Seismic study along the west Spitsbergen continental margin and adjacent area of the West Spitsbergen Fold and Thrust Belt (Isfjorden).

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to my grandfather and parents

Preface

The work described in the thesis was carried out at the University of Bergen, Department of Earth Science. The project was initiated in July 2006 and sponsored by the Norwegian Petroleum Directorate (Norway). The present research is based on 2D multichannel seismic and bathymetric data acquired by the University of Bergen. In the Isfjorden area the seismic data are supported by 2D multichannel profiles provided by Statoil. Processing of the seismic data collected by the University of Bergen was performed by "Sevmorgeo" (Russia).

Interpretation and analysis of available data were performed within the Isfjorden area, along the western Spitsbergen shelf, continental slope and Knipovich Ridge. The thesis is composed from four papers that describe results of the research for each part of the study area.

Acknowledgments

First of all I would like to thank my supervisors Rolf Mjelde, Jan Inge Faleide and Roy Gabrielsen for the assistance and support during the project. I would like to say that it has been an honour for me and my big pleasure to work with them. They shared with me not only those enormous knowledge but also great and bright personalities. As well I express my appreciation to Berit Oline Blihovde Hjelstuen, Ole Meyer, Bent Ole Ruud and Haflidi Haflidason and many others of the university personnel for help and advices. I have furthermore to thank my fellow students Alex Kandilarov, Alexander Minakov, Vibeke Bruvoll, Louise Bjerrum, Sebastien Gac, Vaneeda Allken and others who made the time I spent at the university very pleasant.

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I owe my deepest gratitude to my family who supported me in number of ways during all my life, and my husband Guillermo Ramirez for his patience and a great help in difficult times.

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Introduction

Objectives

Spitsbergen is the largest island of the Svalbard archipelago, which is located in the north-western corner of the Barents Sea (Fig. 1). Since the archipelago was submerged during most of its geological history, the rocks outcropping on Svalbard comprise almost a complete stratigraphical column from Precambrian to Tertiary. Sparse vegetation makes Svalbard a unique area for onshore geological studies. The western coast of Spitsbergen parallels the sheared continental margin of the western Barents Sea and exposes structures that provide an insight into the tectonic history of the North Atlantic opening.

One of the main tectonic features along the western coast is the West Spitsbergen Fold and Thrust Belt (WSFTB) affecting Carboniferous - Tertiary strata. The existence of a fjord system in that region provides a possibility to compose extensive profiles through the major tectonic features of the area, including the West Spitsbergen fold-and-thrust belt, combining onshore and offshore data sets (e.g. Bergh et al. 1997). Rich sediment supply induced by glacial erosion from the north-western Barents Sea and Spitsbergen across the continental margin left remarkable signs of the sedimentary processes active during the Cenozoic evolution of the area.

The study area for the present research extends from the western part of Spitsbergen across the continental shelf and slope towards the Knipovich Ridge, and comprises all zones reflecting the comprehensive history of the region’s development in the Cenozoic (Fig. 1). Relatively close location of all topographic features provides the possibility for a joint study of the main processes controlling the evolution of the western continental margin of Spitsbergen.

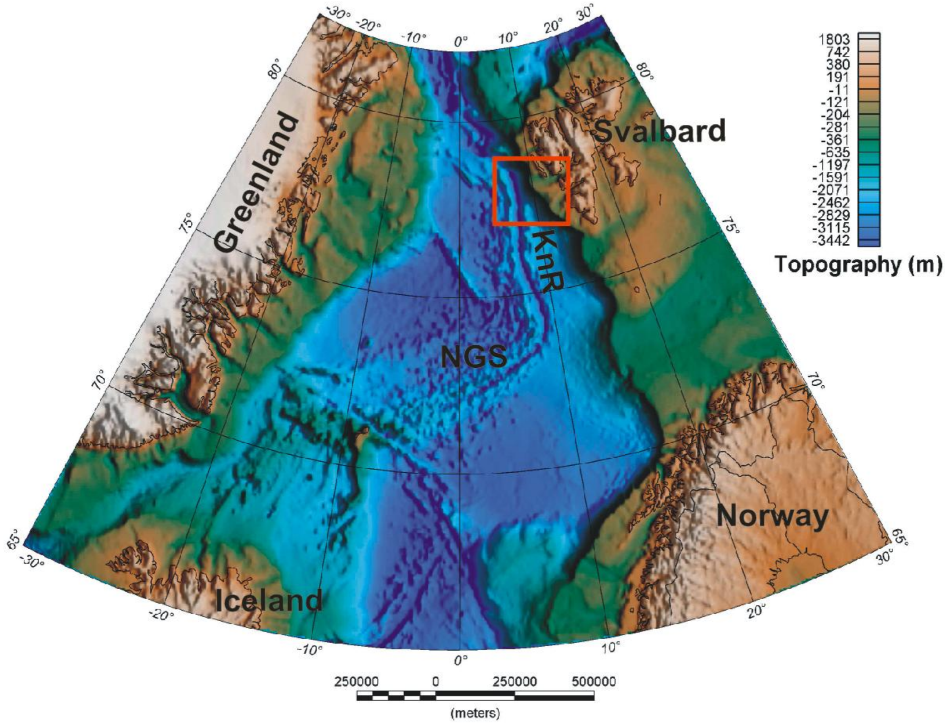

Figure 1. Topographic map of the North Atlantic. Study area is marked by red square. KnR – Knipovich Ridge, NGS – Norwegian-Greenland Sea.

The western coast of Spitsbergen and particularly the structures within the WSFTB have previously been extensively studied onshore (Steel & Worsley 1984, Worsley & Aga 1986, Dallmann et al. 1993, Harland 1997, Dallmann 1999 and the CASE team 2001). Several geological maps covering the western Spitsbergen have been published by Norsk Polarinstitutt: Major & Nagy (1972), Lauritzen et al. (1989), Ohta et al. (1992), Bergh et al. (2003). Offshore studies of the region are mainly related to marine seismic surveys performed within the fjords, along the shelf and across the western margin. A general overview of the seismic studies conducted along western Svalbard was compiled by Eiken (1994).

The present research is based on new multichannel seismic and bathymetric data acquired by the University of Bergen during the years 1999-2007, supported by multichannel seismic data acquired by Statoil in 1985 and 1988. Building on the results from previous regional seismic studies carried out in the region, the new geophysical observations give a possibility to refine the study of the tectonic and sedimentary processes along western Spitsbergen.

The study area is divided into three zones, each of which displays a distinct structural style (Fig. 2).

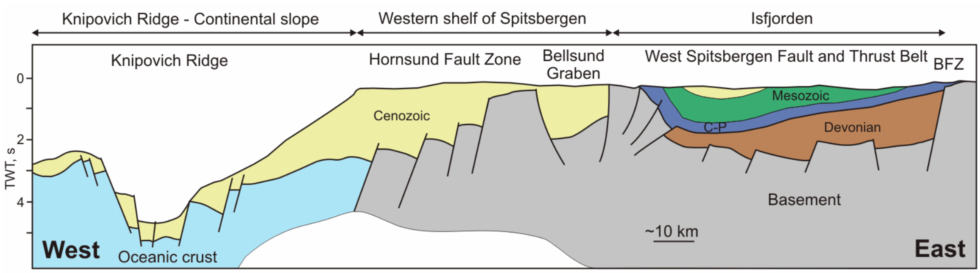

Figure 2. Sketch of a composed transect crossing three zones of the study area. BFZ – Billefjorden Fault Zone.

The easternmost zone covers the Isfjorden and comprises structures of the WSFTB. Graben structure and down faulted blocks of the Hornsund Fault Zone are the main tectonic features of the adjacent zone along the western shelf of Spitsbergen. The westernmost zone spreads from the continental slope towards the oceanic Knipovich Ridge. Each zone represents a subarea where specific studies were conducted and described in separate publications. The main objectives for the studies in the defined zones are:

- *Isfjorden:* A dense grid of multichannel seismic data along with bathymetrical observations within Isfjorden provides the possibility to study sub-bottom structures of the WSFTB and analyze its expression on the seafloor. Closely spaced 2D seismic lines permit observation of the structures of the fold and thrust belt in close to 3D view. In addition, the structures may be traced and compared with onshore observations of the exposed fold and thrust belt.

- *Western shelf of Spitsbergen:* New multichannel seismic data are utilized for definition and analysis of the tectonic structures along the shelf to the south of the Forlandsundet Graben. The main aim with this study is to investigate how the horst and graben system changes along strike.

- *West Spitsbergen continental margin – Knipovich Ridge:* A study of the sedimentary processes and depositional environments along the continental slope, within the Knipovich Ridge rift valley and at its western flank, is based on seismic data and bathymetric observations within the area.

Geological setting of the area

The basement rocks of Svalbard comprise metamorphic and igneous rocks of late Proterozoic to Silurian age. The basement rocks were highly deformed during the Caledonian Orogeny, and they are collectively referred to as Hecla Hoek (Kulling 1934). A thick sequence of Old Red Sandstones of late Silurian - Devonian age overlies unconformably the basement rocks, and is mainly preserved in north-south trending down-faulted crustal blocks. These rocks were affected by the Late Devonian Svalbardian deformation during the latest phase of the Caledonian Orogeny (Dallman 1999, Gee et al. 2008, Bergh et al. 2011). Stable platform conditions were developed in the area by the end of the Carboniferous. Accumulation of carbonates and evaporites took place on the shelf during the late Carboniferous – mid-Permian, whilst the late Permian was characterised by deposition of mainly marine, siliclastic sediments. A thick sedimentary sequence, mainly consisting of shales, siltstones and sandstones, was deposited during the Mesozoic in conditions influenced by pronounced sea level fluctuations (Worsley & Aga 1986, Dallmann 1999, Worsley 2008). Regional uplift of the Svalbard area took place in the Late Cretaceous, leaving a gap in the sedimentary succession.

During the Cenozoic, western Spitsbergen and its continental margin were affected by the evolution of North Atlantic region. The signs of initial stage of continental rifting were reflected in intrusions of dolerite dykes and sills in the latest Jurassic – Early Cretaceous time. The tectonic evolution of the North Atlantic may be divided into three stages (Fig. 3).

During the first stage seafloor spreading was initiated in early Paleocene on the western side of Greenland, which belonged to the Eurasian plate (Srivastava 1978, Chalmers & Pulvertaft 2001). Rifting and dextral wrench movements along an old zone of weakness took place during that stage in the Norwegian-Greenland Sea (Srivastava 1985, Faleide et al. 1993). The second stage of the North Atlantic evolution is characterised by major plate reorganization with beginning of seafloor spreading in the Norwegian-Greenland Sea in Eocene (Talwani & Eldholm 1977). Greenland became a separate plate and started to move northward obliquely to western Spitsbergen along a mega-shear zone. The movements between the Greenland and Eurasian plates induced transpressional deformation along western Spitsbergen, forming the Western Spitsbergen Fold and Thrust Belt. The third stage of evolution is related to early Oligocene cessation of seafloor spreading west of Greenland, docking Greenland to the North American plate (Talwani & Eldholm 1977, Srivastava 1985). Greenland moved WNW relative to Eurasia, and seafloor spreading started between Greenland and Svalbard. Oblique extension in the region caused normal faulting and partial collapse of the earlier compressional structures along western Spitsbergen.

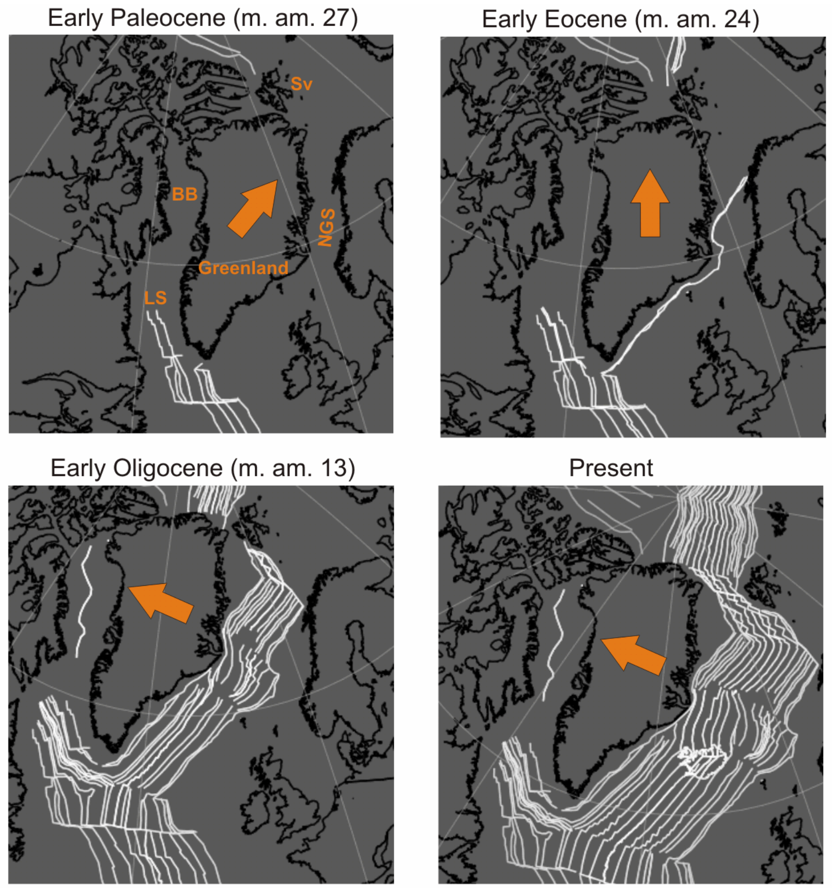

Figure 3. Stages of North Atlantic evolution. Abbriviations: BB - Baffin Bay, LS - Labrador Sea, NGS - Norwegian Greenland Sea, Sv - Svalbard. Arrows indicate movement direction of Greenland. Figures were created by use of GPlates software.

The onset of major Northern Hemisphere glaciations took place in late Pliocene time. Since that time Svalbard has been subject to several glaciations alternating with interglacial periods. The glaciations were responsible for extensive erosion, fjord formation and the accumulation of thick sedimentary wedges along the western continental margin of Svalbard and the Barents Sea (Faleide et al. 1996, Knies et al. 2009).

Synopsis of the study

The Isfjorden area

The main goal of the study within the Isfjorden area was to perform an interpretation and analysis of the sub-bottom tectonic structures of the West Spitsbergen Fold and Thrust Belt by use of a dense grid of multichannel seismic data, supported by bathymetric observations. Isfjorden is the largest fjord of western Spitsbergen and covers a transition area between two zones of fold-and-thrust belts reflecting different deformation rate. Tectonic structures exposed in Oscar II Land to the north of Isfjorden are affected by more intense deformation than those observed to the south of the Isfjorden-Ymerbukta Fault Zone (Fig. 4).

Three distinct tectonostratigraphic levels of sub-bottom structures were observed in the 2D multichannel seismic lines acquired in the Isfjorden area. These include the top of the metamorphic basement, the base of the upper Carboniferous Nordenskiöldbreen Formation and the base of the Lower Cretaceous Helvetiafjellet Formation. The defined reflections are well-pronounced and continuous and can be used to produce time-structure maps within the study area.

The deepest interpreted reflector is inferred to represent the boundary between Caledonian basement and Devonian to mid-Carboniferous sedimentary strata. A map of the interpreted surface shows a pronounced north-south trending graben system that may be correlated with the Raudfjorden and Breibogen faults, which are defined onshore in northern Spitsbergen (Fig. 4).

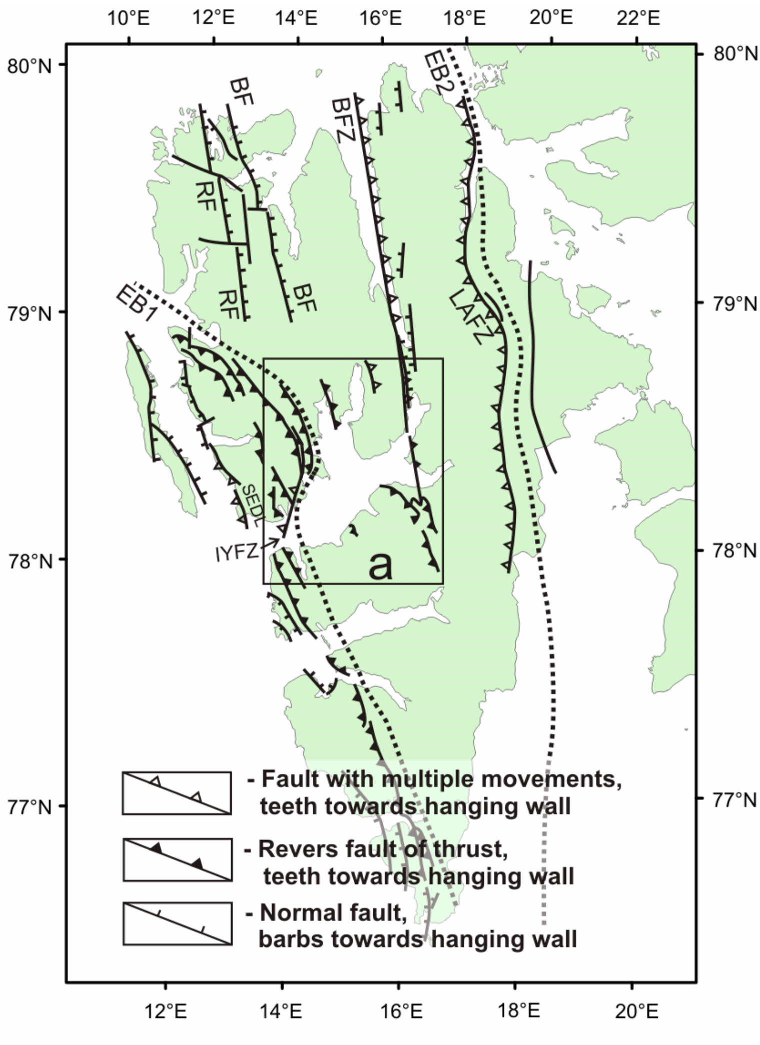

Figure 4. Tectonic map of Spitsbergen (adopted from Dallmann 1999). A – Study area, Isfjorden. BFZ – Billefjorden Fault Zone, LAFZ - Lomfjorden-Agardbukta Fault Zone, SEDL – St. Jonsfj.-Eidemb.-Daudmannsod. Lineament, IYFZ – Isfjorden-Ymerbukta Fault Zone, BF – Breibogen Fault, RF – Raudfjorden

Fault, EB1 – the boundary of the WSFTB structures, EB2 - The eastern boundary of observed Tertiary folding and thrusting.

The base of the upper Carboniferous Nordenskiöldbreen Formation is defined as a transition between the Devonian – mid-Carboniferous unit and the upper Carboniferous-Permian succession. This transition represents an unconformity between the units, and is characterised by gentle southwest-ward dip. North-south trending reverse faults cutting the base of the upper Carboniferous Nordenskiöldbreen Formation in north-eastern Isfjorden, might be correlated onshore with the Blomesletta Fault.

The base of the Lower Cretaceous Helvetiafjellet Formation is clearly identified in the seismic lines as a boundary between shales in the Janusfjellet subgroup and sandstones of the Helvetiafjellet Formation. The sequence defines a syncline and represents the base of the foreland basin.

The fold-and-trust belt of western Spitsbergen evolved during the Eocene transpressional event in relation to three decollements within the Permian gypsum, Middle Triassic and Upper Jurassic organic rich shales, respectively. The decollements were identified in the seismic sections within the unit bounded by the base of the upper Carboniferous Nordenskiöldbreen Formation and the base of the Lower Cretaceous Helvetiafjellet Formation. The structures that reflect the most intense contractional deformation are situated between the middle and the uppermost decollements.

A detailed map was constructed of the major tectonic features in the shallow part of the fold-and-thrust belt and features reflected in the seafloor morphology derived from bathymetric data. These structures in Isfjorden are mainly foreland-directed in-sequence thrusts and folds of NW-SE and NNW-SSE strike. The new data refine the previous interpretations of the sedimentary and tectonic structures in the area. The different degree of correlation between structural observations derived from bathymetric and seismic data is related to varying lithology and erosion of the rocks outcropping on the seafloor.

Western shelf of Spitsbergen

This part of the study area is located in the western hinterland zone bounded to the east by the basement-involving West Spitsbergen Fold and Thrust belt (Fig. 5). Interpretation of new 2D multichannel seismic data acquired on the western Spitsbergen shelf enabled definition of the main tectonic structures of the area, which are the Hornsund Fault Zone and the Forlandsundet and Belsund grabens.

The Forlandsundet Graben is confined by the Prince Karls Forland to the west and the Spitsbergen coastline to the east. The graben structure is characterised as a NNE-SSE striking, steeply dipping en echelon system of faults separating the Tertiary sediments from the basement. A contrast in seismic reflectivity pattern of the sedimentary fill is observed along the strike of this structure (Gabrielsen et al. 1992). The southward continuation of the Forlandsundet Graben into Bellsund was postulated by Eiken & Austegard (1987) by use of two seismic lines. The new data acquired along the shelf enabled a more detailed study within the area. The Bellsund Graben, was clearly seen in the seismic lines. Along with extensional tectonic features, signs of the reverse faulting and folding were observed within the sedimentary succession of the graben. The seismic reflectivity pattern along the southernmost profile just outside Renardodden shows an abrupt termination of the thick sedimentary succession, which is related to the termination of the Bellsund Graben. Similar characteristics of tectonic and sedimentary features of the Forlandsundet and Bellsund grabens imply that the grabens evolved during the same tectonic regime. The tectonic history of the Forlandsundet graben (Gabrielsen et al. 1992 and Gosen & Paech 2001) could be described by three stages of evolution: accumulation of a thick sedimentary succession within a broader basin than the present Forlandsundet (probably during the latest Palaeocene to early Eocene), onset of graben formation in transtensional settings along with latest contractional movements (latest Eocene), and the final development of the normal faults defining the boundaries of the present grabens during the extensional regime prevailing in the area since early Oligocene.

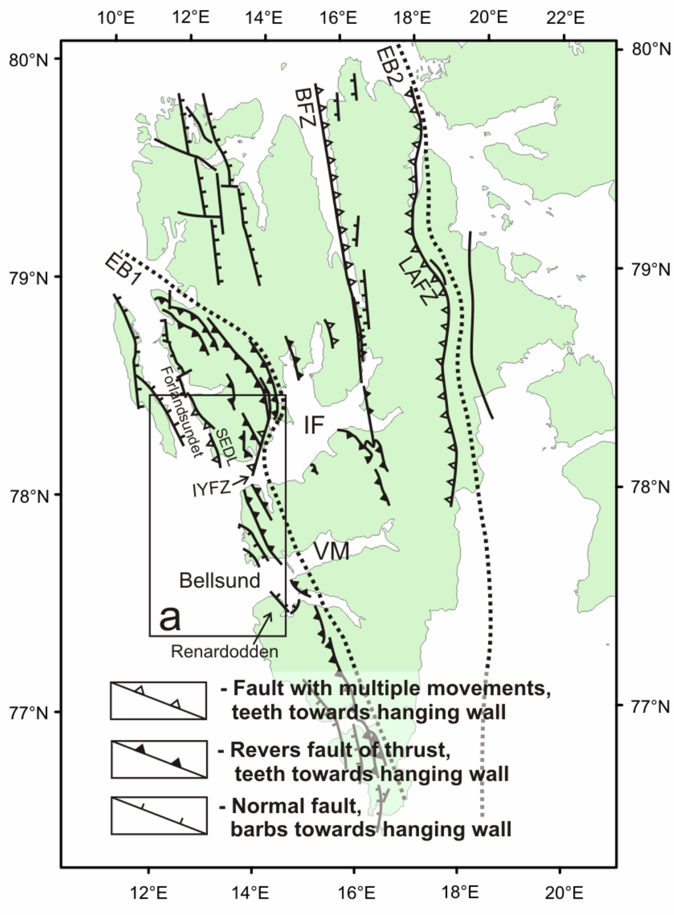

Figure 5. Tectonic map of Spitsbergen (adopted from Dallmann 1999). A - area of investigation, shelf. IF – Isfjorden, VM – Van Mijenfjorden, BFZ – Billefjorden Fault Zone, LAFZ - Lomfjorden-Agardbukta Fault Zone, SEDL – St. Jonsfj.-Eidemb.-Daudmannsod. Lineament, IYFZ – Isfjorden-Ymerbukta Fault Zone, EB1 – the boundary of the WSFTB structures, EB2 - The eastern boundary of observed Tertiary folding and thrusting.

The reflectivity picture along the seismic sections that cross the Bellsund Graben displays a sub-horizontal and continuous reflector below the graben. The reflection is interpreted as a detachment within the basement-involved thrust complex. To the west of the graben structures, the Hornsund Fault Zone is observed as an area characterised by down-faulted blocks evolved during the post Eocene extensional regime.

West Spitsbergen continental margin – Knipovich Ridge

New multichannel seismic data acquired along the outer continental margin off western Svalbard were utilized for analysis of sedimentary processes and depositional history in relation to tectonic events. The main features within the study area are the Bellsund and Isfjorden fans deposited along the continental slope, and the asymmetrical ultraslow spreading Knipovich Ridge (Fig. 6).

The late Plio-Pleistocene Isfjorden and Bellsund fans are mainly characterised by deposition of turbidities and glacigenic debris flows, with minor influence of slide processes. Depositions of contourites, caused by periodic inflow of the West Spitsbergen Current, are defined along the lower continental slope.

The Knipovich Ridge represents the western boundary of the continental slope off Svalbard. A detailed picture of the sediment sequences within the spreading ridge and along its western flank is obtained from interpretation of new seismic data. The rift valley of the Knipovich Ridge is bounded by 20-40º dipping faults overlain by an around 950 m thick sedimentary succession. Besides the hemipelagic sedimentation in the ridge area, accumulation of such a thick sedimentary pile could be related to depositions influenced by turbidity currents, glacigenic debris flows, meltwater sedimentation and slide processes. A slide debrite recognized at the western flank of the Knipovich Ridge implies that some sediments in that region were sourced from the western Spitsbergen – northwestern Barents Sea continental margin.

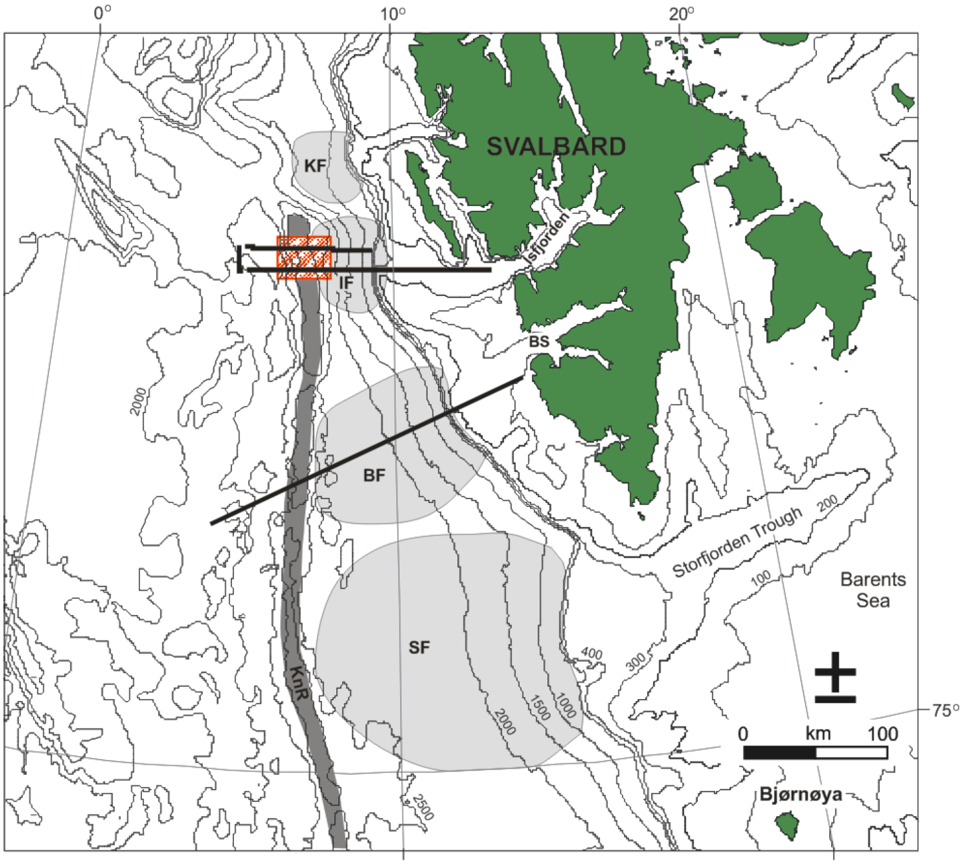

Fig. 6. Study area along the west Spitsbergen continental margin. Thick black lines correspond to seismic profiles; red box represents area of bathymetric data. Light grey colour – trough mouth fans (KF, IF, BF and SF – Kongsfjorden, Isfjorden, Bellsund and Storfjorden Fans correspondingly); dark grey colour – Knipovich Ridge (KnR) rift valley.

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List of papers

The articles presented in the thesis are listed in chronological order according to the geological evolution of the study area:

- **Paper 1:** Blinova, M., Faleide, J.I., Gabrielsen, R.H. & Mjelde, R.: Analysis of structural trends of sub-seafloor strata in the Isfjorden area of the West Spitsbergen Fold-and-Thrust Belt based on multichannel seismic data. *In review*.

- **Paper 2:** Blinova, M., Faleide, J.I., Gabrielsen, R.H. & Mjelde, R. 2011: Seafloor expression and shallow structure of a surfacing fold-and-thrust system: an example from Isfjorden, West Spitsbergen. *Polar Research, in review*.

- **Paper 3:** Blinova, M., Thorsen, R., Mjelde, R. & Faleide, J.I. 2009: Structure and evolution of the Bellsund Graben between Forlandsundet and Bellsund (Spitsbergen) based on marine seismic data. *Norwegian Journal of Geology 89, 215-228*.

- **Paper 4:** Amundsen, I.M., Blinova, M., Hjelstuen, B.O., Mjelde, R. & Haflidason, H. 2011: The Cenozoic western Svalbard margin: sediment geometry and sedimentary processes in an area of ultraslow oceanic spreading. *Marine Geophysical Research*, *DOI 10.1007/s11001-011-9127-z*.