will be used to tie the different seismic sections and to develop maps and cross sections that will be helpful in interpreting basin-boundary fault architectures and fault geometry. These ties can then further be used to correlate the offshore fault data to onshore observations and measurements of fault trends, dip and kinematic characters. Such a correlation will be done first in map view (based on a time map of the intra Early Carboniferous horizon) and then by use of the interpreted seismic cross sections (Seismic Profile 1 - 4). A sub-division of the seismic stratigraphy are defined and represent four age determined intervals that have been assigned the colour codes, seen in . These sequences will be referred to when describing the internal seismic expressions of the different sedimentary infills in the seismic sections (chapter 3.3.5).

Stratigraphy	Age	Color code
Sequence 1	Caledonian/Precambrian basement rocks	
Sequence 2	Paleozoic sediments	
Sequence 3	Mesozoic sediments	
Sequence 4	Cenozoic sediments	

Table 4 Subdivision of the seismic stratigraphy

3.2.3 Regional Trends (Map View)

A Time-Surface representation (TWT) of the interpreted Intra Early Carboniferous horizon was made to create a structure contour map that shows the variation in time values caused by Carboniferous faults offshore. The Base Early Carboniferous horizon was chosen instead of the Top Basement because of the difficulty in mapping the Top Basement. The faults that are mapped in the Top Basement also cut through the Carboniferous strata but mostly, do not affect the overlying strata, suggesting that faults in the basement rocks onshore as well may be of Carboniferous age (see discussion chapter 4.3.3). Due to the large displacement of the Troms-Finnmark Fault Complex, there is a great difference in time across this fault complex, as shown by the contrast in colour between the platform and the basins (Fig. 3.8). Consequently, the time-surface map will only show major faults with large displacement, and not all the mapped faults with minor displacement on the Finnmark Platform. The NW-SE trending fault that seems to link with the Troms-Finnmark Fault Complex and Måsøya Fault Complex are also significant. In addition, two areas of deepening on the eastern part of the Finnmark Platform can be recognized (Fig. 3.8). The depressions are delineated by NE-SW and ENE-WSW trend that dip toward each other.

The interpreted time-surface map shows that the Troms-Finnmark Fault Complex and related faults have an irregular, step-wise geometry with alternating NE-SW, ENE-WSW and NW-SE trends that segment the adjacent Hammerfest Basin and the Finnmark Platform (Fig. 3.8). The Troms-Finnmark Fault Complex consist of three main isolated segmented of differently trending normal faults, with an average dip to the NW, and where the segments defines an “en echelon” geometry of right-stepping NE-SW trends and with NW-SE to WSW-ENE trends in between. On the Finnmark Platform, the time-surface map shows a general northeast deepening of the Early Carboniferous horizon, and a significant drop by an E-W major fault that delineates the Gjesvær low. A major NW-SE trending fault delineates the Gjesvær low from the Northern part of Hammerfest Basin and seems to branch into a fan of splay faults that terminates towards the Måsøya Fault Complex. Faults with ENE-WSW to E-W trend continuous further southwest from Måsøya Fault Complex. The minor faults mapped on the Finnmark Platform (see next section) show also a dominant trend of NE-SW to E-W normal faults. In addition, there are a few NW-SE trending faults that seem to correlate with the same NW-SE trends as for fracture lineaments mapped on the shallow shelf (see chapter 3.1.3).

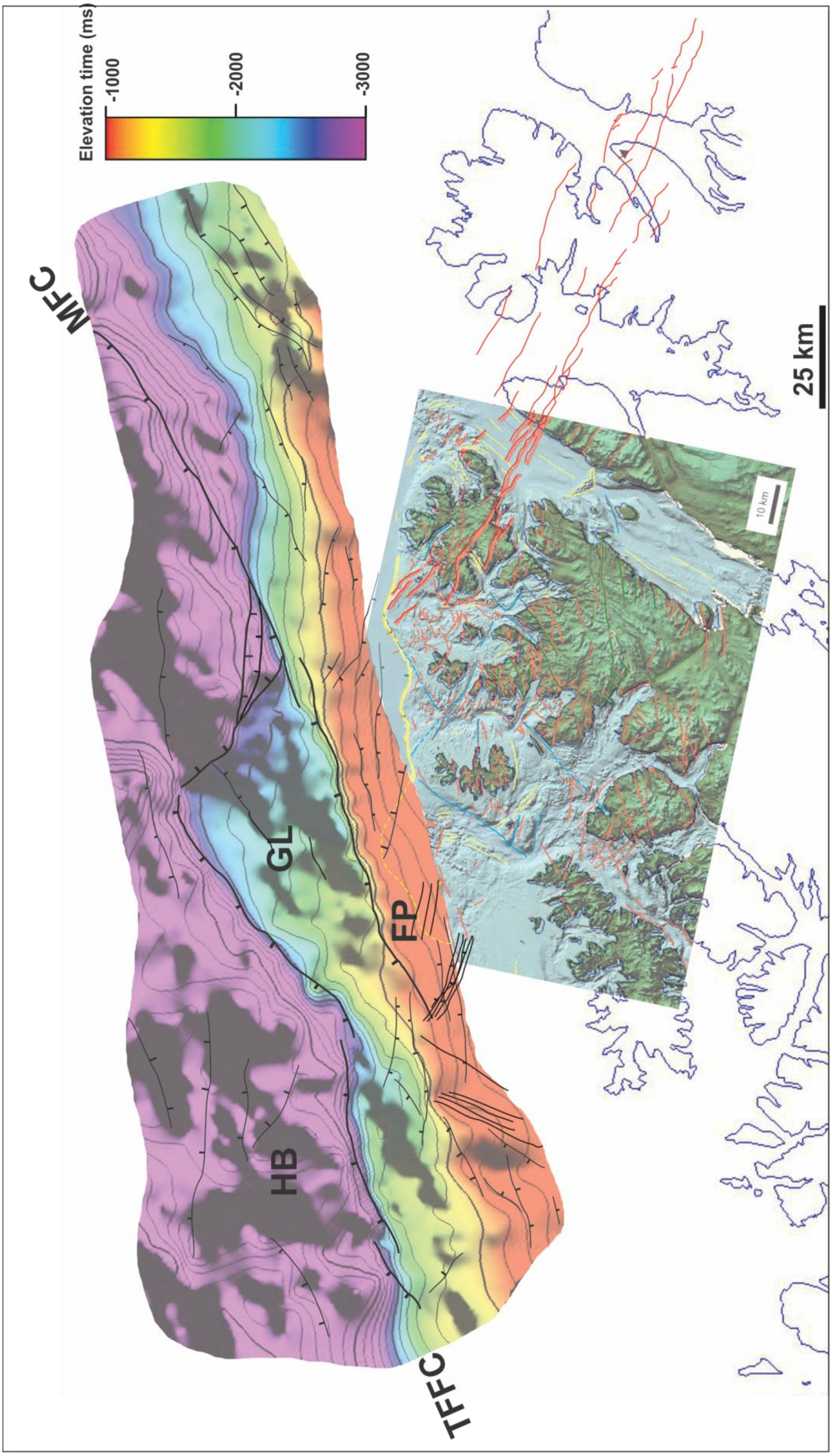

Fig. 3.8 Tectonic map of interpreted faults based on fieldwork and DEM (green), bathymetry (blue), magnetic data(red) and seismic interpretation(black). Time-surface of the Early Carboniferous horizon showing the Carboniferous architecture of the Finnmark Platform and accompanied major offshore and onshore faults in map view (bathymetry map of the shallower shelf) HB: Hammerfest Basin, FP: Finnmark Platform, GL: Gjesvær Low, TFFC: Troms-Finnmark-Fault Complex

3.2.4 Seismic interpretations

The interpreted seismic lines (Sections 1-4) are shown on Fig. 3.6, and will be described in successive order. Note that the sections 1-3 are oriented NW-SE (across strike of the margin) while section 4 is oriented NE-SW (along-strike), thus allowing tie of horizons and faults. These four sections were chosen because they display a representative view of the major structural elements and cut across-strike of the dominant fault and basin geometry of the southern Barents Sea margin.

Seismic section 1

This seismic section belongs to one of the westernmost lines of the 2D seismic survey used in this study. The seismic line is oriented NW-SE and crosses the Finnmark Platform and the Hammerfest Basin (Fig. 3.9). The seismic section is divided into four main sequences based on seismic signature and nature of internal horizons (Chapter 3.3.2.). The lowermost sequence (sequence 1) is the basement characterized by a chaotic seismic signature. The red dashed line represents the base of the Hammerfest basin, which can be traced onto the Finnmark Platform. The boundary between the basement and the sediment package is easily observed on the Finnmark Platform due to the well-stratified sediments above the presumed “Top-Basement horizon” with strong and continuous seismic signals.

The lowermost sediments in sequence 2 are weakly-stratified with a “wavy character” and scattered parallel seismic reflections, likely representing the Early Carboniferous strata. The interpreted Intra Early Carboniferous horizon is an unconformity characterized by on-lapping reflections in some areas where the seismic signal is well imaged. The Carboniferous units also make up a weak wedge prism that thickens towards the NW, and within opposite portions of the Hammerfest basin, confirming a syn-Carboniferous rift origin. Sequence 3 is defined by the Base Triassic horizon that is characterized by a strong seismic signal. The Triassic sequence is characterized as a well-stratified reflection with strong amplitude in the upper part, and on the Finnmark Platform this sequence dips gently towards the NW and is unconformably overlain by Quaternary strata (see below). On the Finnmark Platform the Triassic unit is unconformably overlain by subhorizontal, presumably Quaternary deposits, whereas in the Hammerfest Basin is overlain by a thick Cretaceous unit, thus suggesting that the sediment package between the Base Cretaceous Unconformity and Upper Regional Unconformity has been eroded on the Finnmark Platform. The thickness of the strata from the Finnmark Platform and into the Hammerfest basin are therefore not easily determined. In the Hammerfest basin, great thickness variations can be seen of sequence 2 and 3. The Cretaceous sequence is seen as a wedge-shaped unit in the Hammerfest Basin thickest towards the NE-SW trending Troms-Finnmark Fault Complex where the strata onlap the fault surface. The base Paleogene horizon (part of sequence 4) is only present in the Hammerfest basin, where it is characterized by a strong seismic signal that is continuous and dips toward the NNW. The Paleogene sequence laps onto the Troms-Finnmark Fault Complex and truncates onto the URU and overlying Quaternary sediments that are characterized by flat-lying, parallel horizontal reflections.

The mapped brittle faults are usually identified as narrow sub-vertical, tabular zones of reflection discontinuities on vertical seismic sections. On the Finnmark Platform, planar normal faults are generally steep and have minor throws, whereas the more deep-seated structures are located in the basins further north and display a listric fault geometry. Faults mostly affect sequence 1 and 3 and the middle part of sequence 3, where the major faults terminates in the upper part (below BCU horizon). Except the major Troms-Finnmark Fault Complex that also affect sequence 4, where Cenozoic sediments are deposited. Faults in the center of the basin (in the deeper parts) delineate the largest thickness of sequence 3, down to -4000 ms (TWT). Reflections up to near base Paleogene exhibit a thickening toward the major Troms-Finnmark Fault Complex in the footwall and thus, provide support for a syn-rift origin.

On the Finnmark Platform, the faults display mostly a planar geometry with NE-SE and ENE-WSW trends and dip apparently to the NE. The faults can be traced from the basement upward until they terminate in the lower part of sequence 3. The top basement horizon is shallow on the platform, where the Carboniferous and Triassic horizons are gently dipping north towards the Hammerfest basin, and overlain by sub horizontal Quaternary sediments. Notably on the platform, the Carboniferous and Triassic strata show a small normal drag effect along the Troms-Finnmark Fault Complex, and the successions are tilted gently toward the south indicating rotation of fault blocks. The NE-SW to ENE-WSW trending and NW-dipping Troms-Finnmark Fault Complex separates the Finnmark Platform and the Hammerfest basin. This major fault shows a listric geometry and dips to the NNW. The faults can be traced deep down into to the basement rocks, where they follow the irregular shape of the top basement unconformity. The faults further north (The Asterias Fault Complex), that delineate the Hammerfest basin from the Loppa High, display a listric geometry and are dipping toward the south. Minor normal faults dipping NE below the Base Cretaceous Unconformity in the Hammerfest basin are also observed.

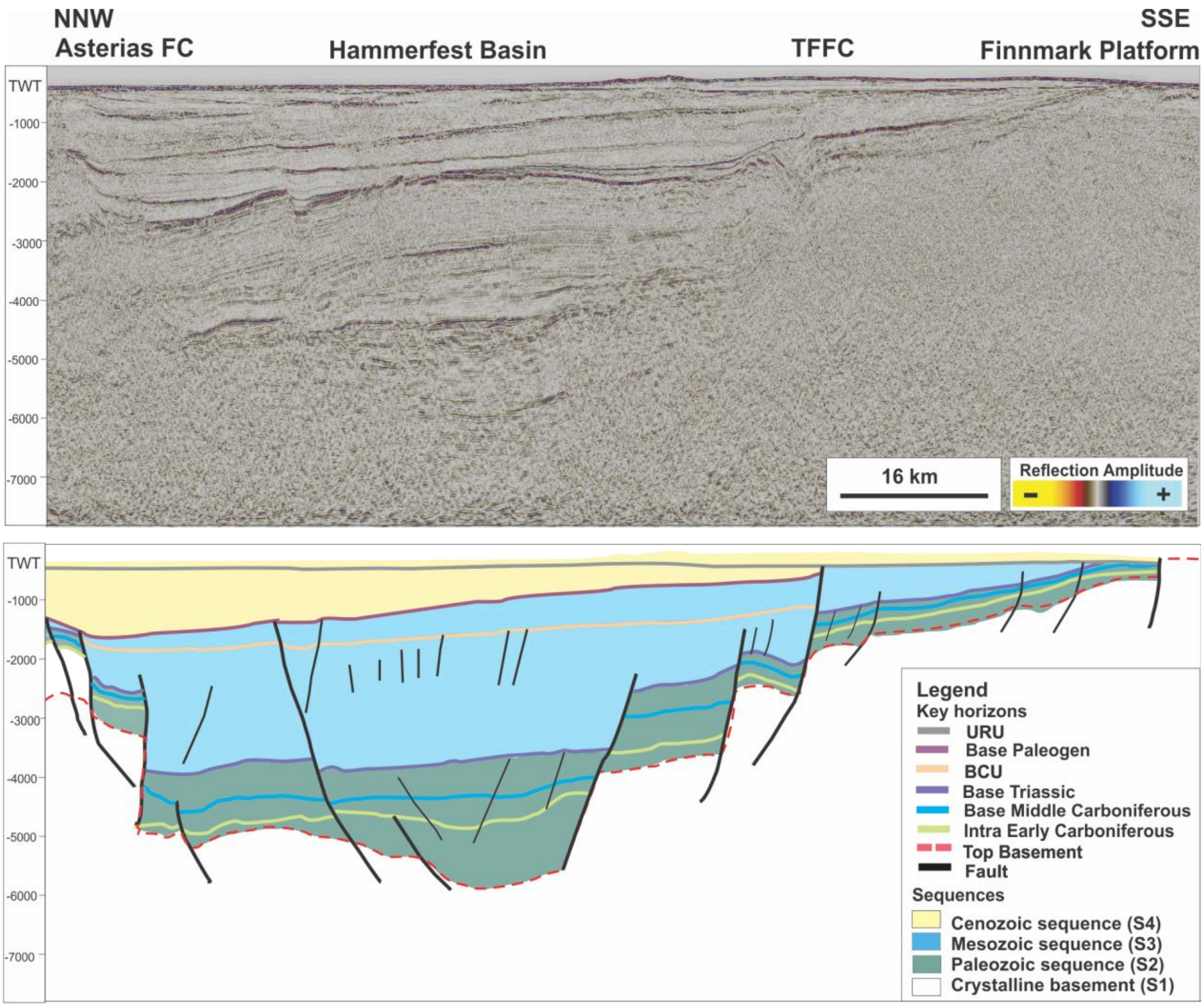

Fig. 3.9 Seismic profile 1 (BSS01-103), Show the seismic cross-section and the intepretation below. See fig. 3.6 for location.

Seismic section 2

This interpreted seismic section (Fig. 3.10) is located further east of section 1 (i.e. east of Sørøya) and has a NE-SW orientation (Fig. 3.6). The section covers the Finnmark Platform and southwestern part of the Hammerfest basin (Fig. 3.6). Similar seismic sequences as those described in the seismic profile 1 are observed in this section, and are identified by the same criteria.

Sequence 1 dip gently seawards on the platform and steepens more significantly along with Troms-Finnmark Fault Complex and becomes almost horizontal in the basin below 5000 ms (TWT). The overlying sequence 2 have an almost constant thickness on the platform around 400-500 ms (TWT), but thickens to 1000 ms (TWT) northwards on the basin. Here a small but thick Lower Carboniferous unit can be seen in a basement depression. Notable drag effects are observed in the Early Carboniferous sequence, producing low-angle down-laps, along the fault surface. In the hanging wall, drag-folded Carboniferous strata dip steeply into the Hammerfest basin. There, the reflections in this interval are irregular and display small normal displacements in the section where it curves upwards into to the anticline near the footwall. Further into the hanging wall, the seismic reflection is parallel, well-stratified and gently dipping towards the northeast of the Hammerfest basin. In the overlying interval between the Base Cretaceous Unconformity and Mid Carboniferous Unconformity, a major anticlinal fold system occurs in the footwall to the Troms-Finnmark Fault Complex, and farther SE in the footwall.

In sequence 3, the reflection above the Base Cretaceous Unconformity laps onto the horizon, which in the hanging wall is involved in another, major anticline where strata are tilted southeastward into the Troms-Finnmark Fault Complex. The reflections above the Base Cretaceous Unconformity are parallel and even out the anticlinal geometry to a more horizontal seismic character with a gentle dip towards the northeast. Sequence 4 displays parallel, almost horizontal seismic reflections that lap onto the Base Cretaceous Unconformity in the basin. The upper reflections truncate onto an almost horizontal erosional unconformity defining the base of the glacial sediments. This Quaternary sequence above URU thickens towards the mainland represents a large fan (Rolvsøy delta), that can be seen on the bathymetry data.

The Finnmark Platform has higher frequency of planar normal faults (compared to the seismic section 1) with a WNW-ESE trend closest to the mainland (Fig. 3.9). The faults are generally characterized as steep, narrow zones with diffuse reflections. These near-shore faults dip steeply to the NE and seem to correlate with the NW-SE trending lineaments seen on the bathymetry that define a step-wise geometry and can be traced onshore south of Lillefjord (Fig. 3.1). Further north on the platform, a small basin is mapped and bounded by an E-W trending fault dipping towards the north and a WNW-ESE trending fault dipping northeast. This basin corresponds with a system of minor faults near the southern part of the Gjesvær low with same orientation as the Troms-Finnmark Fault Complex. The major NE-SW trending and NE-dipping Troms-Finnmark Fault Complex is well imaged and shows a listric geometry (Fig. 3.10) This major fault complex shows a huge displacement around 1200 ms (TWT) and thickening of the strata in the Hammerfest basin compare to on the Finnmark Platform. The seismic reflections are irregular and chaotic in the basin close to the major fault complex, and do not show any clear stratification. The roll-over anticline in the basin affects sequence 3 by a number of planar normal faults at the top of the anticlinal structure. This is especially seen along the strong reflection of the Base Cretaceous Unconformity that has a numerous of small offsets.

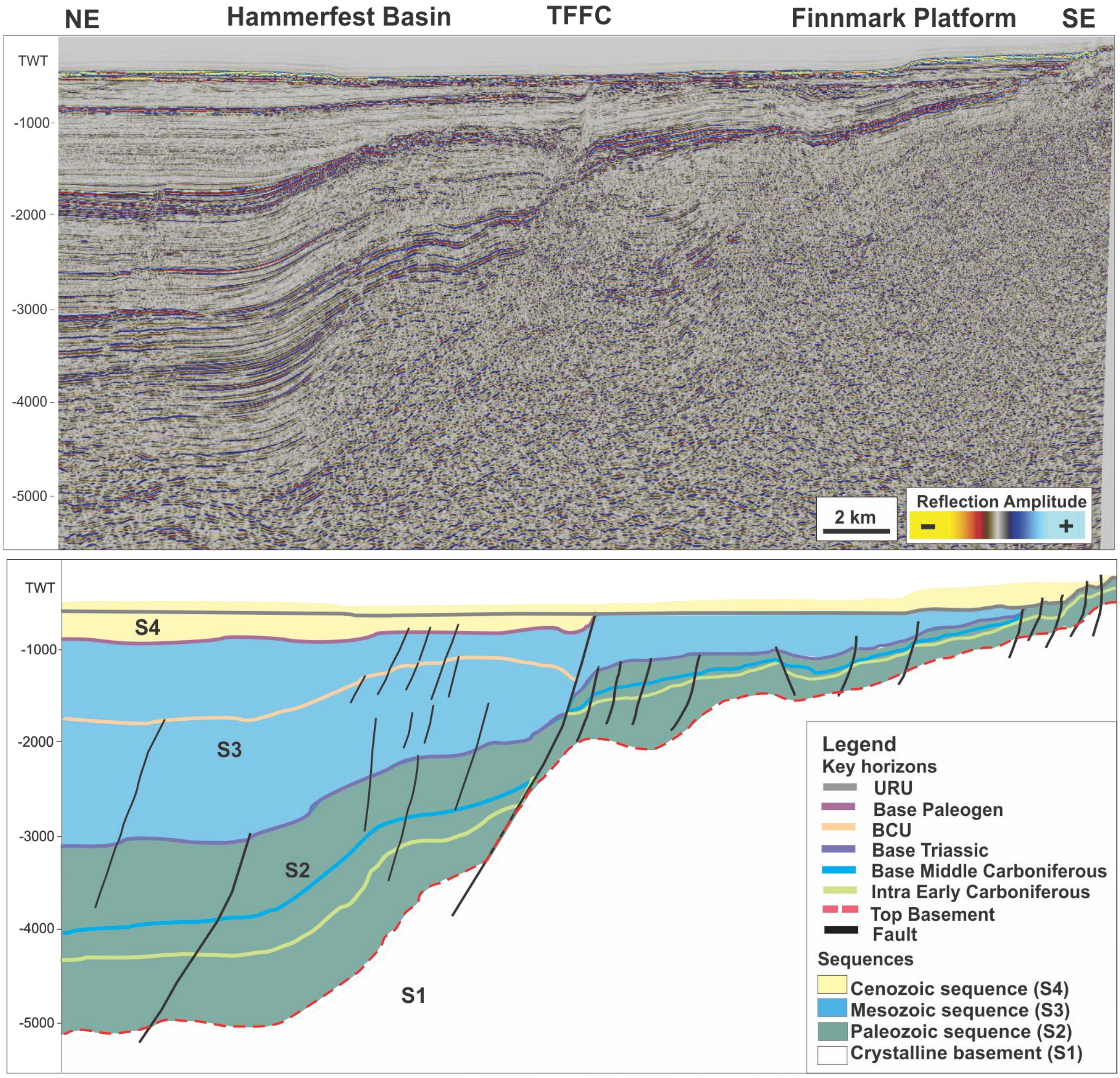

Fig. 3.10 Seismic profile 2 BSS01-112 show the seismic cross-section and the intepretation below. See fig. 3.6 for location.

Seismic section 3

This seismic section is located northeast, further offshore between Rolfsøya and Måsøy and oriented NNW-SSE (Fig. 3.11). The profile displays the Finnmark Platform, Gjesvær low and Hammerfest basin (Fig. 3.6). The stratigraphy in this section is defined by the four sequences described on the two previous sections and the seven key horizons (Table 3) are mapped in this section.

The Top Basement is very shallow on the Finnmark Platform with less sediments on top compare to the seismic profiles further southeast, and deepens significantly in Gjesvær low. Between the Gjesvær low and Hammerfest basin reflections are characteristically concave upwards and this is interpreted as a basement high. Distinct seismic reflections below sequence

2 are gently dipping SSE in the Gjesvær low and the strata between these reflectors display curved geometry that may be folds, suggesting that the reflections can represent Caledonian back-thrusts. The lowermost reflections in sequence 2, between the Intra Early Carboniferous horizon and the strong tilted reflections seem to be onlap the thrust and the major E-W fault, and thins out toward the NNW. The reflections are parallel and weakly stratified which could possibly represent Late Devonian sediments. The Early Carboniferous sequence rest on sequence 1 on the platform and pinch out towards the south where the reflections truncates against the Upper Regional Unconformity. In Gjesvær low, the Early Carboniferous sequence is thickening and the reflections lap onto the Intra Early Carboniferous horizon. The Early Carboniferous sequence show a wedge-shaped geometry indicating activity along fault surface during deposition. The Carboniferous strata are also thickening in the Hammerfest basin, especially the Mid Carboniferous sequence with an increase of almost 1500 ms (TWT). The Mid Carboniferous sequence is absent on the Finnmark Platform.

Sequence 3 is defined by the base Triassic horizon that overlying the Early Carboniferous unit and pinch out to the south on the platform and truncates the URU. The base Triassic horizon is characterized by strong and continuous reflection in Gjesvær low and Hammerfest Basin. The horizon gently dips toward the northwest in Gjesvær low and deepens below -3000 ms (TWT) in Hammerfest basin. The BCU is characterized with strong seismic signal that is interrupted by normal faulting and truncates against the Upper Regional Unconformity towards the south. The Cretaceous strata are characterized by almost horizontal reflections with weak amplitude and lap onto the erosional base Cretaceous. Sequence 4 is defined by the near base Paleogene horizon that truncates against the URU in Gjesvær Low and is almost horizontal.

There are three major faults in this seismic profile. One E-W major fault dipping NNW with listric geometry and delineates the platform and Gjesvær low where the top Basement deepens significantly. The second main fault is part of the Troms-Finnmark Fault Complex and is an isolated segmented normal fault that displays listric fault geometry. The third main fault is located further NNW in the Hammerfest Basin and is a deep-seated fault that can be traced below URU and down to Top Basement. The fault display a more planar geometry than the other two major faults, and are almost vertical (steeply dipping). The irregular shape of Top Basement have a step-wise geometry in Gjesvær low, which are interpreted as faults. These faults have low-angle with planar geometry and are traced in the undefined interval between the Intra Early Carboniferous horizon and the Top Basement. On the platform, two major normal planar faults are found with NW- orientation dipping SSE. The Top Basement and the overlying sediments are tilted towards the Gjesvær low and a set of small southeast-tilted fault blocks are in between the major faults on the platform that delineates the half-grabens. One of the major fault is half-graben filled with wedge-shaped Early Carboniferous strata. Shallow faults below the Base Cretaceous Unconformity cut the internal basin strata and terminates in sequence 3 or in the upper part of sequence 2.

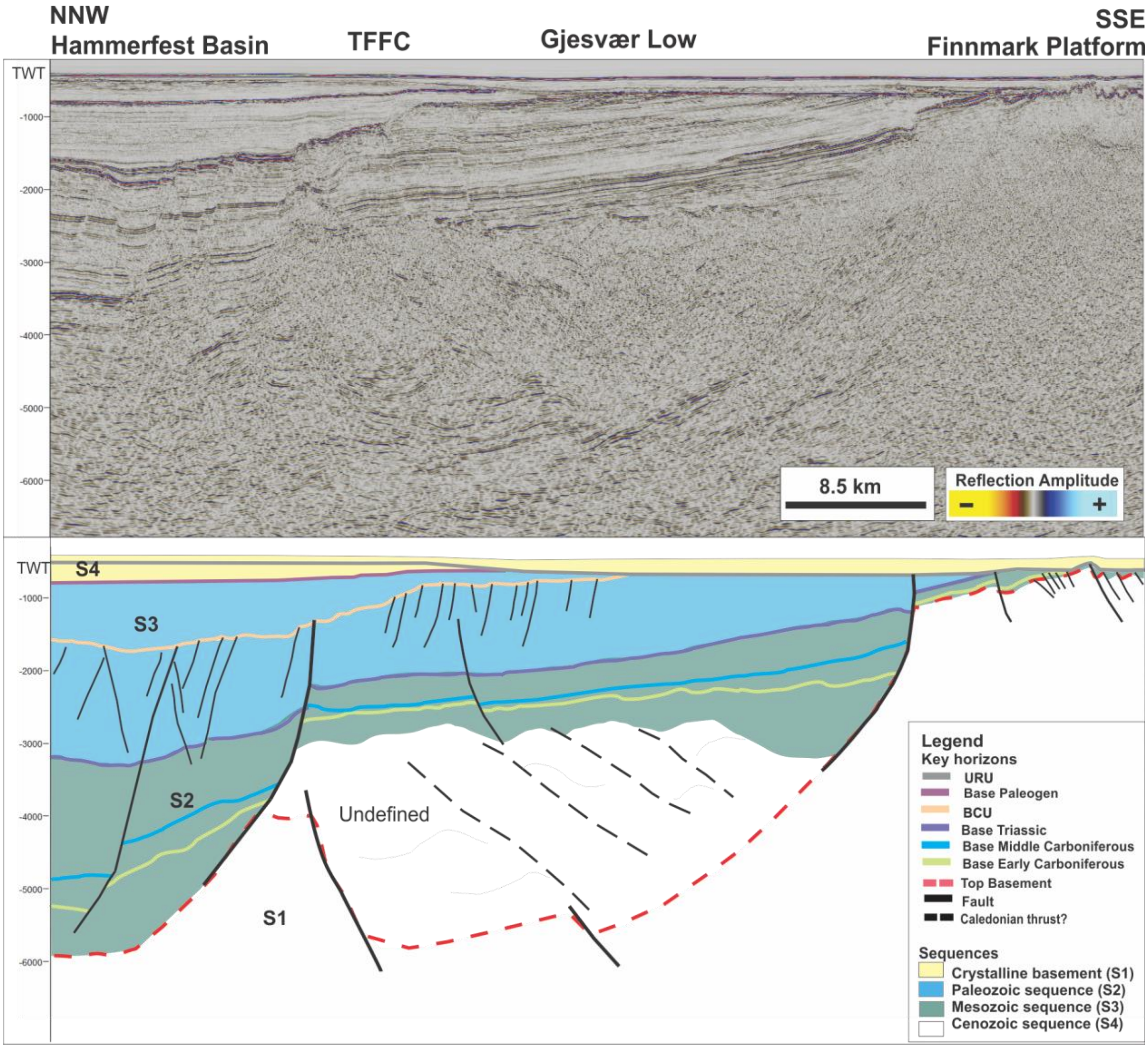

Fig. 3.11 Seismic profile 3 (BSS01-122) showing the seismic cross-section and the intepretation below. See fig. 3.6 for location.

Seismic section 4

This seismic section (Fig. 3.12) is located further south with a SE-NW orientation crossing the other lines to tie the interpretation. The profile displays the Finnmark Platform, Gjesvær low, Troms-Finnmark Fault Complex, Måsøya Fault Complex, see Fig. 3.6. All the seismic horizons except base Paleogene, are observed in this profile, and are identified by the same criteria as the already described seismic sections.

Sequence 1 is defined by an irregular Top Basement Unconformity, which is shallow on the platform in the southeast and deepens toward northeast in a stepwise manner. A small Basement High delineates the platform from Gjesvær low, the same observed in Seismic section 3 (Fig. 3.11). Significant thickening of sequence 2 in Gjesvær low and further northeast on the platform are seen, compare to the southwestern part of the platform. The Early Carboniferous succession varies the most in thickness, especially at the northeast part of the platform where a wedge-shape unit thins out away from the fault suggesting movement along the fault during deposition. The near base Mid Carboniferous horizon deepens northeast where the sequence is thickening with a fairly constant thickness throughout the basin.

Sequence 3 is characterized with parallel and continuous reflection that are well stratified with fairly constant thickness in the northeastern part of the platform. The near base Triassic horizon deepening gently towards the northeast and the sequence truncates against the Upper Regional Unconformity (sequence 4) in southeast. The Base Cretaceous Unconformity pinch out towards the southeast in the Gjesvær low area and the overlying reflections lap also on to sequence 4. Since the seismic line are located on the Finnmark Platform further south towards the mainland, the base Paleogene horizon are not present. Sequence 4 only consist of the quaternary sediments that are placed on top of the Upper Regional Unconformity.

Several faults can be traced from the basement (sequence 1) up to top Sequence 3. The irregular Top Basement Unconformity seems to be tectonically controlled, whereas the faults are following the shape of the basement and terminate in the upper to middle part of the basement. These fault are more low-angle than what they appear as in the seismic profile due to the “squashing” of the seismic line. In Gjesvær low, the low-angle reflectors that define the stepwise pattern of the basement could possibly be the low-angle reflections that are recognized in the seismic section 3 (Fig. 3.11), but are difficult to recognize in this profile. The offset character of the faults pre-dominantly indicating down-to-the-northeast movement and display listric fault geometry.

On the Finnmark Platform, a small deepening of the Top Basement horizon are bounded by E-W trending fault dipping towards the NW and a WNW-ESE trending fault dipping SW and define the left side of the basement high that separates the platform from Gjesvær low. The WNW-ESE fault seem to display the largest accommodation where Carboniferous strata thickening along the fault surface. Close to the major Troms-Finnmark Fault Complex, the shallow part of Gjesvær low and the internal strata are faulted by NE-SW trending fault with minor throws that terminate below the Intra Early Carboniferous horizon.

A small depression are bounded by very steeply dipping faults that have planar geometry. The bounding fault to the SE is the major NW-SE fault segment between Troms-Finnmark Fault Complex and Måsøya Fault Complex (Fig. 3.12), and are steeply dipping to the NE (almost vertical). In map view, this depression has a triangular shaped geometry (Fig. 3.8), and the NW-SE trending fault seem to splay out in three segments that are steeply dipping, almost vertical, seen in the cross-section (Fig. 3.12). The other bounding fault to the NE is a splay fault from the major NW-SE segment that bending into a more E-W orientation and dipping S. The Carboniferous sequence is significantly thicker in this depression, from about 850 ms (TWT) and only around 150 ms (TWT) on the platform. The ENE-WSW striking Måsøya Fault Complex dipping NW and display listric geometry.

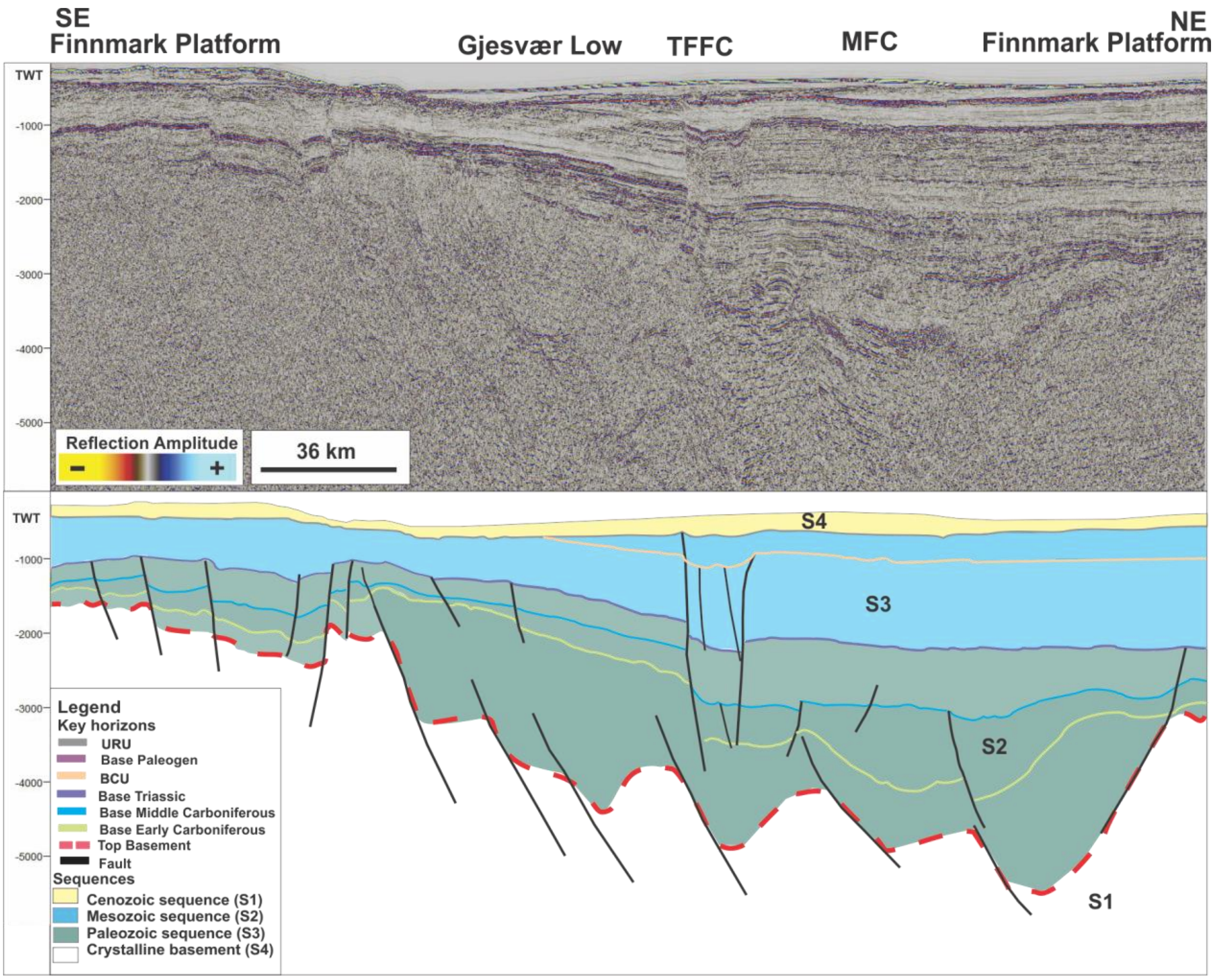

Fig. 3.12 Seismic profile 4 (BSS01-204) is the tie line for the other seismic profiles. Show the seismic cross-section and the intepretation below. See fig. 3.6 for location.

4 Discussion

4.1 Introduction

The studied faults and associated fractures on the Porsanger Peninsula have been mapped, described and analysed at several localities, with the aim of identifying major trends, geometry, fault rocks and kinematic characters from outcrops and micro-scale data. The onshore faults-fractures and their association to the regional brittle fault lineaments offshore have been inferred in the area between Sørøya and Magerøya (Fig. 2.1). This correlation was competed in order to link the onshore trends with the major offshore fault-systems on the Finnmark Platform (Fig. 3.8). This link between onshore and offshore trends are done by combining data (in chapter 2.1, 3.1 and 3.2), applying relevant methods and combining structural fieldwork with interpretations of Digital Elevation Model data/bathymetry, aeromagnetic anomaly data and seismic data (see chapter 1.6).

The fault-fracture linkage inferred from the fieldwork will be used to discuss the fault geometries and interactions/linkage, kinematic characters, timing relationships and structural development of the faults. In addition, the nature and formation of the fault rocks, mineral assemblages in fault rocks, associated alteration processes and secondary mineral precipitation in veins and fractures will also be addressed. The onshore faults and fractures will then be considered in a regional context in order to compare them with the major offshore fault-systems on the Finnmark Platform, western Troms and the Lofoten-Vesterålen margin (Indrevær et al., 2013).

4.1.1 Dicussion of onshore structures

The results (see chapter 2.1) show that there are two dominant onshore structural trends: 1) NW-SE trends with faults dipping mainly NE and 2) NE-SW trends with faults dipping mainly NW. In addition, there is a less dominant fault-fracture set with E-W strike and faults dipping either N or S that is seen in a few outcrops, such as at Havøysund, Skjarvodden and Bakfjorden.

The bedrock of the onshore studied areas are mostly Caledonian nappes belonging to the Kalak Nappe Complex, gneisses (mainly paragneisses) and different intrusives including both pre- and syn-Caledonian ages of intrusion. The faults and fractures mapped in the area are generally developed at a high angle to the flat-lying foliation which is dipping 10-30º, and does not seem to have controlled the development of brittle faults and fractures, exept in one outcrop (Havøysund), where the NW striking foliation with gently NW dip (30º) had mineral growth and slickensides indicating normal dip-slip top-NW movements (Fig. 2.5). Thin-section analysis also indicates that the observed micro-fractures generally cut through old mylonitic fabrics and are not seen to be superimposed on the pre-existing ductile fabrics (Fig. 2.20). However, the pre-existing Caledonian thrust boundaries seen in Porsanger Peninsula seem to have acted as possibly weakness zones and contibuted to the localization of the brittle faults and fractures. The thust boundaries that are mapped in the area change in orientation from more E-W and ENE-WSW trending in the north (Havøysund and Snefjord) to NE-SW and NNE-SSW trends further south. The ENE-WSW and E-W faults and fractures seem to correlate in strike with the major lineaments that bend from E-W to NE-SW trend. This is seen in the major lineaments between Bakfjorden, Ryggfjorden and Snefjorden area (Fig. 2.4 and Fig. 2.5). The map pattern displays distinctive complex gemetries and intersection of different sets of fault and fractures.

Earlier studies from mapped brittle faults and fractures in the coastal areas in Troms, Lofoten and Vesterålen (Bergh et al., 2007; Hansen et al., 2009; Koehl, 2013; Forthun, 2014; Indrevær et al., 2014) indicate that ductile basement fabric has been an important controlling factor, at least locally, for the formation of brittle faults and fractures. However, there are also outcrops in Lofoten showing ductile fabric that has little impact on development of brittle faults and fractures (Haraldsvik, 2015).

NE-SW striking faults dipping SE are most abundant in the study area. These faults display both planar and listric geometries with slickensides indicating mainly normal dip-slip movement. They have a similar attitude as the main NE-SW faults offshore (Troms-Finnmark Fault Complex and Måsøya Fault Complex). The major NE-SW fault zone observed in Snefjord (Fig. 2.18), that was described by Passe (1978); Townsend (1987) and named as the Snefjord-Slatten fault seems to link up with the major Vargsund-Langfjord Fault further south. The high frequency of NE-SW lineaments seen onshore between Snefjord and Revsbotn/Lillefjord (Fig. 1.2) is a possibly continuation of the Langfjorden Fault. This fault is suggested to strike through Sammelsundet by Roberts and Lippard (2005), as seen in Fig. 1.2. They also suggest that the Vargsund-Langfjorden Fault possibly bound a half-graben.

The NW-SE fracture trend in the Porsanger Peninnsula is the most abundant among presumed extensional fractures/joints (mode I) and they have less fault surfaces (Mode II) when compared to the fractures that trend NE-SW. Steeply dipping NW-SE to NNW-SSE trending fault and fractures where seen throughout the area, especially in Skjarvodden where a high frequency of parallel fractures with distinct planar geometry had the same trend (Fig. 2.10). Porsanger Peninsula is close to several major NW-SE fault systems, such as the Fugløya and Senja transfer zone found further south (Indrevær et al., 2013), and the major

Trollfjord-Komagelv Fault zone that is further to the northeast, near Magerøya. There are also postulated major NW-SE faults that cut through some of the major faults in Porsanger Peninsula. Examples include the Kokelv fault (Roberts & Lippard, 2005), which is suggested to continue in Revsbotn, and the Magerøysundet fault (Townsend, 1987; Gabrielsen & Færseth, 1989) that splays out through Havøysundet and between Havøya and Hjelmsøya Islands (Fig. 1.2).

The E-W trending fault-fracture set looks to interact with both major trends (NE-SW and NW-SE). The NW-SE to WNW-ESE fractures seen on Magerøya appear to change to a more E-W trend further southwest towards the Porsanger Peninsula. The NE-SW regional lineaments on the eastern side of the Porsanger Peninsula bend into a more E-W trend on the western side in Bakfjorden. This can be interpreted as due to rotation of NE-SW striking fractures into parallelism with E-W striking fractures due to dextral shearing along the E-W trend, a feature also described near Andøya in Vesterålen by Forthun (2014). This nature of bending suggests that the NE-SW trending fractures represent an older fundamental joint system bent into a younger E-W trending oblique strike-slip fault system (Mandl, 2005). Havøysund-Myrfjord area show slickenside surfaces with oblique dextral movements (Fig. 2.2) Alternatively these two trends may be a conjugate set of shear fractures formed at the same time and related to NNW-SSE directed oblique extension (Katz et al., 2004). The data discussed above suggest that major E-W trending oblique strike-slip faults may be present in the study area. One example is in the Havøysund area, which is dominated by E-W striking meso-scale faults and fractures that are parallel to the narrow sound (Havøysundet) that separates Havøya from the mainland (Porsanger Peninsula). Consequently, this suggests that the narrow sound may be fault controlled. Another example is Bakfjorden (Fig. 2.12), which is also follow the major valleys/gullies in the area.

Previous workers in Troms and Lofoten-Vesterålen (Bergh et al., 2007; Eig et al., 2008; Hansen et al., 2011) identified faults-fracture sets with a NE-SW and NW-SE trend (including NNE-SSW and ENE-WSW trend) with similar bending interactions in map scale.

4.1.2 Interaction of the fault-fracture trends

Previous work further northeast from the study area, including on Magerøya show that the most abundant fault-fracture set in eastern Finnmark has an NW-SE orientation (Roberts & Lippard, 2005; Herrevold et al., 2009). NE-SW faults-fractures have also been mapped, for example in Varanger Peninsula where NNE-SSW and NE-SW extensional faults splay off the main Trollfjord-Komagelv Fault Zone (Rice & Gayer, 1989). These are suggested to be related to post-Caldonian reactivation of Trollfjord-Komagelv Fault Zone (Herrevold et al., 2009).

Further south along the western Troms margin, NNE-SSW and ENE-WSW trending faults onshore are dominating (Indrevær et al., 2013; Koehl, 2013). Porsanger Peninsula is located in between these areas and this can be the explanation for the high frequency of both these two major trends in fault-fracture orientation.

In a traverse from N to S on the western side of Porsanger Peninsula, there is observed changing frequency and change in the dominating fault-fracture trends (Fig. 2.1) suggesting fault-fracture partitioning (strain partitioning) in the area. The fault-fracture geometries observed in the different localities (described in chapter 2.3 – 2.9) will be further discussed below to see the relationship between geometry and the fault-fracture trends.

4.1.3 Fault-fracture geometries

The very complex fault-fracture geometries observed in map view on the Porsanger Peninsula, e.g. such as zig-zag patterns, anastomosing (rhombic-shaped) patterns, en echelon and stepping fault segments suggest they may have formed in a variety of regional strain fields. For example, similar geometries are known from both extensional, oblique extensional and strike-slip settings (Morley et al., 2004). However, the majority of the fault-fracture geometries observed in map view by aerial photographs, in outcrop-scale (cross-section) and in thin section from the studied areas, are considered to be dominantly extensional and/or oblique-extensional. This is inferred from the known setting along the rifted Barents Sea margin. In the following, these aspects are discussed further using mesoscale fault geometries that will be compared and discussed relating to the associated fault-fracture sets in a regional context.

Planar and listric fault-fracture geometries

The faults-fractures mapped on the Porsanger Peninsula, including Magerøya, are dominated by steep planar geometries. This is especially true for the NW-SE striking fractures which have a distinctive steep planar geometry (Fig. 2.10a), similar attitude as the NW-SE trending faults offshore seen on seismic sections (Fig. 3.11) (see later discussion chapter 4.2.2). The NE-SE striking faults and fractures are also dominated by planar geometry but they also display listric geometries seen in outcrop and micro-scale (Fig. 2.7a and Fig. 2.20 a and b). In Selvika,rotation of fault blocks seem to have occured along the listric NE-SW trending faults that merge towards a major NE-SW fault (Fig. 2.7). This interpretation is supported by the gap seen along the fault blocks and the bed offset showing that they are tilted relative to the undeformed rocks in the area. Similar listric geometry and dextral offset is also seen along NE-SW trending faults in Snefjorden, in micro-scale. The oriented thin-section shows a foliated porphyroblast that is cut and displaced by several listric micro-faults (Fig. 2.20 a and b) that seem to rotate and show normal dextral offsets. The listric fault geometry of the NE-SW striking fault observed onshore have similarites to the major NE-SW to ENE-WSW basin bounding faults offshore (Fig. 3.9), discussed in chapter 4.2.2.

Normal fault linkage geometries

The E-W trending escarpment with variable height observed at Havøysund (Fig. 2.2b) has a geometry that resembles a normal fault linkage structure with an upper ramp breach (Crider, 2001) in between two stepping E-W trending boundary faults (Fig. 4.1a, b) The fault linkage cuts across at the topographically higher end of the ramp and a possible inactive termination of the fault segment is preserved (Fig. 4.1a and b). This suggests that the overlapping fault segment has an opposite slip sense and step sense. Similar geometries have been described (Crider, 2001) in the Basin and Range in Oregon, USA, by aerial photographs. Crider (2001) investigated the geometry of normal fault linkages and found that there is a relationship between the position of relay-breaching structures and the slip sense. The geometry of the ramp indicates that the E-W overlapping fault segment pair consists of both dip-slip and oblique-normal slip movements produced at a restraining step. These fault linkage geometries indicate that the closely located narrow sound with the same trend (Havøysundet) (Fig. 2.2) possibly follows these weakness zones (oblique-normal fault segments). Similar NE-SW striking possible fault linkage structures are observed on bathymetry data on the Rolvsøy delta (Fig. 4.1.c,d) and are discussed later (chapter 4.2.1) (Fig. 3.3).

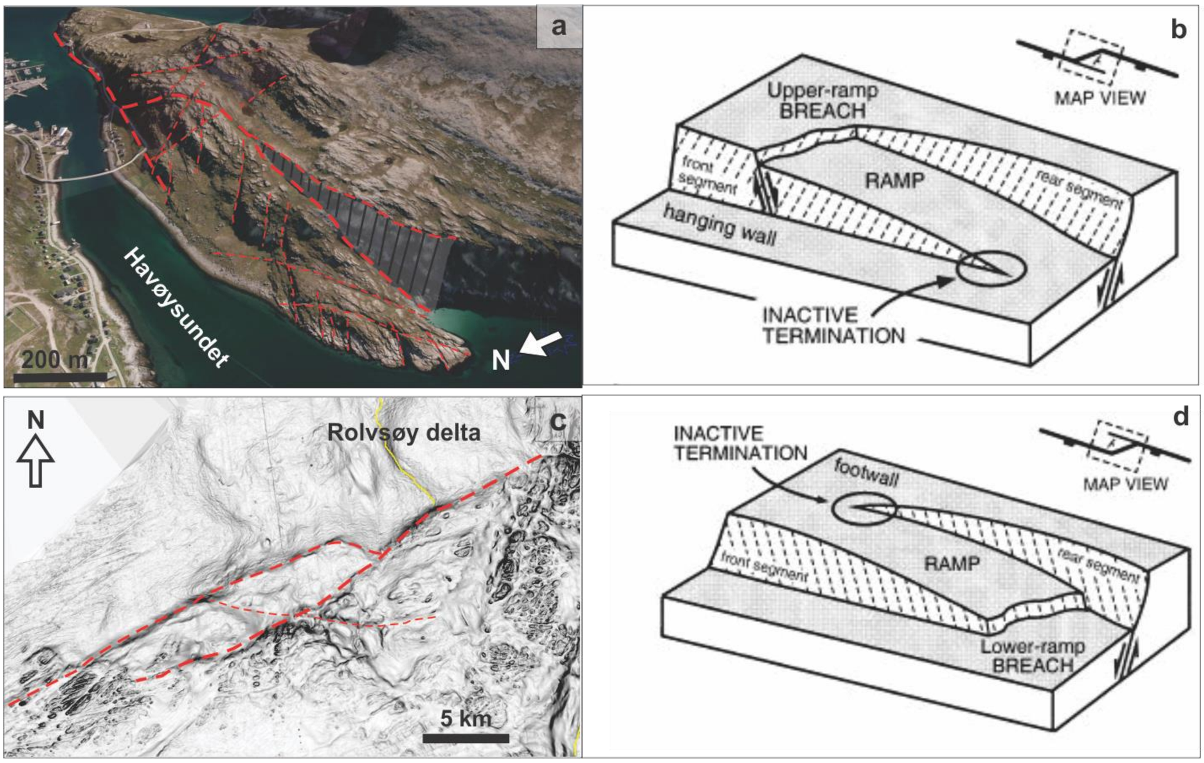

Fig. 4.1 a) Aerial photo of interpreted upper ramp branch structure formed by E-W striking en echelon fault segments in Havøysund. b) Block diagram and map view of upper ramp breach is used as an analouge for the observed structure in Fig. 4.1a. c) Interpreted lower ramp breach of two NE-SW en echelon fault segments on the bathymetry data close to Rolvsøy delta. d) Block diagram and map view of lower ramp branch is used as an analouge fro the observed structure in Fig. 4.1c. For locality, see **Error! Reference source not found.**. The block diagrams are from Crider (2001).

Similar E-W striking possible fault linkage structures are observed on aerial photos between Bakfjorden-Ryggefjorden and Snefjord-Lillefjord areas (Fig. 2.4).The zone that is formed by the linked overlapping lineaments has a sigmoidal shape geometry with internal lineaments that are oblique to the main bounded E-W striking faults. These structures are interpreted as releasing bend geometries and can be formed by oblique slip or strike-slip faulting (Morley et al., 2004). As a consequence, the breached linkage zone may be part of an oblique, releasing bend basin (or a pull-apart basin) in between two NE-SW trending masterfaults with oblique-strike-slip character. The sense of shear on on such faults can than be determined by the geometry of the linking faults seen onshore, suggesting a sinistral sense of slip on both structures (Fig. 4.2). The releasing bend geometry in Fig. 4.2 a and b, is characterized by two E-W fault segments that seem to be located in a small zone of transtension where oblique en echelon faults have started to developed. They have similar geometry as a pull-apart basin, but the en echelon fault does not terminate close to the major E-W boundary segments. Rahe et al. (1998) divided the evolution of pull-apart basins into three main stages of development (inicipent, early and mature) based on the internal structure and geometry. The early stage is characterized with cross-basin faults transect the interior having orientations similar to Riedel shear fractures that are not linked to the main boundary fault, similar to the internal sigmoidal structure seen in Fig. 4.2 a and b. This suggests that onshore E-W trending faults between Bakfjorden and Ryggefjorden may have formed in a similar manner, and potentially, that early stages of pull-apart basins may have formed.

Another observation that supports the presence of oblique-extensional features is seen near the thrust boundary close to Lillefjord that delineates the paragneiss from the meta-sandstone, (Fig. 2.21). This contact is characterized by oblique-extensional fault geometry (Fig. 2.4 and Fig. 4.2 c and d) indicating possibly normal oblique or transtensional reactivation along this thrust boundary. The E-W overlapping lineaments form a lense-shape zone that are characterized by several parallel NE-SW trending faults that are oblique to the main NE-SW trending boundary faults. The internal structures in the sigmoidal structure along the Snefjorden thrust boundary form a similar geometry as extensional strike-slip duplexes that have been described by Woodcock and Fisher (1986). Transtensional and transpressional lense-shaped structures along Trollfjord-Komagelv fault Zone are described on Varanger Peninsula (eastern Finnmark) by Rice and Gayer (1989), which could indicate that the E-W faults seen on Porsanger with these structures could possibly be linked to Trollfjord-Komagelv Fault Zone (splay faults). There is however no kinematic data along this thrust boundary that can support this.

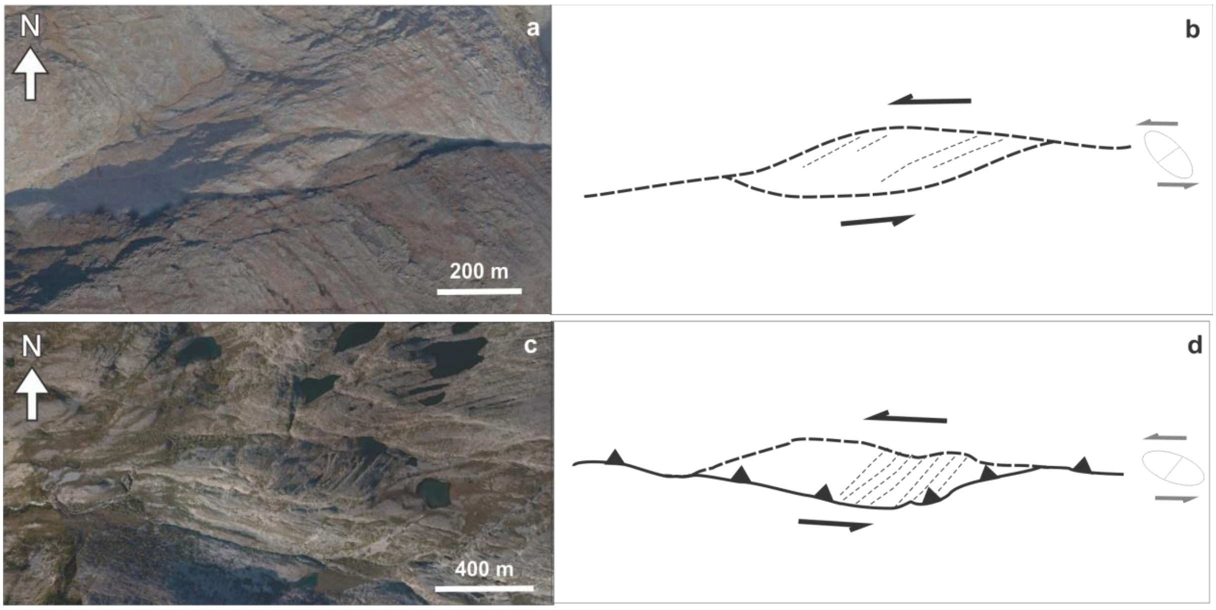

Fig. 4.2 a) Aerial photographs of a sigmoidal topographic depression bounded by E-W striking lineaments that are traced from Bakfjorden and Ryggefjorden. En echelon NE-SW lineaments soft-linking to the main boundary E-W lineaments. b) Aerial photograph of a sigmoidal lense-shape that runs parallel to Snefjorden thrust bounded by E-W lineaments. Internal oblique faults with NE-SW trend that dipping NW seem to terminate towards the main boundary E-W lineaments.

Syntethic-anthitetic faults/graben geometries

Syntethic- antitethic fault geometries are observed in several localities (Chapter 2.3 - 2.9), and these geometries together suggest both orthogonal and/or interacting oblique extension. One example is from Bakfjorden,where a graben geometry of an E-W conjugated fracture set was observed (Fig. 2.14), indicating orthogonal extension. Conjugate faults/fractures generally form synchronously according to Anderson (1951) brittle fault theory (Fossen & Gabrielsen, 2005). They may be used to infer the timing relationships between faults, and to calculate paleostrass axes. Strike-slip conjugate faults in Lillefjord show lateral displacement of an E-W pegmatitic dyke and indicate a N-S maximum stress axis. The NE-SW striking Snefjorden-Slatten fault (Fig. 2.18) also had fault surfaces that change dip direction along strike forming a possible conjugate set, indicating a NW-SE extensional direction and possibly graben formation.

Wedge-shaped graben geometries where observed several places, such as Selvika (Fig. 2.6 b) and Magerøya (Fig. 2.28) formed by two different fracture sets. One fracture set is oblique to the other. An example of wedge-shaped graben geometry where observed in Selvika. An iron-oxidized bed rock marker horizon shows normal offset along the NW-SE trending fault and the bed rock strata/foliation there dip gently towards a major NE-SW trending bounding fault (Fig. 2.6) In combination, these two fault sets interact to produce a graben structure. The NW-SE trending fault of these two faults seems to have largest subsidence.

Another example is observed in Magerøya, (Fig. 2.28) where similar graben geometries are made up of E-W trending fractures and a major NW-SE trending fault. Unfortunately there is no bed marker or other evidence of displacement along these two fracture sets that can confirm that they form a graben. Steep parallel escarpments with N-S to NNE-SSW trend and dip to the E in Magerøya form domino-like geometry (Fig. 2.27). This may be interpreted as rotated fault blocks with boundary normal faults. A light-coloured distinctive horizontal bed rock marker unit is displaced along the NNE-SSW faults and indicates down-to-the-east movement. NW-SE fractures cut and displace the NNE-SSW faults, suggesting the NW-SE faults are younger than the N-S and NNE-SSW faults. These two sets together also form graben geometry, as seen in Fig. 2.27 b. Half-graben geometries are also seen in micro-scale, where a cataclasite with WNW-ESE trend in Lillefjord is cut and displaced by oblique fractures that form a set of fault blocks that show normal dextral offset (Fig. 2.24).

The major NE-SW fault in Selvika (Fig. 2.7) with subsidary faults have same dip-polarity and small normal offsets along the subsidary faults, creating synthetic tilted blocks that are characteristics for half-graben geometries (Gawthorpe & Hurst, 1993). All these observations may support that both oblique-extensional (simple shear) and orthogonal (pure shear) extension has occurred during formation of graben geometries. Oblique-extensional basins form when the trend of basin is oblique to the extension direction, whereas pure extensional graben form when faults strike parallel to the graben by a conjugate set (Boulton & Robertson, 2008).

Fault lenses

Several faults-fractures had large lenses with unconsolidated fault gouge material in between. The fracture lense geometry has been classified using the Riedel fracture classification (Braathen et al., 2009) by describing the bounding surfaces and their relationship to the main fault surface.. This classification of fault lenses indicates the relative movement of the crushed lenses within the fault core (Fig. 2.5). In Havøysund, fault lenses display a rhombic geometry and are interpreted to be bounded by R- and P-shears, indicating normal dextral movement along the low-angle NE-SW fault.

4.1.4 Fault kinematics and fault-fracture trends – populations

In order to further characterise and discuss similarities and/or differences between the variuos fault-fracture trends (NE-SW, E-W, and NW-SE), their kinematics/movement characters where analyzed. Several kinematic indicators used to infer the sense of shear/movement characteristics of faults where observed and measured in the field (see chapter 2.1). Kinematic indicators were also observed in micro-scale (thin-section). Such indicators include surface lineations (slickensides) on fault slip surfaces, offset marker beds, drag folding or rotation of layering/foliations in blocks along major faults (Fossen, 2010). Surface lineations reflect the shear sense, and the movement on the slip surface can also be determined by drag-folding and fault-block rotations (Fossen, 2010). In situations were subsidary fractures can be interpreted as Riedel-shears (Petit, 1987; Dresden, 1991; Fossen & Gabrielsen, 2005), such structures will be discussed in order to determine the overall sense-of shear (see chapter 1.7 for definition). In this chapter, the observed and measured kinematic indicators from the studied areas will be discussed.

In general, the kinematic characteristics of the NE-SW trending faults in the study area indicate predominantly dip-slip normal movement, whereas the NW-SE faults show mainly strike-slip movement with sinistral and dextral components (Fig. 4.3) (see chapters 2.1). The E-W trending faults are characterized mainly with normal dip-slip movement, except in Havøysund/Myrfjord area where slickensides also show oblique dextral slip, whereas the E-W trending faults in Bakfjorden is both dip-slip and oblique-slip. This suggest that the area has undegrone both pure extensional and strike-slip dominated stresses, and further on, in combination makes it most comparable with an oblique extentional or transtensional setting (Boulton & Robertson, 2008).

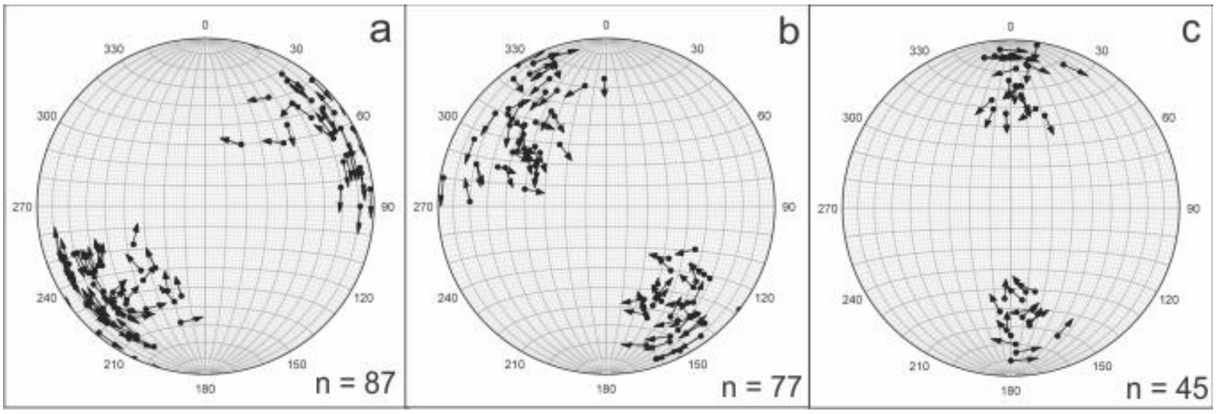

Fig. 4.3 slip-linear plot of the three major fault-fracture trends in Porsanger Peninsula. a) NW-SE trend show mainly oblique-slip. b) NE-SW trend show mainly normal dip-slip, but also normal dextral obliqe-slip. c) E-W trend show mainly normal dip-slip and less dextral oblique-slip.

The best example to illustrate and interpret such aspects of kinematic behaviour, is by using the WNW-ESE trending fault at Lillefjord (Fig. 2.21). There, a set of subsidiary fractures occur at an angle to the main fault/shear zone. These fractures, observed both in outcrop and micro-scale, have different kinematic characters and orientation relative to the main fault zone, that largely match with the Riedel shear theory (Fossen & Gabrielsen, 2005). Riedel shear was first defined by Riedel (1929) and refers to a geometric fracture pattern that develop in relation to faulting, commonly assicoated with faults formed by simple shear (Ahlgren, 2001). The Riedel shear fracture pattern has been documented in natural systems in all scales (Tchalenko, 1970; Rutter et al., 1986), and has also been used to describe the bounding surfaces of fault lenses depending on their angle with respect to the main fault surface (Braathen et al., 2009). This classification of fault lenses indicates the relative movement of the crushed lenses within the fault core (Fig. 2.5) bounded by R- and P-shears to be normal dextral movement along the fault. The angular relationship between the shear/fractures to the main fault varies and depends on a number of factors, such as the mechanical strength of the rock, strain rate and stress state at the time of faulting (Ahlgren, 2001). R-shears are usually the first fractures that develops and form at an approximate angle of 15 degrees to the fault and are followed by P and R'-shear as brittle deformation continues (Fossen, 2010). P-shears are synthetic fractures with a lower angle that R-shear. R´-shears are antithetic faults conjugated with the R-shear. T-shear are extensional veins that show the extensional strain movement perpendicular to the direction of maximum stretching. Three different sets of secondary fractures have been identified in fault rocks sample from Lillefjorden Fig. 2.23. These three fracture sets have similar orientation to the main fault surface as the characteristic Riedel shear pattern (Dresden, 1991). Rutter et al. (1986) show that Riedel shear pattern often develops in micro-scale in both natural and experimental fault gouge and can be used to infer the movement. In their experiment, P-foliation and R-shears were the first micro-structures that developed. Similar pattern are observed in fault rock sample from Lillefjord (Fig. 2.24) The interpreted riedel shear pattern in thin-section from Lillefjord indicate normal dextral movement along the fault surface, that coincides with the foliation-drag seen along the fault surface (Fig. 2.23).

Bed offsets along NW-SE trending faults (Trollfjord-Komagelv Fault Zone trend) show sinistral displacement in both meter- and kilometer-scale observed onshore in Lillefjord and offshore (Magerøya) with bathymetry data. In Lillefjord, a NNE-SSW quartz vein shows 1 m displacement by a NW-SE fault, whereas a lithological boundary at Magerøya shows a 1 km sinistral displacement. Since the cross-cutting relationships do not involve both major fault trends the relative age can not be determined. However, both displacements show sinsistral movement, which can infer that the long-lived Trollfjord-Komagelv fault zone had a sinistral stage of movement.

4.1.5 Discussion of fault rocks

In this chapter, the presence of fault rocks, the different alteration processes observed in thin section that may be a side effect of faulting, and their mineral assemblages (SEM analysis) that can possibly indicate P-T conditions will be discussed. The numerous faults and fracture surfaces observed in Porsanger peninsula show quartz, chlorite, epidote, hematite and biotite precipitations. Fault gouge and cataclasites are very common in the area. The cataclasites are both clast dominated (proto-cataclasites) and matrix dominated (ultracataclasites). Several alteration processes in the fault rock samples are observed, such as chloritization, epidotization, zeolitization and seritization and hematite alteration.

Chloritization and epidotization is an alteration processes associated with mafic minerals (Bruhn et al., 1994). Chlorite is a hydrous phyllosilicate and typically replace the less hydrous mafics at low temperatures when water is available (Winter, 2010). In thin section, various stages of chloritization of biotite were observed (Fig. 2.20). Very fine-grained mica occurs as sericitic alteration of feldspar and is seen in the cataclastic matrix in some samples. The alteration from biotite to chlorite occurs when biotite looses potassium, and may be a side effect to the faulting event when fluids have migrated along the fractures (Bruhn et al., 1994). Fractures with iron-oxide precipitation cuts through/overprint many of the cataclasites suggesting a later stage with Fe-rich fluids flowing through the fault systems.

SEM results indicate the presence of fine-grained matrix consisting of different crushed minerals. These minerals have mainly undergone mechanically reduction (crushing) of the host rock material with minor evidence of new growing minerals. The mechanically crushed fault product may form under shallow crustal depth with low temperature and pressure. Some low-grade metamorphic minerals where present in the fault rocks, such as chlorite and epidote. These minerals are not particularly diagnostic since they have a wide range of stability, but these greenschist-facies minerals are indicative of a minimum temperature during the formation of cataclasites of c. 300°C (Bucher & Grapes, 2011). Vein-filling zeolitization of numerous small E-W trending extenional joints in Snefjorden indicate formation under zeolite facies metamorphic conditions that form at temperature up to 300°C and pressures less than 500 MPa (Bucher & Grapes, 2011). Zeolite minerals were also observed in a cataclasite at Magerøya where they are found in extensional veins and seem to be affected by cataclastic deformation (Fig. 2.29), which indicate a late cataclastic fracturation under zeolite metamorphic facies.

The SEM result show that the zeolite minerals is a calsium-bearing mineral and the most common are laumontite, stilbite and heulandite. Stilbite and Heulandite usually have tabular or sheet-like aggregates crystal habit (Nesse, 2000), whereas Laumontite form prismatic crystals, which correlates well with the minerals observed in Snefjord and Magerøya (Fig. 2.17 and Fig. 2.28). Laumontite appears at greater depth and higher temperatures (than the other calsium-bearing zeolites) and forms from heulandite at lower pressures and from stilbite at higher pressures (Nesse, 2000; Bucher & Grapes, 2011). The formation of laumontite occurs between 180-260 °C with an upper pressure limit at 300 MPa. Fig. 4.4 show that the zeolite-pumpellyite facies boundary (laumontite are replaced by pumpellyite) occur around 270 °C with geoterm of 30°C/km (Bucher & Grapes, 2011).

However, the laumontite minerals in Snefjord seem to cross-cut major NE-SW fault-fractures in the area and do not seem to be affected by deformation, suggesting that the zeolite veins occur during a later rifting stage and post-date the NW-SE fractures and fault slip of the NE-SW faults. In Magerøya, the laumontite minerals seem to be affected by cataclastic deformation that cuts the greenschist facies fracturation, which indicating a late cataclastic fracturation under syn/post laumontite metamorphic facies.

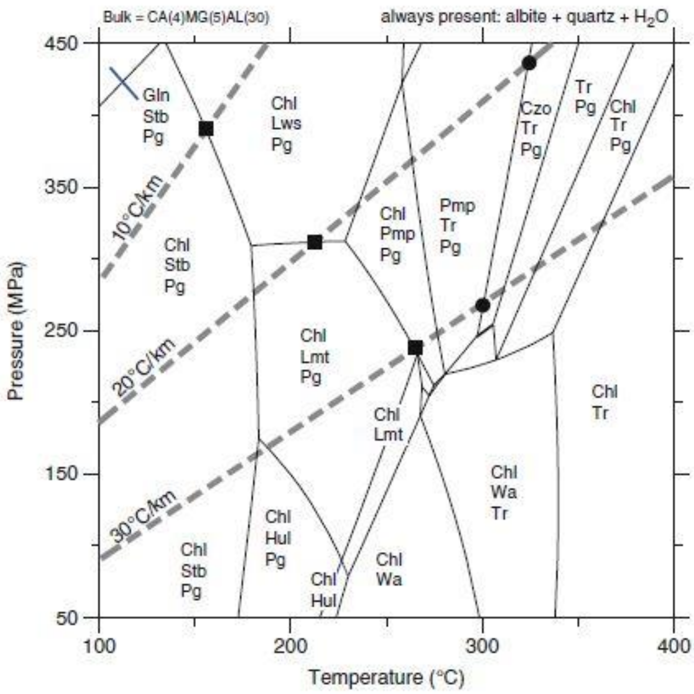

Fig. 4.4 P-T diagram of low-grade minerals and stability fields from Bucher and Grapes (2011). Dashed lines represent geothermal gradients. Upper T-limit of zeolite indicated by black squares, beginning of greenschist facies marked by black circles. Mineral abbrevations: Lmt: laumontite, Chl: Chlorite, Hul: heulandite, Pg: paragonite, Wa: wairakite, Tr: tremolite, Lws: lawsonite, Stb: stilbite, Pmp: pumpellyite, Gln: glaucophane.

These low-grade minerals found in fault rock and veins (laumontite, chlorite) form at shallower crustal depths than the mineral assemblages in fault rocks found further south. P-T studies in Troms by Indrevær et al. (2014) show greenschist facies during early stages of faulting (ca 300°C and 240 MPa) indicating burial of ca 10 km depth, and a later stage with pumpellyite (ca 275°C and 220 Mpa) yielding a burial of ca. 8,5 km depth, while Lofoten area indicate lower metamorphic grade (Davids et al., 2013). Laumontite and chlorite may form at temperatures ranging from 220-270 ºC, suggesting formation at a crustal depth around 7-9 km with a normal geothermal gradient (30 ºC/km).

4.1.6 Fault-fracture correlation and relative time constraints

The studied regional fault-fracture sets and their large and mesoscale geometry and kinematics in the onshore areas on the Porsanger Peninsula have been used to tentatively correlate with similar trends and structures on the Finnmark Platform (Fig. 3.8). Notably, the two dominant trends onshore, i.e. NE-SW and NW-SE, can be linked up to the major NE-SW basin-bounding faults offshore, such as the Troms-Finnmark Fault Complex and Måsøya Fault Complex and possible the major NW-SE fault systems (Trollfjord Komagelv Fault Zone). These major structures are all long-lived faults formed in the Neoproterozoic (Trollfjord-Komagelv

Fault Zone) and Paleozoic (Carboniferous, i.e. Nordkapp basin), and both of these trends are thought to have been reactivated several times (Roberts et al., 1997; Herrevold et al., 2009). The nature and size of reactivation may affect the overprint evidence, so that earlier movements are masked and both major fault trends may be active at the same time. This makes it challenging to determine relative timing of fault activity, and thus also to propose a valid tectonic model for the area. A few cross-cutting relations of fault and fractures where observed in the area and will be discussed in this chapter. Timing constraints from previous studies of brittle fracture-faults in Troms, Lofoten-Vesterålen and Eastern Finnmark will be compared.

Distinct and reliable cross-cutting relationships are generally lacking in the studied area, but the few observations are included here as it is interesting to compare them with results from previous studies (Bergh et al., 2007; Hansen & Bergh, 2012).

The NNW-SSE and NNE-SSW trending fractures are orthogonal (conjugate geometries) suggesting synchronous formation. These conjugate fractures (Fig. 2.22) are cut and displaced by NW-SE striking fault and show 1 meter lateral displacement in Lillefjord (Fig. 2.21b). This suggest that the NNE-SSW quartz-filled fracture is older than the NW-SE fault. Similar cross-cutting relations by these two trends is also seen in Magerøya where N-S and NNE-SSW trending fractures are cut and displaced by NW-SE striking fractures (Fig. 2.27).
In Snefjord, a NW-SE fracture is cut by NE-SW trending fault (Fig. 2.17) suggesting that the NE-SW trending fault is younger. In addition, fracture surfaces with a NW-SE trend show less slickensides which can suggest that they are older than the NE-SW fractures. On the bathymetry, NW-SE planar lineaments are cut and displaced with 0,5 m by NE-SW faults (Fig. 3.3c) which also suggest that the NW-SE faults are older.
E-W fractures cut NNW-SSE and NW-SE fractures and displace them by 0,5 m in Skjarvodden (Fig. 2.10), suggesting the E-W fractures are younger. The E-W fractures filled with zeolite cut both NW-SE fractures and NE-SW faults in Snefjord, indicating the E-W fault-fractures possibly formed at a late rifting stage (Fig. 2.17). However, there is no observed cross-cutting relations of the NE-SW and E-W and can therefore not determine if these trends formed simultaneously or at different times.

From these observations the time-relationship of the faults onshore on the Porsanger Peninsula (including observations from Magerøya) indicate relative age to be (starting with the oldest set):

1. N-S to NNE-SSW
2. NW-SE
3. NE-SW and E-W

Onshore faults and fractures with similar trend have been described from Lofoten-Vesterålen (Bergh et al., 2007; Hansen & Bergh, 2012) and time constrains of the different fault-fracture sets have been divided into three stages, proposed to be:

1. The N-S to NNE-SSW faults-fracture represent first faulting event.
2. The NE-SW faults-fracture set represent second fault event, and have been suggested to be younger/ or developed simultaneously with the the ENE-WSW to E-W striking faults.
3. NW-SE represent the youngest faulting event

The NW-SE trend in the study area differs from the relative timing further south, and is most likely due to the closely located Trollfjord-Komagelv Fault Zone that have been suggested to be active since Neoprotozoic age (Siedlecki & Siedlecka, 1967), and later been reactivated as an extensional fault. Dated NW-SE dolerite dyke in Magerøya yield Early Carboniferous age (Roberts et al., 1991; Lippard & Prestvik, 1997), and Early Carboniferous syn-rift sediments are described along NW-SE trending faults offshore in eastern Finnmark (Bugge et al., 1995). The relative timing of the brittle fault trends is uncertain and there is limited data, such as cross-cutting relationship available in the sudy area. It is possible that the brittle faults and fractures formed synchroneously during the WNW-ESE directed extension, causing the formation of NE-SW to E-W normal faults (i.e. Hammerfest and Nordkapp basin trend), while the NW-SE trend (i.e. the Trollfjord-Komagelv Fault trend) have then formed as accomodation, transfer zones (Fig. 4.5). Alternatively, the NW-SE striking brittle faults formed first and separately from the NE-SW and E-W brittle fault-fracture trends. However, more data is needed to clearify this.

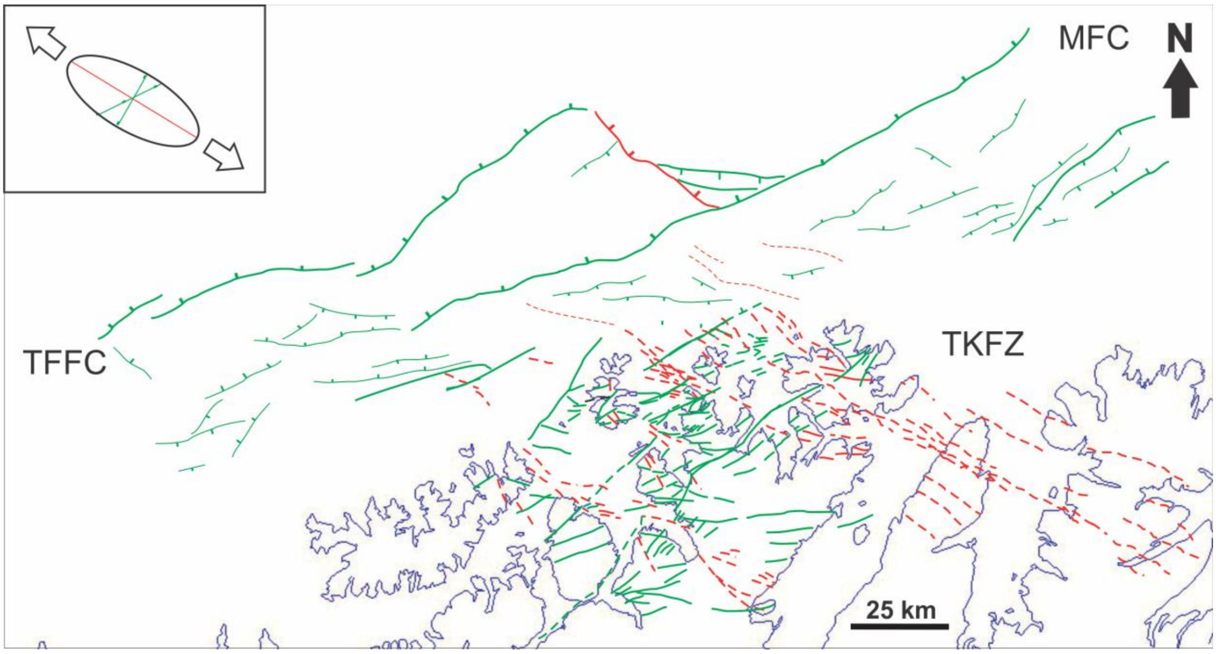

Fig. 4.5 sketch of a possible extensional strain field scenario if the brittle faults formed synchroneously. WNW-ESE directed extension cause normal faults of NE-SW and ENE-WSW (i.e. Nordkapp basin trend) striking faults (marked in green), while the NW-SE (i.e. the Trollfjord-Komagelv fault trend) form synchroneously as accomodation transfer zones (marked in red).

The studied regional fault-fracture sets and their large and mesoscale geometry and kinematics in the onshore areas on the Porsanger Peninsula show different characteristics. The NE-SW trend is characterized by mainly normal dip-slip movement with both planar and listric geometry, and can be linked up to the major NE-SW basin-bounding faults offshore, such as the Troms-Finnmark Fault Complex and Måsøya Fault Complex that are related to Paleozoic (Carboniferous, i.e. Hammerfest and Nordkapp basin). The NW-SE trend are characterized with mainly steep planar fault that dip dominantly towards the NW and can be linked up to the major NW-SE striking Trollfjord Komagelv Fault Zone that are a long-lived faults formed in the NeoProterozoic. The E-W trends are mainly characterized with normal dip-slip movement and with less oblique dextral component.

4.2 Discussion of offshore data

4.2.1 Bathymetry; shallow shelf

The shelf areas between Sørøya and Magerøya is characterized by both glacial and structural lineaments. The prominent NE-SW structural trend on the shallow shelf links up with a similar trend onshore, and further offshore, this trend is associated with the Palaeozoic-Mesozoic basin formation (Troms-Finnmark Fault Complex and Måsøy Fault Complex).

Possible fault linkage structures were also observed on the bathymetry expressed as relatively steep topographic escarpments trending NE-SW that are parallel and overlapping, thus forming a relay structure between them (Fig. 4.1 c and d). The fault linkage cuts across the lower part of the ramp and is interpreted as a lower ramp breach, suggesting echelon fault segments with same sense of step and oblique slip (Crider, 2001).

The high frequency of parallel NW-SE striking lineaments on the shelf on the western side outside Havøysund and Hjelmsøya (Fig. 3.2) suggest the presence of a major fault. The deep distinctive escarpment on the shelf is possibly due to erosion, since the Hjelmsøya delta is deposited not far away. Glacial lineations also form several lineaments that are parallel to each other, but are usually not as prominent with high escarpment. This make it more reasonable to suggest that the erosion in this area is controlled by these NW-SE weakness zones (faults) in the bedrock.

Townsend (1987) suggested that the E-W trending fault close to the coast of Finnmark,(through Havøysundet) indicated in the bathymetry data of Vorren et al. (1986) is linked to the Trollfjord Komagelv Fault as a continuation or a splay from this major fault. This was also based on the E-W trending faults that have been described onshore on the Varanger Peninsula and are related to the Trollfjord-Komagelv Fault Zone (Johnson et al., 1978). (Gabrielsen and Færseth (1989) argued that it was more reasonable to link the E-W fault to the Troms-Finnmark Fault Complex. The onshore data support that the E-W trending narrow sound is fault controlled and the distinctive NW-SE striking lineaments (Fig. 3.2) could possibly be a continuation of this fault, since the Trollfjord-Komagelv Fault Zone has been described by both NW-SE and E-W trending segments. The NW-SE trending dykes interpreted from magnetic anomaly data and NW-SE trending lineaments from DEM/bathymetry data suggest that the Trollfjord-Komagelv Fault Zone is a fault system with complex geometry that conisist of numerous segments of various length with both NW-SE and E-W trend. The Trollfjord Komagelv Fault Zone seem to splay out on Magerøya.

The complex geometry of lineaments in Ryggefjorden (Fig. 3.4) have similar geometry as an oblique-extensional/transtentional basin bounded by major NE-SW faults (the same trend as the fjord) with oblique normal rotated fault blocks with respect to the main boundary faults. There are two set of oblique trends, one is cross-cutting the fjord and can be traced onshore as lineaments observed on the DEM. The other oblique trend seems to be an internal structure in the fjord, terminating towards the major NE-SW boundary faults. The 3D view in Global Mapper demonstrates very well the domino-geometry of blocks that are delineated by straight lineaments interpreted as normal faults. The E-W lineaments that cut through the main NE-

SW boundary faults do not support an internal oblique extenional basin or pull-apart basin. Hovewer, these cutting through E-W faults could be formed in a later stage. The ENE-WSW oblique faults in segment 2 (Fig. 3.4) seem to be have an irregular pattern with the main boundary faults which support rather an extensional basin with activation of pre-existing ENE-WSW faults than a pull-apart basin. Similar rift oblique pattern have been described by Morley et al. (2004) from rift basins in Thailand. Fig. 4.6 show different splay geometries in map view found in rift basins of Thailand that have been influenced by the pre-existing fabric (Morley et al., 2004). Although this complex pattern of lineaments are similar to fault and basin geometry, it is of course uncertain since this can only be seen in map view (including 3D view) of the bathymetry data and there is unfortunately no seismic data that can study the fault pattern in cross-section.

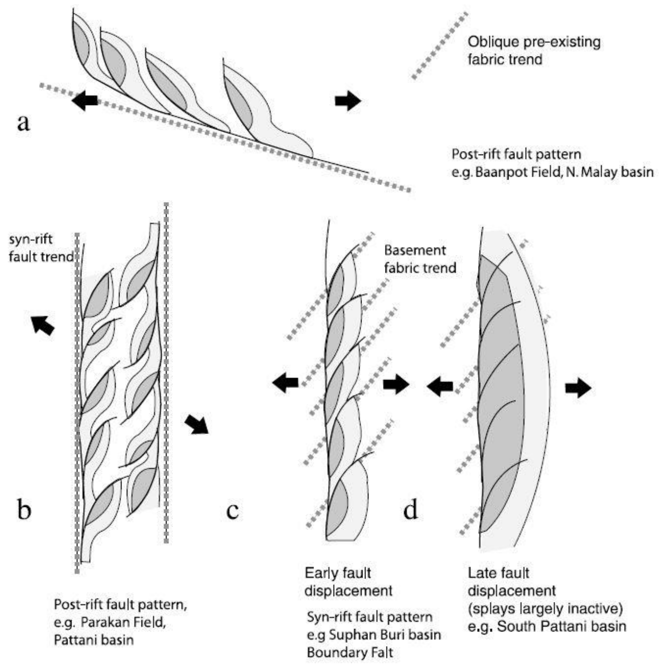

Fig. 4.6 Illustration of splay geometries in map view influenced by pre-existing fabric leading to either splays sub-orthogonal or oblique to the extension direction. From Morley et al. (2004)

4.2.2 Seismic data: Finnmark Platform and Gjesvær low

Based on the interpreted seismic sections (chapter 3.3), the offshore margin architecture consist of basement rocks (gneissic and quartzitic meta-sediments) overlain by two major sedimentary sequences. The sedimentary sequences have been identified as: i) Upper Paleozoic sedimentary rocks that experiences a gradual thickness increase (especially in Early Carboniferous) towards the basin-bounding faults and, ii) Mesozoic sequence that displays a fairly constant thickness throughout the study area. There is also identified a thin sediment package of Cenozoic age in all the seimsic sections, but this sequence is substantially thicker in the Hammerfest basin.

The sedimentary stratigraphy is build on Statoils regional interpretation (Henningsen, pers. Comm. 2016) that is based on several wells (Table 1). The location of these wells will constitute an uncertainty in the stratigraphic interpretation since there is no direct tie well in the study area. This uncertianty places in question the reliability of the stratigraphic interpretations, especially the lowermost key horizons (Top Basement, Intra Early Carboniferous horizon, Mid Carboniferous horizon etc.). Top Basement is easily identifiable on the Finnmark Platform, as it represents the boundary between the chaotic/diffuse and more stratified continous seismic facies (Fig. 3.7). However, the Top Basement horizon is more diffuse in the deeper parts of the basin in Gjesvær low and Hammerfest Basin. The interpreted Intra Early Carboniferous horizon is mapped as the deepest strongest reflection, formed by coal beds in the eastern part of the platform (Henningsen, pers. comm. 2016). On the western part, the strong reflection is most likely an unconformity with an overlying dowlapping sequence that most likely represent fan deposits. This interpretation gives an interval between top Basement and the Intra Carboniferous Horizon that is undefined and show thickening in the basins. A significant thickening of this interval is especially seen in seismic profile 3 (Fig. 3.11) in Gjesvær low (see later discussion).

The Finnmark Platform and the adjacent areas offshore (Gjesvær low and the southern part of the Hammerfest basin) are dominated by NE-SW to ENE-WSW faults that display listric geometry. Especially the major Troms-Finnmark Fault Complex and the Måsøya Fault Complex and the major E-W fault that delineates Gjesvær low. A major NW-SE fault inbetween the Troms-Finnmark Fault Complex and Måsøya Fault Complex differ in both steepnes and seem to have less seem to have less listric, more planar geometry. The major NW-SE fault was considered as a fault segment belonging to the en echelon stepping Troms-Finnmark Fault Complex (Gabrielsen, 1984) but have later been suggested to be a continuation of the major Trollfjord-Komagelv Fault Zone that is partly running onshore (Gabrielsen & Færseth, 1989), The continuation of the prominent NW-SE structure is not easily traced on the 2D seismic lines on Finnmark Platform towards the mainland, which would be expected since it has been proposed to be related to the Trollfjord-Komagelv Fault Zone (Gabrielsen & Færseth, 1989). The explanation to this could be that strike-slip faults are less well imaged by the seimsic reflection due to their steep, almost vertical dip (Barka & Kadinsky-Cade, 1998). Hovewer, vertical zones of disturbances in the seismic signature and discontinuation has been recognized on the Finnmark Platform that could possibly be strike-slip faults linked to Trollfjord-Komagelv Fault Zone. This disturbance on the seismic imaging could also be formed by artefacts, but is more unlikely since the disturbance can be traced on several seismic lines. On top of these disturbed reflection, a larger zone of acoustic masking that may represent gas leakage, in that case, this would support that there could be a fault in that area where fluids have been migrated. In seismic section 3 (Fig. 3.11), several shallower faults below the Base Paleogene horizon in the Hammerfest basin seems to branch into a major fault with very steep, almost vertical geometry that can be traced down to the basement that have a stepping geometry downwards. This could also be the continuation of the NW-SE fault segment between Troms-Finnmark fault Complex and Måsøya Fault Complex, but the orientation of this fault have not been mapped further by the 2D lines in this study.The normal displacement along the steep subsidary faults do not display any rift-infill geometry or thickness along these faults in the upper part suggesting that the graben structure could possibly be a a late reactivating structure under strike-slip regime, rather than pure extension. A possible conitnuation of the NW-SE fault segment have been mapped in that area by Berglund et al. 1986 and are parallel with the NW-SE Trollfjord-Komagelv trend.

The interpreted seismic section 3 (Fig. 3.11) shows that the Gjesvær low has a large area between the interpreted intra Early Carbonfierous horizon and top Basement horizon with strong seismic reflections that are tilted and parallel that have been proposed to be Caledonian collapse structures (Johansen et al., 1994) or it can represent possibly rotated fault blocks. If these reflections are rotated fault blocks, the sediments deposited on top in the half-graben filled spaces would then be older than Carboniferous age, which suggest that Gjesvær low is a possible Devonian basin. It has been speculated that sedimentary infill in the shallow half-graben on the Finnmark Platform have deposits of possibly Devonian age (Roberts et al., 2011). The seismic reflections below the interpreted intra Early Carboniferous horizon are weakly stratified and lap onto the tilted reflection (rotated fault blocks) suggesting that this is sedimentary. Since the base Carboniferous is not mapped, this could also possibly represent Carboniferous age. If the southward tilted reflection is Caledonian collapse, these reflection could possibly be back-trusts since they are tilted towards the mainland. The wavy character seen in the reflection close to the thrusts can possibly represent folds that would fit well with the thrusting model. These wavy reflections can also be due to the irregular Top Basement. It is also important to mention that these tilted reflection can be artefacts and not represent real structures, and these reflections are not easily traced on the other 2D lines that are nearby.

4.2.3 Implication of rift-margin evolution and basin formation

Based on the discussion above about the major trends of brittle fault-fracture sets (Fig. 3.8), geometry and kinematics from onshore data, combined with bathymetry and seismic interpretation, a tentative model can be proposed and discussed for the structural evolution of Gjesvær low area and the interaction of the major fault systems on the Finnmark Platform (Fig. 4.7). To get an understanding of the whole picture of the rift-margin evolution, the fault activity of the Neoproterozoic Trollfjord-Komagelv Fault Zone have to be considered first. The Trollfjord-Komagelv fault zone initiated as a strike-slip fault in the Neoproterozoic (Siedlecki & Siedlecka, 1967; Rice & Gayer, 1989) and have later been reactivated during extensional events in Early Carboniferous (Lippard & Prestvik, 1997). The post-Caledonian brittle fault activity in the SW Barents Sea margin have occurred since Devonian time, after the orogenic collaps of the Scandinavian Caledonian and rifting and basin formation have last until Cenozoic times (Chapter 1.3.5). The structural trends in southern part og the Barents Sea have dominant NE-SW to ENE-WSW trend (Gabrielsen et al., 1990) that delineates the major Hammerfest and Nordkapp Basin (Troms-Finnmark Fault Complex and Måsøya Fault Complex) and several periods of rift stages are recognized along these faults. The major rifting episode is from Early Carboniferous (possibly Late Devonian) time in the northerneastern part of the SW Barents Sea, while the area further southwest has been most active in the Mesozoic and Cenozoic times (Gabrielsen et al., 1990; Bugge et al., 1995).

The deposition patterns according to pre- syn and post-rift of the sedimentary interval and their seismic reflections and thickness increase towards the major basin-bounding faults makes it possible to determine fault activity on the margin. The Paleozoic sequence indicate increase in thickness towards the Troms-Finnmark Fault Complex and Måsøya Fault Complex and smaller basins on the Finnmark Platform, especially the Early Carboniferous sequence display syn-tectonic wedges along the fault surfaces. The undefined interval between the lowermost interpreted sedimentary horizon (Intra Early Carboniferous) and the Top Basement also show increase in thickening in the basins and could possibly be Late Devonian deposits. This is especially seen in seismic section 3 and 4 (Fig. 3.11 and Fig. 3.12).

The onshore observations may support that both oblique-extensional (simple shear) and orthogonal (pure shear) extension has occurred during formation of graben geometries by the NE-SW to E-W and NW-SE fault-fracture sets, and since these fault-fracture sets are most likely linked to the major fault systems offshore, suggesting that the Carboniferous basins offshore are formed in same manner.

The major NW-SE Trollfjord Komagelv Fault Zone that partly runs onshore in eastern Finnmark have been suggested to continue offshore along the major NW-SE segment (between Troms-Finnmark Fault Complex and Måsøya Fault Complex) and even further out in the Hammerfest Basin (Gabrielsen, 1984; Berglund, Augustson, Færseth, Gjelberg, et al., 1986; Gabrielsen & Færseth, 1989). NW-SE to N-S tranfser zones further southwest segment the major offshore fault systmens on the SW Barents Sea margin (such as the Fugløya transfer zone and Senja tramsfer zone), and influence the changing fault polarity and the stepping manner of the faults

(Olesen et al., 1997; Tsikalas et al., 2001; Tsikalas et al., 2005; Bergh et al., 2007; Indrevær et al., 2013)

The continuation of the Trollfjord-Komagelv Fault zone on the Finnmark Platform is not recognized by the 2D seismic data used in this study. The resolution, and the kilometer grid spacing of the 2D data (described in chapter 1.5.6) make it almost impossible to show this continuation, and this is especially challenging for steeply (almost vertical) faults, that would be expected for the Trollfjord-Komagelv Fault Zone. The NW-SE segment offshore (between Troms-Finnmark Fault Complex and Måsøya Fault Complex) are almost parallel with the Troms-Finnmark Fault Complex, and make it reasonable to suggest this continuation. Although, the aeromagnetic data, DEM/bathymetry show several splaying segments on Magerøya and NW-SE and E-W trending lineaments towards the Porsanger Peninsula that could possibly be related to Trollfjord-Komagelv Fault Zone. Fault surfaces with these trends show kinematics (slickensides) that support this (see chapter 4.1.4). The minor sinsitral strike-slip displacement observed in Magerøya (Fig. 3.3b) could also be an indication that Trollfjord-Komagelv Fault Zone have less displacement further northwest and gradually splays out. The splays and minor offset, and lack of major NW-SE trending faults on the Finnmark Platform could suggest that the Trollfjord-Komagelv Fault Zone do not continue offshore and the NW-SE fault segment offshore is part of the stepping Troms-Finnmark Fault Complex and Måsøya Fault Complex. However, It can not be excluded that Trollfjord-Komagelv Fault Zone may have had an impact on the NW-SE fault offshore, although the 2D seismic data on the Finnmark Platform used in this study do not reveal any clear continuation offshore.

Based on the discussion above, the following tectonic hypotheses are suggested for the Late Paleozoic-Mesozoic major fault systems on the Finnmark Platform and the development of Gjesvær low (Fig. 4.7).

Model 1: Trollfjord-Komagelv Fault Zone control the development of the branching segment between the NE-SW en echelon stepping fault (Troms-Finnmark Fault Complex and Måsøya Fault Complex).

a) The major NW-SE Trollfjord-Komagelv Fault Zone initiated as a strike-slip fault system and continues on the Finnmark Platform and further onshore in the Neoproterozoic.

b) During the NW-SE directed rifting, the NE-SW to ENE-WSW major fault systems (Troms-Finnmark Fault Complex and Måsøya Fault Complex) are believed to be formed simultaneously as normal en echelon right-stepping fault segments that are either isolated or soft-linked (interact and overlap). A relay structure occur between the overlapping segments of Troms-Finnmark Fault Complex and Måsøya Fault Complex and form a ramp that gradually deepening towards the west, forming Gjesvær low. The gradually deepening of Gjesvær low can be seen in of the time-surface of the Intra Early Carboniferous horizon and in seismic section 4 (Fig. 3.12). The Top Basement have a stepping geometry, and this can be due to the fault/fracturing that occurred during the formation of the relay structure.

c) A breaching NW-SE fault segments occur at the lower end of the Gjesvær low and linking the two major stepping fault segments (hanging wall breach). This NW-SE branching segment is most likely controlled by the pre-exisiting weakness zone of the Trollfjord-Komagelv Fault Zone. The Måsøya Fault Complex segment that delineates Gjesvær low from the Finnmark Platform becomes an inactive termination and are not necessarily involved in continued faulting, which can explain the displacement tapered out along strike westwards and the less subsidence along this segment (compare to the fault segments that delineates the Hammerfest Basin and Nordkapp Basin). Fracturing/faulting in Gjesvær low occurred during the development of the relay zone which is common during the development of a relay structure (Fossen & Rotevatn, 2016), which can explain the tilted reflections that are possibly rotated Devonian fault blocks (or Caledonian collapse).

d) Main rifting during the Early Carboniferous time (possibly earlier rifting in Late Devonian after the collapse of Scandinavian Caledonides resulted in Late Devonian sediments). Syn-tectonic wedges are seen along Troms-Finnmark Fault Complex and Måsøya Fault Complex, including minor faults on the Finnmark Platform.

e) During the Mesozoic: SW Barents Sea developed into an intra cratonic basin with low subsidence and sedimentation supply in the Triassic. Rifting in Late Jurassic to Early Cretaceous continued. Reactivation of Troms-Finnmark Fault Complex and Måsøya Fault Complex in Early Cretaceous led to subsidence and rotation of fault blocks. Increase in sediment thickness are seen along Troms-Finnmark Fault Complex and Måsøya Fault Complex. In Late Cretaceous: Equilebrium between sediment supply in the basins/platform areas.

f) Cenozoic: Tectonic uplift of Loppa High north of Hammerfest Basin led to increased sedimentation in the northwestern part of the Hammerfest Basin (Paleogene sequence) Reactivation are seen along Troms-Finnmark Fault Complex. Climate change in Late

Miocene led to periods with glaciations (represent the glacial sediment package above the URU). which led to isostatic uplift of the Barents Sea

Alternatively, the Trollfjord-Komagelv Fault Zone splays out on Magerøya and do not continue offshore. Gjesvær low is a relay ramp formed by NE-SW striking en echelon normal fault segments that link with a NW-SE striking lower breach at the lower end of Gjesvær low.

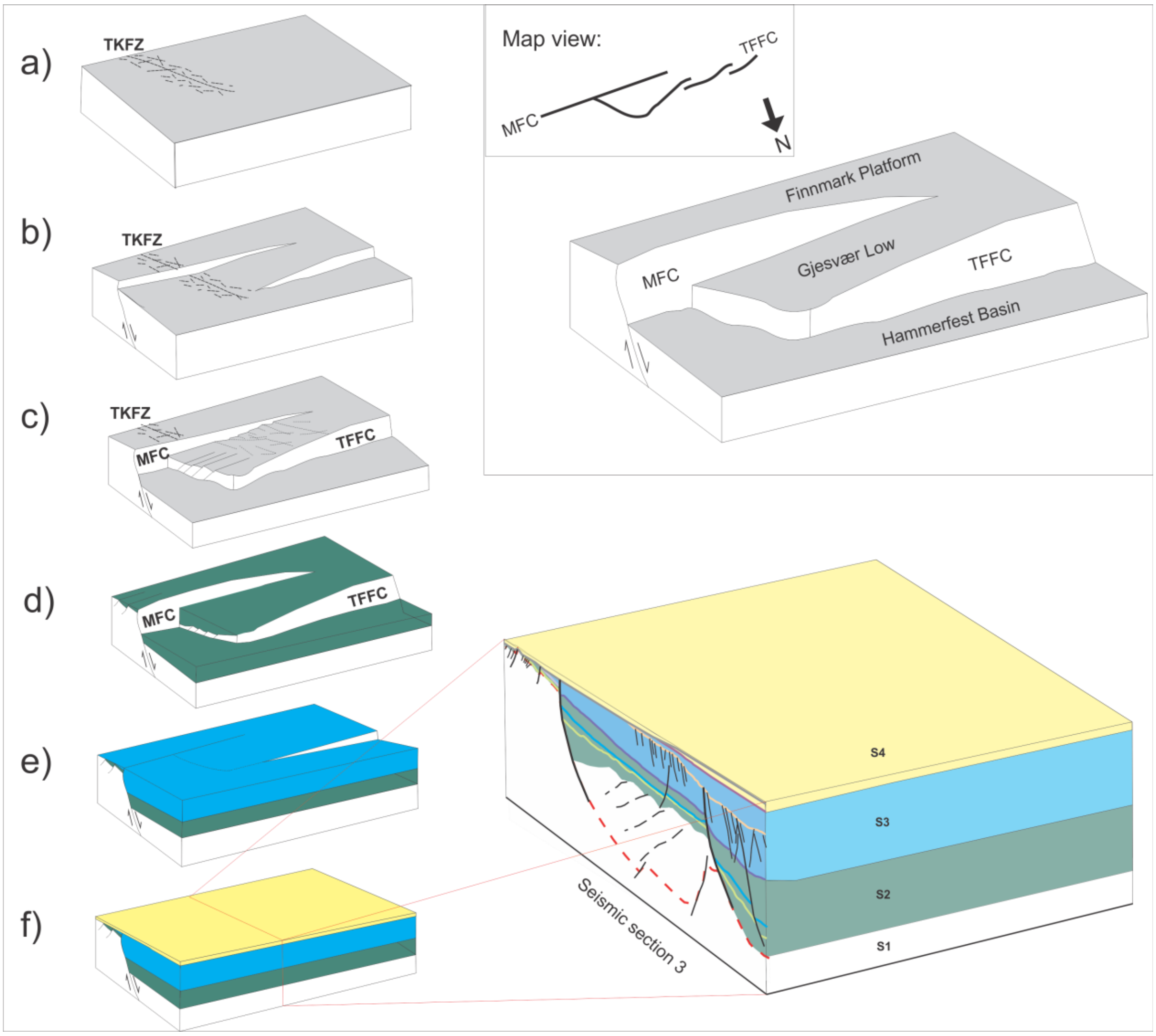

Fig. 4.7 Summary of the proposed structural model of the development of Gjesvær low

5 Conclusion

The present study focuses on the onshore/offshore analysis and correlation of brittle faults and fractures on the Porsanger Peninsula, Magerøya, their shelf areas and the immidiate offshore aeras (Finnmark Platform and Gjesvær low). Structural field observation, interpreted DEM/bathymetric and seismic data, including microstructural and SEM analysis provide the basis for the characterization of the geometry, kinematics and fault rocks to get a better understanding of the regional structural character. The following conclusions can be made by combining the regional, outcrop-scale and micro-scale analysis.

1. Two major structural lineament populations exist in the Porsanger Peninsula area, trending i) NW-SE and ii) NE-SW, and a subsidary E-W trend. The latter trends has the largest impact on the topography and defined a zigzag-rhombic fault pattern.

2. The NE-SW and E-W striking onshore faults and fractures are likely related to the offshore Troms-Finnmark Fault Complex and Måsøya Fault Complex, and can therefore be linked to Palaeozoic (Late-Devonian-Early Carboniferous) basin formation. The NW-SE striking faults and fractures are parallel to the major strike-slip Trollfjord-Komagelv Fault Zone.

3. Kinematic data indicate dominantly normal dip-slip movement along the NE-SW and E-W trending faults, whereas the NW-SE trending faults show mainly oblique-slip. The relative timing of these brittle fault trends is uncertain, but all are possibly related to WNW-ESE directed extension that led to the opening of the NE- Atlantic Ocean.

4. The fault rocks indicate mostly mechanically crushing (frictional) brittle deformation, and show greenschist and zeolite mineral assemblages indicative of shallow cataclastic fracturation. Laumontite minerals indicate maximum P-T conditions of 450 MPa and 260º C giving a maximum burial depth at 9 km. The juxtaposition of lower amphibolite facies host rock with greenschit facies fracturation and zeolite facies fracturation may indicate that the study area is part of a progressively exhumed margin.

5. Bathymetry data reveals three trends of lineaments with NW-SE, NE-SW and E-W orientation that coincide with faults and fractures onshore. Aerial magnetic anomaly data show distinct positive anomalies with WNW-ESE trend offshore and onshore on Magerøya and further east that coincides with the major Trollfjord-Komagelv Fault.

6. The Gjesvær low is a possibly Devonian- Early Carboniferous basin that likely initiated during fault linkage of the overlapping fault segments of the major NE-SW to ENE-WSW basin-bounding faults (Troms-Finnmark Fault Complex and Måsøya Fault Complex) in late Devonian times. There is a NW-SE branch fault segment that connects these two basin bounding faults in the east end of Gjesvær low. This NW-SE fault appears to be related to the major Trollfjord-Komagelv Fault Zone. Fault activity continued along the major basin-bounding faults and the branching NE-SW trending segment. This resulted in further subsidence of Hammerfest Basin and Nordkapp Basin, while Gjesvær low is shallower due to the inactive termination of the Måsøya Fault Complex on the platform. This suggests that the Trollfjord-Komagelv related, NW-SE trending fault segments acted as transfer faults that decoupled the Gjesvær low from deep-basins such as the Nordkapp and Hammerfest basins.

7. The flat-lying ductile foliation in the onshore study area do not seem to influence the localization of brittle faults and fractures, but pre-exisitng zones of weakness along thrust boundaries and possibly older pre-exisitng faults (Trollfjord-Komagelv Fault Zone) may have had an influence.

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