On the evolution of the North Atlantic

-from continental collapse to oceanic accretion

Ph.D. thesis

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Preface

This thesis is based on interpretation and modelling of geophysical data, collected from the subsurface. Like for most scientific data, the interpretation and modelling of geophysical data can result in an infinite amount of models. Therefore, the best we can achieve through carefully modelling is, not unique models, but models which are consistent with our data. If any statements or figures in the thesis still may be perceived to be the only solution, or if the uncertainties of the models are embellished, this will be my mistake alone. Although the supervision from Rolf Mjelde and Berit Hjelstuen has been outstanding, they cannot detect everything. Neither can my co-authors Jörg Ebbing, Ernst Flüh, Audun Libak, Jan Inge Faleide or Hans Thybo.

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A geologist today is only as good as his software

But it *is* still geology

Malcolm Ryder 1996

Introduction

The North Atlantic between Iceland and Svalbard and surrounding continental areas represent an ideal laboratory for studying plate tectonic processes, due to the presence of well exposed continent-continent collision terranes on the Norwegian mainland and dense coverage of offshore geophysical data documenting subsequent extensional processes, continental break-up and formation of oceanic crust.

Interpretation of crustal-scale wide-angle seismic models suggests that the main Caledonian suture might be linked with bodies of lower crustal eclogites localized along the Norwegian continental margin (e.g. Mjelde et al., 2010). Since terrains of eclogites are exposed in the Western Gneiss Region, a wide-angle seismic profile was acquired across the onshore-offshore transition in this area. The main aim with the research work presented in Paper 1 (this thesis) is to identify possible lower crustal high-velocity bodies, and thus the suture, in this region.

Paper 2 aims at interpreting the suture from the North Sea to Svalbard, by use of available crustal scale models. Furthermore, paper 2 discusses the back-stripping of two crustal-scale transects across the Atlantic, in order to identify the dominant tectono-magmatic processes active at various stages of the area's geological evolution. The two transects are located on opposite sides of the Jan Mayen Fracture Zone, which assures that possible change from upper to lower plate configuration along strike can be addressed.

Paper 3 focuses on interpretation of multi-channel seismic data from the Knipovich Ridge. The main aim with this study is to reveal the interplay between tectonism and magmatism along this ultra-slow oceanic spreading ridge. Furthermore, the sedimentary processes transporting huge amounts of sediments from Svalbard, and their interaction with the spreading ridge, will be addressed.

The main contribution with this thesis is that it discusses a selection of tectonic, magmatic and sedimentary processes active during all stages of ocean basin formation, i.e. collapse of a mountain range, formation of a passive continental margin and active oceanic accretion.

In the following chapters I will first briefly describe the tectonic setting and the geological history of the study areas. Secondly, I will explain the different types of data used, and the methods used for the interpretation and modeling. Then, the three papers will be introduced, and lastly I will give a short summary with proposal for future work.

Study area – structural setting and development

The two major Phanerozoic plate tectonic episodes, the Caledonian Orogeny and the break-up of the North Atlantic, divide the tectonic history of the area into three epochs (Eldholm et al., 1987; Eldholm et al., 1989; Blystad et al., 1995). The first phase comprises the closure of the Iapetus Ocean and onset of the Scandian phase of the Caledonian Orogeny (Late Ordovician/Early Silurian-Devonian) (Koenemann, 1993). The sutures resulting from the collision between the Baltica-Laurentia are called the Iapetus Suture Zone (ISZ) (Abramovitz et al., 1999).

The middle phase after the Late Devonian collapse of the Caledonian Orogeny (McClay et al., 1986) was a period of episodic extension, culminating in continental separation between Greenland and Eurasia in the Early Eocene (Talwani and Eldholm, 1977). Three separate main extensional phases occurred between the Caledonian collapse and the North Atlantic break-up (Brekke, 2000): 1) Carboniferous to Permian, 2) Late Mid-Jurassic to Early Cretaceous, 3) Late Cretaceous to Early Eocene. The Late Palaeozoic rift basins formed between Norway and Greenland, and in the western Barents Sea, along the NE-SW Caledonian trend (Brekke et al., 2001; Faleide et al., 2008). The Late Mid-Jurassic-Early Cretaceous rift episode is responsible for the development of major deep basins which continued to develop by subsidence along the rift axis of the North Sea, in the Møre and Vøring basins, Jameson Land, and the Harstad, Tromsø and Sørvestnaget basins, and probably their north Greenland conjugate parts. Thus, the next major rift episode took place within a region of greatly accentuated lithospheric relief (Eldholm et al., 2002). The Late Jurassic-Early Cretaceous rift episode, in particular, is characterized by considerable crustal extension, and thinning (Gabrielsen et al., 1999). At the onset of the Late Cretaceous rifting, the area between Norway and Greenland was an epicontinental sea covering a region in which the crust had been attenuated by the multiple post-Caledonian rift events (Doré, 1991). Eldholm et al. (2002) points out that there is little direct tectono-stratigraphic evidence to precisely date the onset of the Late Creatceous-Paleocene rift episode leading to complete lithospheric break-up. However, in the northern Vøring Basin Ren et al. (1998) and Skogseid et al. (2000) inferred that rifting occurred for a ca 20 myr period prior to break-up at ca 55 Ma. In Palaeocene (63-62 Ma) the rift was affected by the impingement of the Icelandic mantle plume beneath the thinned lithosphere, which induced considerable regional uplift (Skogseid et al., 1992; Saunders et al., 1997; Mjelde et al., 1998). There is, however, not a complete consensus about the role of the Icelandic Plume in the break-up process.

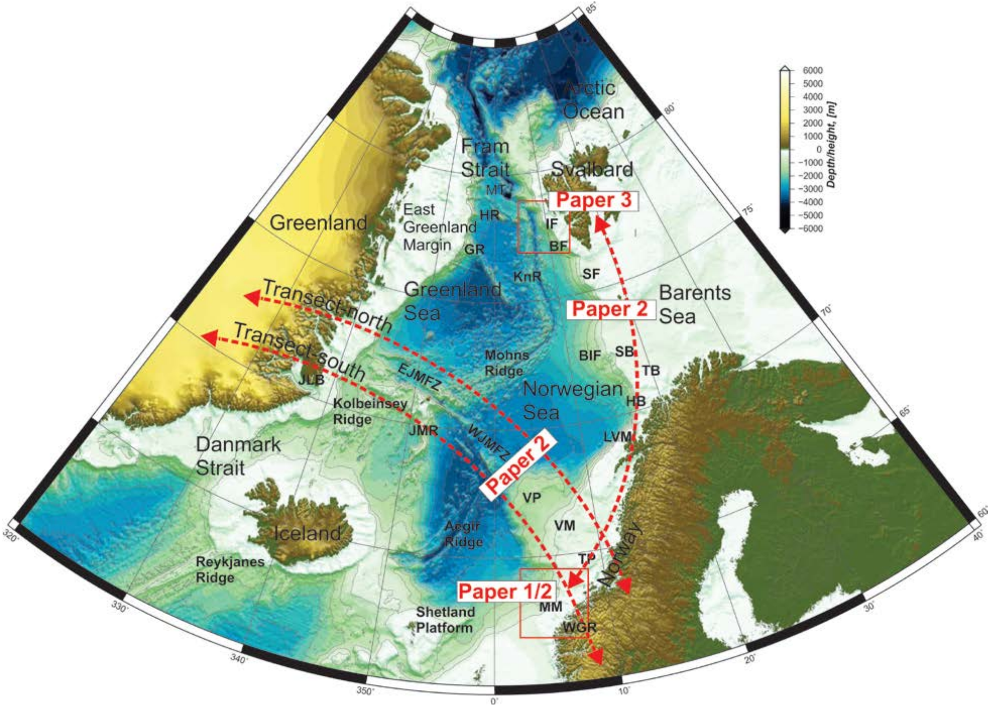

Figure 1. Bathymetric/topographic map for the North-Atlantic. The two study areas and the two cross-Atlantic transects. BF= Bellsund Fan, BIF= Bear Island Fan, EJMFZ= East Jan Mayen Fracture Zone, GR= Greenland Ridge, HB= Harstad Basin, HR=Hovgard Ridge, IF=Isfjorden Fan, JLB= Jameson Land Basin, KnR=Knipovich Ridge, LVM= Lofoten-Vesterålen Margin, MM=Møre Margin, MT= Molloy Through, SF=Storfjorden Fan, SB= Sørvestnaget Basin, TB= Tromsø Basin, TP=Trøndelag Platform, VM=Vøring Margin, VP=Vøring Plateau and WJMFZ=West Jan Mayen Fracture Zone. Data for depth and highs from ETOPO2: http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.

The last phase, from Early Eocene to Present, is a period characterized by active seafloor spreading (Eldholm et al., 1987; Eldholm et al., 1989). From the North Atlantic break-up in Early Eocene to early Oligocene Greenland was acting as a separate continental plate with active seafloor spreading in the Labrador Sea and on the Gakkel Ridge (Kristoffersen and Talwani, 1977). This movement resulted in transpression between East Greenland and Svalbard, which generated the Spitsbergen Orogeny and the Spitsbergen Shear Zone (Crane et al., 2001). When the transpression between East Greenland and Svalbard terminated, the area was exposed to stretching (Talwani and Eldholm, 1977) and ultimately to seafloor spreading when the Knipovich Spreading Ridge propagated northwards (Eldholm et al., 1984).

The major glaciations of Scandinavia and the Barents Sea – Svalbard area started at 2.5–2.8 Ma (Mangerud et al., 1996). During this period the Northern Hemisphere has been exposed to numerous glaciations. During the Weichselian, three major glacial advances have been documented on western Svalbard (Mangerud et al., 1998). Huge trough-mouth fans have been deposited along the NE-Atlantic Margin, with the Bellsund, Isfjorden and Kongsfjorden fans as the dominating fan systems (Faleide et al., 1996) (Fig. 1).

Methods

Two types of seismic data are used in the study; 1) Multichannel 2D seismic data (MCS) from both industrial and academic surveys are used for interpretation and construction of the upper part of the seismic wide-angle velocity-depth models; 2) Wide-angle seismic data recorded by ocean bottom seismometers (OBS) and land-stations are used for constructing the deeper part of the depth-velocity models. The physical principles are the same for both types of seismic data; energy in the form of body waves, which can propagate through the interior of an elastic solid, is generated by airguns or explosives, and the up-coming wave-field is recorded by sensors. In order to create a continuous image of the underground, with high signal to noise ratio, the MCS data are recorded by a dense collection of hydrophones mounted inside a 5-6 km long cable, which is towed behind a ship. This allows energy from each subsurface reflection point to be recorded multiple times, and the signal-to-noise ratio will hence be substantially improved. The main use of MCS data, however, is for hydrocarbon exploration. Hence, the resolution of these data is very good in the upper (sedimentary) part of the profiles, but correspondingly poor in the deeper (crystalline crustal) parts. Although reflections from the Moho (PmP-phase, Fig. 2a) theoretically can be observed on MCS data acquired with a 5-6 km long streamer, wide-angle seismic data with longer source-receiver distance is needed in order to record refractions from the top of the mantle (Pn-phase). For a Moho-depth of 30 km and P-wave velocity of the crust and top mantle of 6 km/s and 8 km/s, respectively, we need a minimum source-receiver distance of about 70 km to record Pn-phases (Fig. 2a). Consequently, we have to use wide-angle seismic data to construct a velocity model of the crust and upper mantle. There are, in addition, several other advantages with wide-angle data compared to MCS data: the receivers can be 3-component, with one vertical and two horizontal geophones, which also allows for the recording of S-waves, and the deployment of the recording instruments at the sea bottom usually provide good signal-to-noise ratio. However, a drawback is that the coupling to the ground, which is difficult to control when the instrument is submerged, is critical for the data quality. No stacking to improve the signal to noise ratio is normally possible due to large receiver spacing.

Modelling of wide-angle seismic data is normally achieved either by forward modelling or seismic tomography (inverse modelling), or by a combination of both approaches. All these approaches are based on the same input, namely travel-time data. One obvious advantage of using inversion instead of forward modelling is that inversion implies a more objective interpretation of the seismograms. When preparing input data for forward modelling, all the interpreted arrivals have to be manually assigned with uncertainties. Furthermore, they need to be organized into different refraction and reflection arrival groups, according to their apparent velocity and travel-time. When the interpreter is preparing data for inversion, only the first arrivals are picked. In some inversion codes, one reflection phase is picked in addition (e.g. Tomo2D, (Korenaga et al., 2000), and in other inversion codes several reflection phases are picked (e.g. Jive3D, (Hobro et al., 2003). However, the final velocity model will have to be both damped and smoothed, and will thereby represent a blurred picture of the real structures (Koulakov et al., 2010). Forward modelling is indubitably a more subjective method. Guided by the depth-converted starting model, the interpreter tries to match the observed calculated travel-time curves with the observed travel-time curves, using every available reflection- and refraction phase (not necessarily first-arrivals) in the seismograms. More data, and subsequently more details, are expected to be modelled when using forward modelling. Nevertheless, there is always a risk of over-parameterization, and the number and spacing of nodes may bias the final model (White and Smith, 2009). Another limitation is the restricted possibility of exploring the velocity-depth ambiguity of the models (White and Smith, 2009). Although the velocity-depth ambiguity is easier to explore and display with inversion codes, it will also constitute a challenge when using seismic tomography.

The inversion codes Tomo2D (Korenaga et al., 2000) and PROFIT (Koulakov et al., 2010) were tested during the initial phase of modelling, but without satisfactory results. Consequently, the geophysical modelling of the profiles in this study are performed with the combined forward/inverse modelling software package Rayinvr (Zelt and Ellis, 1988; Zelt and Smith, 1992). Rayinvr is a layered-based forward modelling and inversion code that permits the use of all observed phases, both refractions and reflections. In order to constrain the velocity model, synthetic seismograms were created by solving the 2D acoustic wave-equation in the time-domain using finite-differences. We applied seismic reciprocity in both the travel-time modelling and in the simulation of synthetic seismograms. The source was placed at the OBS position, and calculations were done at the shot positions. This is valid in acoustic simulations and results in a significant reduction in computational cost. Ultimately, the final depth-velocity models were validated within a 3D model of the Møre Margin (Reynisson, 2010).

The development of an S-wave model, in addition to the existing P-wave model, is done in order to estimate the Vp/Vs ratios. This parameter is an effective indicator of the quartz content in a rock. The S-wave modelling is also performed with Rayinvr (Zelt and Ellis, 1988; Zelt and Smith, 1992). The standard modelling approach is to keep the boundaries in the existing P-wave model fixed, and only vary the Vp/Vs ratios and the converting boundaries until a satisfactory match is achieved.

The Vp/Vs ratio will inevitably inherit both the independent uncertainties of Vp and Vs. Together with the uncertainty connected to the converting boundaries, this will cause ambiguities in the final Vp/Vs model. However, careful modelling of the Vp/Vs ratio allows for a qualitative separation of rocks into mafic, intermediate and felsic composition. Figure 2b shows the most common types of seismic arrivals detected by the horizontal geophones in the seismic instruments. The PPS-phase travels most of the ray-path as P-wave, as the conversion to S-wave occurs on the way up to the OBS instrument. The Sg- and SmS arrivals are common PSS-phases. For these phases the conversion occurs when the wave is travelling downwards. Despite the multiple conversion phases mentioned above, the ray coverage of the final Vp/Vs model is normally less extensive compared with the corresponding P-wave-model.

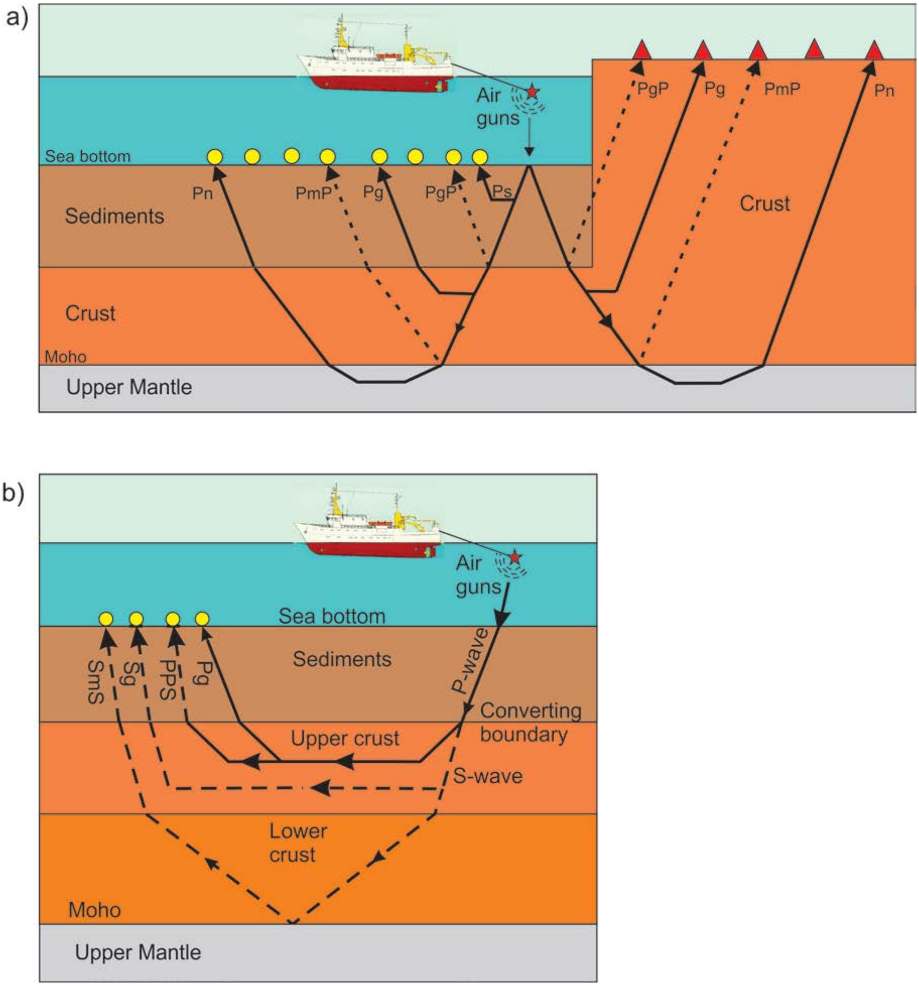

Figure 2. a) P-wave wide-angle survey. Yellow circles indicate ocean bottom seismometers (OBS) and red triangles show land-stations. Ps=sediment refracted waves, Pg=crustal refracted waves, PgP, reflection from the top of the crust, PmP= freflections from the top of the mantle (Moho), Pn=refractions from the upper mantle. Dotted ray paths=reflected waves, continuous ray paths=refracted waves. b) S-wave conversions from air-gun generated P-waves. The PPS-phase is S-waves generated from P-waves returning to the surface. The PSS-phase (e.g. Sg and SmS) is converted from P-waves on the way down. The converting boundary is boundaries with large difference in acoustic impedance. The Pg-arrival illustrates a PPP-phase.

Main results

Paper 1 – Crustal structure across the Møre margin, mid-Norway, from wide-angle seismic and gravity data.

The Møre Margin consists of the Møre Basin and the Møre Marginal High (Fig. 1). The Møre Basin is separated from the Vøring Margin by the Jan Mayen Lineament, and the Møre Marginal High is capped with Eocene breakup-related extrusives. The Møre Basin is mainly the result of Late-Jurassic - Early-Cretaceous continental stretching, thinning, faulting and subsequent subsidence (Eldholm et al., 1987; Eldholm et al., 1989). The depth to the Base Cretaceous unconformity and the thickness of the pre-Cretaceous sedimentary section are uncertain. However, sedimentary thicknesses of more than 15 km have been reported (Raum, 2000). Two types of lower crustal high-velocity bodies (LCBs) have been inferred; eclogite bodies close to the coast (Olafsson et al., 1992; Raum, 2000) and Eocene magmatic underplating below the marginal high and the western part of the basin (Mjelde et al., 2009b). The tectonic development of the area is controlled by two structural trends; NE-SW and NW-SE (Brekke, 2000). The overall NE-SW structural grain is constituted by faults and basin axes that probably originated in Late Palaeozoic time and were active during all subsequent tectonic phases (Brekke, 2000). The transverse NW-SE trend is expressed as major lineaments (Jan Mayen Lineament and Bivrost Lineaments) that probably reflect the old Precambrian basement grain (Blystad et al., 1995; Skogseid et al., 2000; Eldholm et al., 2002). This is substantiated by the NW-SE strike of the fjords and major faults where the lineaments meet the mainland (Fig. 3).

In order to constrain the eclogite body inferred by Olafsson et al. (1992), and link it to onshore structures, three regional wide-angle profiles were acquired near the Møre coast. Two of the profiles cover the onshore-offshore transition, based on data acquired from land-stations and OBSs. The profiles extend from the Western Gneiss Region, approximately 100 km onshore, to the Møre Marginal High, located approximately 300 km off the coast of mid-Norway. The third profile is a tie-profile with OBSs only, along the strike of the inner flank of the Slørebotn Sub-basin (Fig. 3).

In the Møre Basin we observed a sedimentary thickness of 12-15 km, underlain by a highly thinned continental crust. On the northern dip-profile we observe a prominent intra-crustal reflector close to the coast. We interpret this reflector as a remnant of the Caledonian orogeny. We observe an outer LCB on the northern profile, which pinches out under the mid-Møre Basin. On the southern profile we observe both an outer and an inner LCB. We interpret the outer LCBs as mafic underplating, related to the Early Eocene break-up, and the inner LCB as high-grade metamorphic remnants from the Caledonian orogeny. These observations suggest a different geodynamical history between the two dip-profiles. On the tie-profile we observe a systematic variance in the P-wave velocity structure of the crust from 6.1-6.6 km/s in the northeast to 6.3-6.8 km/s in the southwest. The difference in P-wave velocity may reflect a change in lithology along this transect. The onshore- to offshore-transition is 100-150 km wide and is marked by a prominent change in Moho depth from 18 to 40 km associated with a significant change in seismic velocity structure.

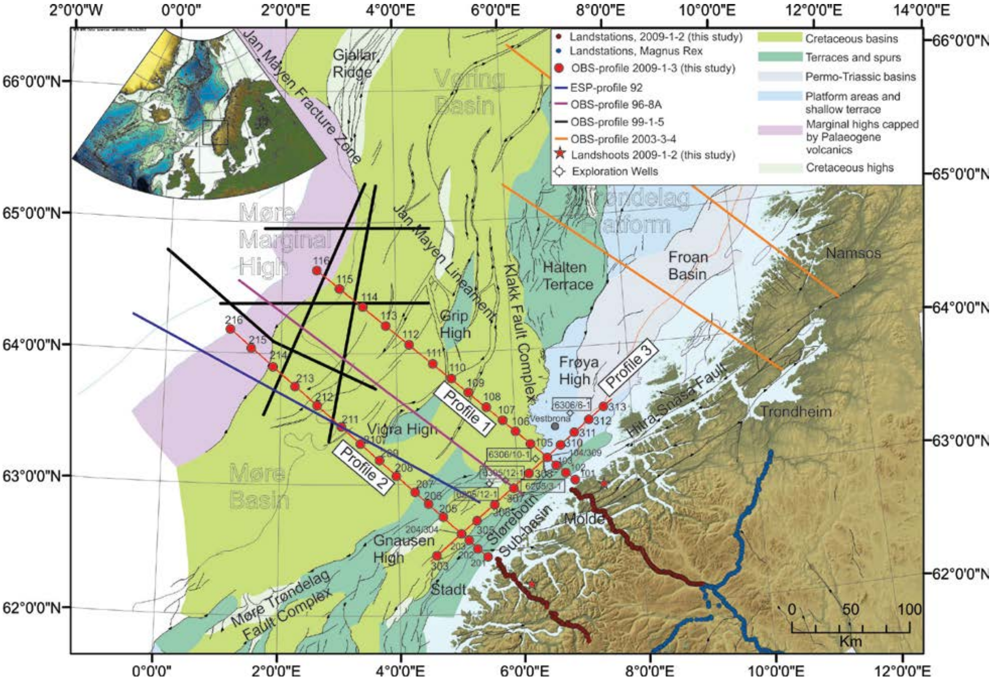

Figure 3. The Møre Margin with wide-angle seismic surveys. The profiles which are modeled in this paper are marked in red (airgun shots – solid line, recording instruments - dots, stars – land-shots). Blue circles indicate an Extended Spreading Profiles (ESP) (Olafsson et al., 1992). The green lines and dots show the parallel OBS study of Raum (2000). The black lines and dots indicate the OBS study of the outer Møre Margin (Mjelde et al., 2009b). The orange circles show the OBS/land-station study on the Trøndelag

Platform (Breivik et al., 2011). The dark blue circles mark the land-stations of the Magnus Rex experiment (Stratford and Thybo, 2011).
Map modified from Norwegian Petroleum Directorate's web page: http://npdwms.npd.no/npdwmsmap_wgs84.asp and from Norwegian Mapping Authority's web page: http://wms.geonorge.no/skwms1/wms.terrengmodell?

Paper 2 – Lower crustal eclogites and structural geometry of the conjugate East Greenland and Norwegian margins

During subduction of Baltica below Laurentia, the western margin of Baltica was buried to eclogite facies at about 125 km depth (Roberts, 2003). Remnants of these eclogites can at present be observed onshore in the WGR (Fossen, 2010), and are inferred offshore in the Cretaceous Møre and Vøring Basins (Fig. 4) (Olafsson et al., 1992; Mjelde et al., 2009a). The crustal composition of the onshore-offshore transition on the mid-Norwegian Margin is, however, mostly unexplored.

The modelling of the P- and S-waves provides the Vp/Vs-ratio, which is used as a parameter for estimating the lithological composition of the crust. Vp/Vs-ratios of 1.73-1.75 from the modelling suggest a crystalline basement dominantly felsic in composition in the onshore-offshore transition. The Vp/Vs-ratio of the LCB (Fig. 4) is modelled at 1.81 in the lower part and 1.73 in the upper part. This suggests a more mafic composition in the lower part of the LCB compared to the upper part. One possible explanation for the variations in Vp/Vs-ratios within the LCB is that the LCB represent a zone of mixture of continental blocks and blocks with higher concentration of eclogites.

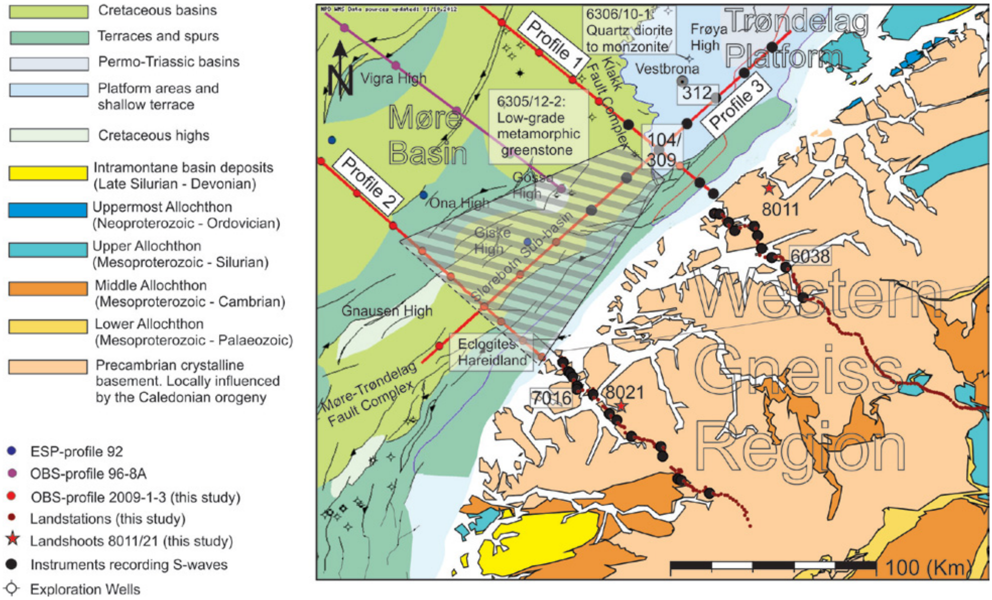

Figure 4. The study area in the eastern Møre Basin with wide-angle seismic surveys. The profiles discussed in this paper are marked red. Light blue circles indicate the Extended Spread Profiles (ESP) (Olafsson et al., 1992). The green circles show the parallel OBS study of Raum (2000). The instruments containing S-waves are pink. The hatched area indicates the lower-crustal eclogite inferred by Olafsson et al. (1992), Raum (2000) and Kvarven et al. (Subm.). Sources for the map are http://npdwms.npd.no/ and http://www.ngu.no/no/hm/Kart-og-data/nedlasting/

During the Eocene break-up of the North-Atlantic, the two continental margins of eastern Greenland and western Norway constitute the present day remnants of the upper plate and the subducting plate, respectively. However, the plate tectonic evolution of this area is controversial (Peron-Pinvidic et al., 2013), and all processes responsible for the development of the margins are not yet fully understood. Among the processes which generally is considered to have played an active role in the tectonic development, is the influence of the Icelandic Plume (Japsen and Chalmers, 2000) and the upper-plate versus lower plate configuration (Torske and Prestvik, 1991; Mjelde et al., 2003; Mosar, 2003). The large scale geometrical differences might also be attributed to lithospheric break-up styles (Huismans and Beaumont, 2011).

In order study the North Atlantic conjugate margins of East Greenland and mid Norway, we have constructed two cross-Atlantic transects on either side of the JMFZ/JML transfer zone based on published and new crustal models (Fig. 1). In order to compare the two conjugate margins on both sides of the transfer zone, three reconstructions were made. First, the present day model was back-stripped to the time of breakup (Fig. 5), secondly, the body interpreted as Early Cenozoic magmatic underplating was removed, and thirdly, the model was back-stripped approximately to Devonian, after the collapse of the main Caledonian mountain range. The new transects display differences in Moho depth below the mountainous areas between the two margins. Furthermore, the amount of magmatic underplating north of the JMFZ largely exceeds the amount of underplating observed on the south side of the JMFZ (Fig. 5).

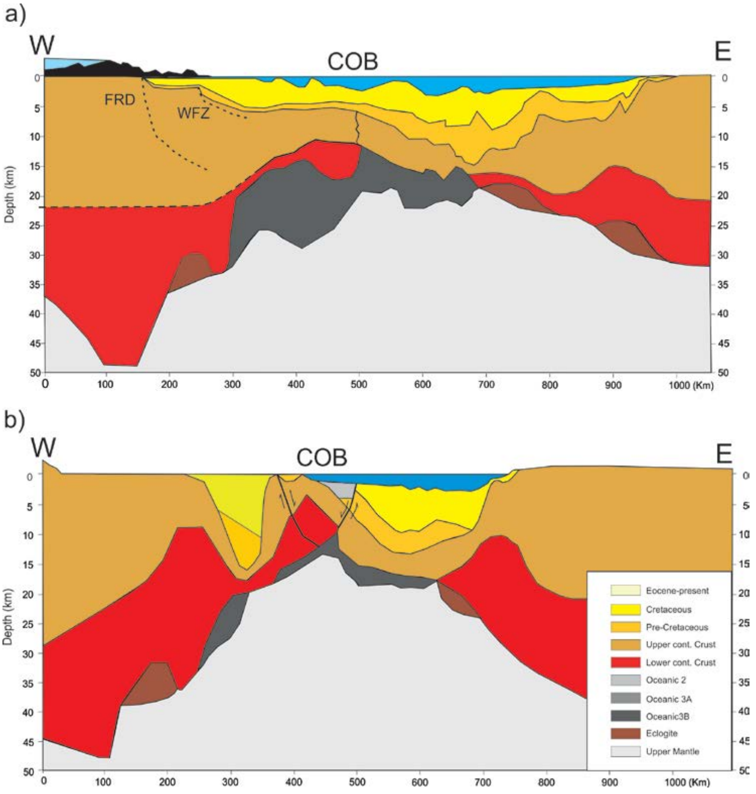

Figure 5. Simplified reconstruction of the North Atlantic conjugate margins to pre-break up. Method and data are described in paper 2. See figure 1 for location. a) Transect north of the Jan Mayen Fracture Zone

from the East Greenland mountain chain to the Norwegian mainland. b) Transect south of the Jan Mayen Fracture Zone from the Scoresby Sund, East Greenland to the Norwegian mainland. COB= Continent ocean Boundary.

The Early Cretaceous opening of the Atlantic Ocean did not follow the precise junction (ISZ) formed by the closing of the Iapetus Ocean (Wilson, 1966). Thus, the Iapetus Suture can be defined as the zone separating the continental crustal blocks, which in Early Palaeozoic were on opposing margins (Wilson, 1966; Beamish and Smythe, 1986). Neither the position of the suture zone across the North Sea, the northern continuation along the mid-Norwegian Margin, or the continuation of the ISZ on the Lofoten-Vesterålen Margin and into the Barents Sea, is well known.

In this paper we have studied the possible location of the Iapetus Suture Zone based on interpretation of lower-crustal eclogites (Figs. 6a,b). Several studies have namely shown indications of high-velocity lower crustal bodies (Olafsson et al., 1992; Christiansson et al., 2000; Raum, 2000; Breivik et al., 2002; Breivik et al., 2003; Mjelde et al., 2012), sometimes accompanied by high-density terranes (Breivik et al., 2011; Wangen et al., 2011), which have been interpreted as eclogitiziced remnants from the Caledonian Orogeny. In perhaps the most controversial area regarding the position of the ISZ, the Barents Sea, we support the interpretation of Breivik et al. (2005) with a western and an eastern branch of the ISZ (Fig. 6a). The eastern branch is re-interpreted from new seismic wide-angle data (Clark et al., Accepted).

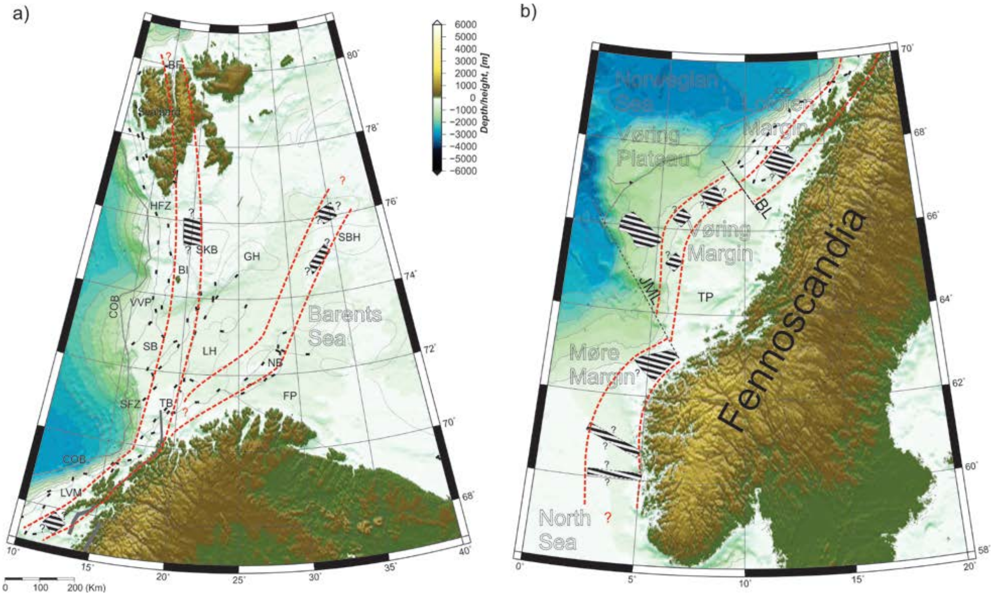

Figure 6. The eclogite bodies (hatched) used for reconstruction of the ISZ. a) The Barents Sea. BI= Bear Island; BB, Bjørnøya Basin; FP, Finnmark Platform; GH, Gardabanken High; LH, Loppa High; NB, Nordkapp Basin; SB, Sørvestnaget Basin; SBH, Sentralbanken High; SFZ, Senja Fracture Zone; TB, Tromsø Basin; VVP, Vestbakken Volcanic Province. b) The mid-Norwegian Margin, from Lofoten to the North Sea. BL, Bivrost Lineament; COB, Continent-Ocean Boundary; JML, Jan Mayen Lineament; TP, Trøndelag Platform. The dashed red lines mark our suggested track of the Caledonian Suture Zone. Faults, lineaments, tectonic structures and units and abbreviations are adapted from Ritzmann and Faleide (2007). Data for depth and highs are retrieved from the ETOPO2 bathymetry database: http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.

Paper 3 – Tectonic and sedimentary processes along the ultraslow Knipovich spreading ridge

The glacial western Barents Sea and Svalbard Margins are characterized by troughs and large submarine trough-mouth fans (Faleide et al., 1996; Hjelstuen et al., 1996). At the Barents Sea Margin, the prominent Storfjorden- and Bear Island Troughs dominate the morphology, whereas on the western Svalbard Margin the minor Kongsfjorden-, Isfjorden- and Bellsund troughs are the most significant features (Faleide et al., 1996) (Fig. 1). Locally, in the study area off Isfjorden, the spreading ridge is buried below fan-sediments.

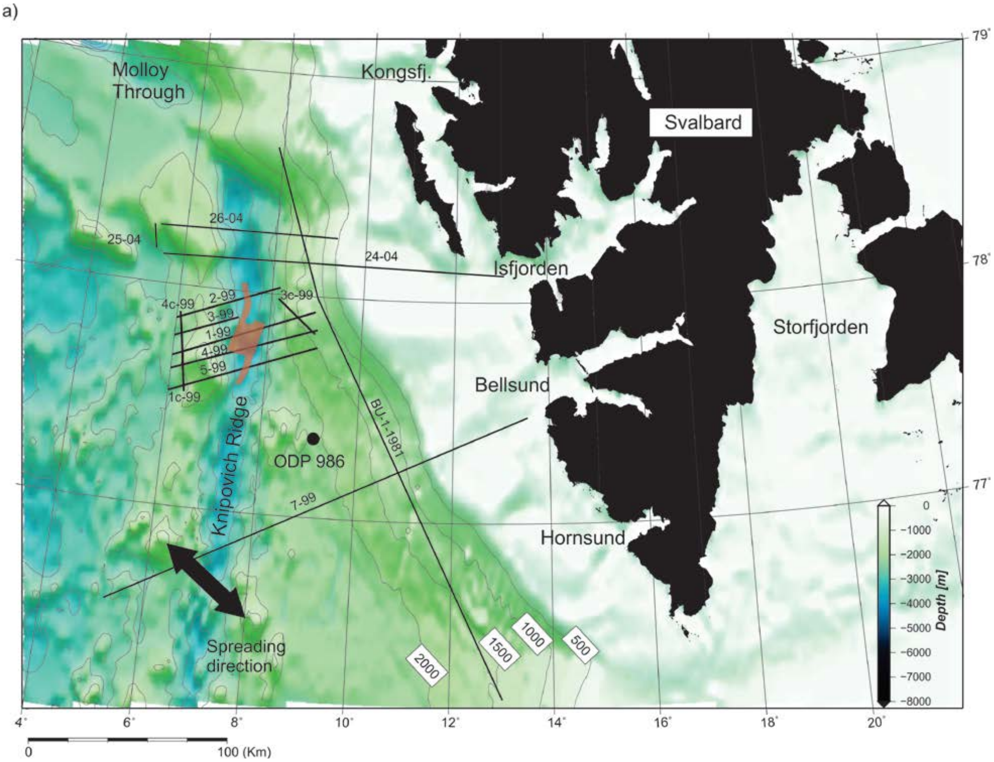

Figure 7. Bathymetric map of the Western Svalbard Margin and Knipovich Spreading Ridge. Profiles 1-5, 1c, 3c and 4c 1999: This study. Profiles 7-99 and 24-26: Amundsen et al. (2011). BU-1-1981: Faleide et al. (1996). The red area in the rift valley shows the extension of the 2004 EM300 bathymetric data. Bathymetric data retrieved from ETOPO2: http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.

The spreading rate controls the geometry of spreading ridges; fast spreading ridges exhibit an elevated and smooth topography, while slow and ultra-slow spreading ridges have a pronounced rift-valley and generally rough topography (Macdonald, 1982). On spreading ridges the production of new oceanic crust represents an interplay between tectonic, magmatic and hydro-thermal processes (Dick et al., 2003). On ultra-slow spreading ridges, however, the spreading is less robust and significant magmatism is restricted to so-called magmatic segments, whilst other segments of the same spreading ridge apparently have no magmatic activity (Cannat et al., 2006). The ultra-slow Knipovich Spreading Ridge exhibits this separation in magmatic and tectonic segments (Okino et al., 2002).

In this paper we have compared the differences in tectonic and sedimentary processes along and across the Knipovich rift-valley (Fig. 7).

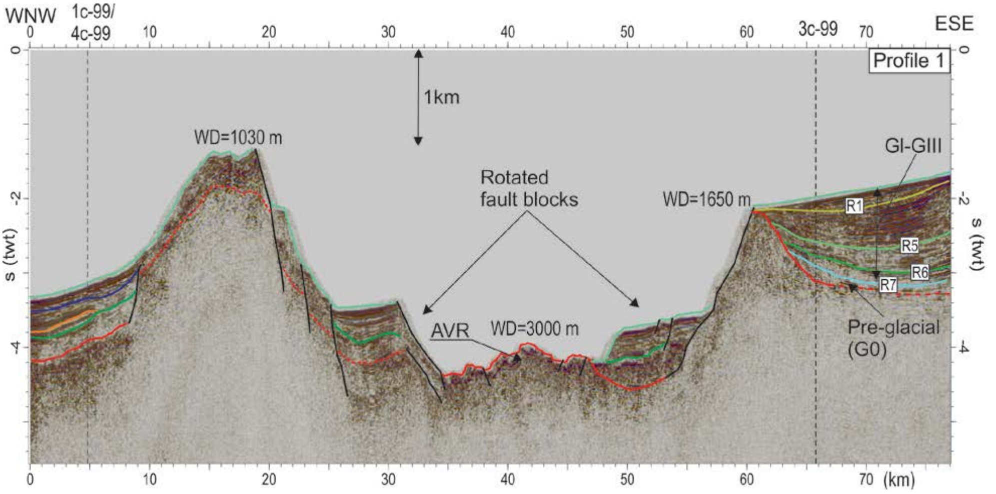

Figure 8: MCS profile 1 acquired across an inferred magmatic dominated segment of the Knipovich spreading ridge off Isfjorden, Svalbard. The profile exhibits features typical for a magmatic spreading center; Steep rift-valley heights, basaltic extrusions (AVRs) and major faults. WD: Water depth. AVR: Axial volcanic ridge. Vertical exaggeration=5. See fig. 7 for location.

Our results show major variations in morphology, seafloor-spreading processes, sediment thicknesses and sedimentary processes between the magmatically dominated and tectonically dominated segments along the spreading ridge. The inferred magmatically dominated central parts of the study area have steep and elevated rift flanks, and two parallel 5 km long and 500 m high axial volcanic ridges (AVR) are exposed in the rift valley (Fig. 8), whereas the rift flanks on the inferred tectonic dominated northern parts are lower and more hill-like. In the inferred magmatically dominated central parts of the study area sediments are rare or absent in the rift valley. In the inferred tectonic dominated areas a thickness of 500-1000 m of sediments are observed in the rift valley. The southernmost part of our study area, however, seems to contain both tectonic and magmatic characteristics.

An asymmetry in the height between the eastern and western rift flank is observed within the entire study area. This asymmetry reaches a maximum of 800 m in the southernmost part of the study area, and can be related to a combination of glacial sediment loading of the eastern flank and thermal uplift of the western rift flank.

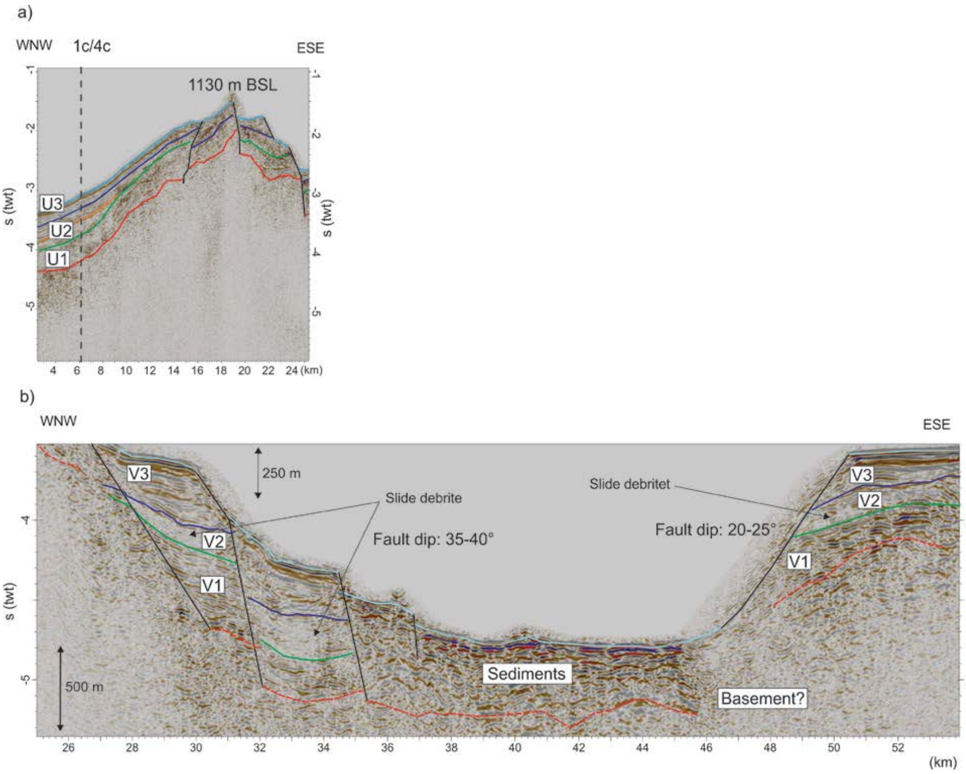

Figure 9. a) The western rift flank of Profile 4. U1 (oldest) to 3 are sedimentary units. b) The rift valley of Profile 4. V1 (oldest) to V3 are sedimentary units; V1-3. WD: Water depth. Vertical exaggeration=5. See fig. 7 for location.

Huge accumulations of sediments are observed; on the eastern flank the mapped glacial units, G0-GIII, within the seismo-stratigraphic framework of Faleide et al. (1996) reach a total thickness of 1500 m, whereas in the rift valley and on the western flank, three sedimentary units of totally 1000-1500 m thickness are observed (V1-3 and U1-3, respectively) (Fig. 9). On the eastern flank, in the rift valley and on the western flank units GI, V2 and U1 show seismically chaotic facies, which are consistent with slide debrites. The reflection pattern in the 400-500 m thick Unit U2 on the western flank is laterally migrating, indicating that this unit is dominated by current-related deposits (contourites). The youngest units (the upper parts of GII and entire GIII, V3 and U3) are interpreted to be composed of hemipelagic/glacimarine sediments.

Any detailed correlation of the identified units across the rift valley is speculative. However, the oldest part of Unit GI on the eastern rift flank, Unit U1 on the western rift flank and Unit V2 in the rift valley is most likely related to the same slide event. The youngest part of GI and GII share many similarities with Unit V3 in the rift valley and unit U2 and U3 on the western flank.

Synthesis and perspectives.

In this thesis several stages of the Wilson Cycle is studied. The two seismic surveys utilized in the thesis represent multiple stages: Convergent continental-continental setting, continental collapse, stretched continental crust and break-up is studied on the Møre Margin off western Norway, whereas oceanic accretion is studied on the Knipovich Spreading Ridge, off western Svalbard. In addition, we have reconstructed the North Atlantic conjugate margins on both sides of the JMFZ, and interpreted the Iapetus Suture Zone from the Møre Margin to Svalbard.

Paper 1 presents the first two continuous onshore/offshore wide-angle profiles on the Møre Margin. Knowledge of the Møre Margin geology is considered as important for understanding the development of the ambiguous uplift of the Norwegian mainland. A careful forward modelling approach, constrained by synthetic seismograms and gravity modelling, has yielded a model that gives new insight to the understanding of the geology in this region. An improved image of the crustal structures could perhaps be obtained by migration of the seismic data, especially the data from the best-quality and densely spaced (1 km) land-stations closest to the coast. A new profile aimed for high-quality imaging of the crust should be designed for stacking and full waveform inversion. This would require acquisition of a new >200 km dip profile across the Møre Margin, with OBS spacing of 1-2 km. The new profile should be accompanied by 3D gravity and magnetic modelling.

The two conjugate margins compiled in paper 2 show a remarkably difference in magmatic underplating on each side of the Jan Mayen Fracture Zone. Furthermore, we note that the East Greenland Mountain Chain, in contrast to the Norwegian mountainous areas, seems to be compensated by a large crustal root. The proposed path of the ISZ, based on the distribution of lower crustal eclogites (paper 2), seem to follow the trend of the continent-ocean boundary (COB) from the mid-Norwegian Margin to Svalbard. To better investigate these variations along strike, more cross-Atlantic transects must be compiled, both north and south of the JMFZ. Eventually, new wide-angle surveys should be conducted.

The main motivation for studying the ultraslow and asymmetrically spreading Knipovich Spreading Ridge, off the glacial dominated Svalbard Margin, is the inferred division into so-called magmatic and amagmatic spreading centres. A striking difference in rift flank topography and rift valley bathymetry within the study area indicates the importance of magmatic and tectonic processes responsible for the development of crustal morphology. While variations in magmatism along the mid-Norwegian Margin often are associated with the proximity to the Icelandic Plume, the variations in magmatism along the Knipovich rift valley seem to be controlled by tectono-magmatic differences inherent in the oceanic accretion process itself.

In addition, observations of significant sedimentary successions west of the spreading ridge, and the internal differences between the sediment units, have yielded new insight (and new questions) about the depositional processes, which cannot be directly connected to the trough-mouth fans. Precise correlation and chronological control of these sediment units can only be achieved through drilling. Furthermore, to gain more understanding of the processes responsible for differences in magmatism along the rift valley (magmatic- and tectonic dominated segments), rift flank height-asymmetry, spreading rate and eventually ridge-jumps, a multi-disciplinary geophysical survey must be conducted. The new survey must cover the rift flanks and the rift valley along both magmatically and tectonically inferred segments. Densely spaced OBS-profiles will provide information about P- and S-velocities, mineralogical composition and thicknesses of sediments and crust. The velocity-depth models from the OBS modelling must be constrained by 3D gravity and magnetic modelling. Lastly, more MCS data must be conducted in order to allow accurate tying of sedimentary units across the rift valley.

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