# Structure and evolution of the Bellsund Graben between Forlandsundet and Bellsund (Spitsbergen) based on marine seismic data.

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Seismic interpretation of multi-channel seismic data acquired along the western shelf of Spitsbergen allowed identification of the main geological features of the area, including the Hornsund Fault Zone, and the Forlandsundet and Bellsund grabens. The Bellsund Graben is defined as a narrow, N-S trending graben structure which is approximately 20 km wide and 70 km in length. The graben represents a southern continuation of the Forlandsundet Graben in the north and in the south, it is limited by E-W trending dextral transverse faults external to Isfjorden and Van Mijenfjorden. Development of the graben structures was related to the formation of the West Spitsbergen Fold and Thrust Belt and opening of the Norwegian-Greenland Sea. Compressional structures observed within sedimentary strata infilling the graben may support the view that three stages can be discerned with respect to the evolution of these structures: 1) An initial stage of sediment accumulation in basins broader than those at present (probably latest Paleocene – Early Eocene); 2) graben formation, possibly as a pull-apart structures during a dextral strike-slip regime with local compression (latest Eocene); and 3) normal faulting and final graben development since the onset of sea-floor spreading between Svalbard and Greenland in early Oligocene. The lowermost reflector that underlies the Bellsund Graben has been interpreted as a detachment surface formed during the Late Eocene-Oligocene(?) extension as reactivation of a thrust plane developed during formation of the West Spitsbergen Fold and Thrust Belt. .

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## Introduction

The sheared continental margin along the western Barents Sea and the western coast of Spitsbergen in the north Atlantic represents one of the longest sheared margin segments in the world, extending for ca 1500 km from the Norwegian Margin in the SE to 82˚ N in the NW (Fig. 1).

Margin formation began in the early Cenozoic as the North Atlantic progressively propagated to the northeast, separating the Eurasian and North American plates. Earlier studies have suggested a complex interplay of strike-slip, compressional and extensional tectonics along the margin (Birkenmajer 1981; Eldholm et al. 1987; Harland & Dowdeswell 1988; Faleide et al. 1991, 1996).

Earlier studies of the continental shelf off Spitsbergen have indicated the location of the margin's main fault system, the Hornsund Fault Zone, and the Forlandsundet Graben (Fig. 1b). In our study we use recently acquired and unpublished Multi-Channel Seismic (MCS) data in Forlandsundet and southward to the Bellsund area. The aim of the study is: 1) to identify the interplay between, and evolution of, the different tectonic regimes in the area, and 2) to identify possible segmentation along the margin.

## Seismic data

The area of investigation is located within the western Spitsbergen continental shelf region seaward of Isfjorden and Bellsund. Interpretation of the MCS data from the shelf region has been made along the seismic lines acquired by the University of Bergen (Norway) during the surveys SVALEX-2001, SVALEX-2002 and Van-Mijenfjorden-2005. In addition, we have used the seismic section along line 37 from the survey Svalbard BU-1981 and geo-seismic section based on line NP-FO-85/11 published by Gabrielsen et al. (1992). A location map of the seismic profiles is shown in Fig. 2.

## Geological setting

The development of the western Svalbard continental margin began at the Paleocene-Eocene transition (anomaly 24), when major plate reorganization took place in the North Atlantic and Arctic, and where Greenland commenced relatively northward movements as a separate plate. (Talwani & Eldholm 1977; Srivastava 1978, 1985; Tessensohn & Piepjohn 2000). Initially, the western Spitsbergen margin developed as a sheared margin and since the Early Oligocene as an obliquely rifted passive margin, associated with the Hornsund Fault Zone

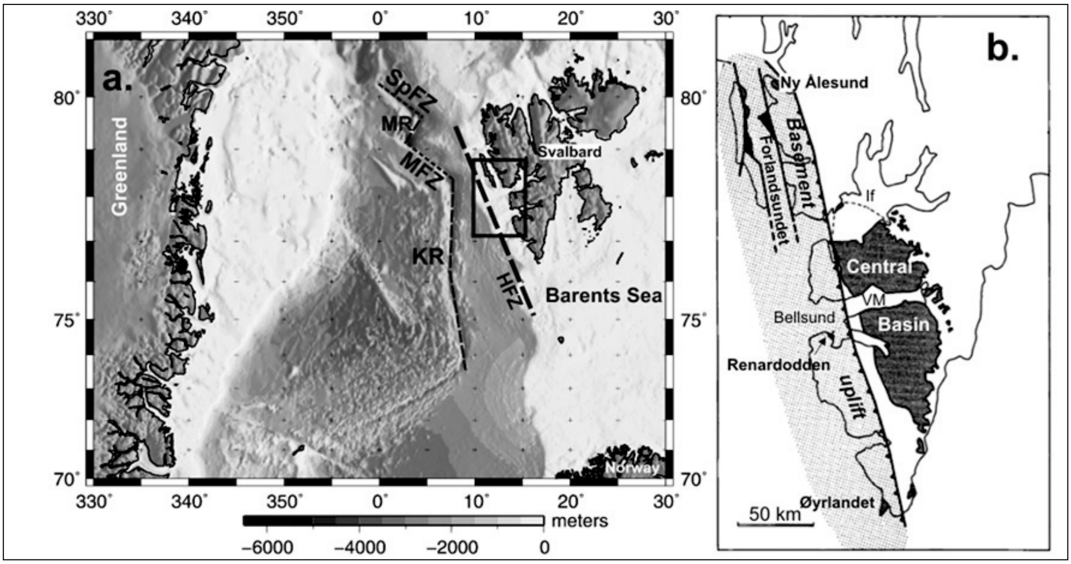

*Fig. 1. a) Location map of the study area. KR – Knipovich Ridge; MFZ – Molloy Fracture Zone; MR – Molloy Ridge; SpFZ – Spitsbergen Fracture Zone; HFZ – Hornsund Fault Zone; square – area of investigation. b) Tertiary sediments and location of uplifted basement along the western Spitsbergen. IF – Isfjorden; VM – Van Mijenfjorden; Dark grey color – Tertiary sediments, Light grey color – Tertiary fold belt. (Manum, S.B. & Throndsen, T. 1986; Myhre et al. 1992; Faleide at al. 1996; Ritzmann et al. 2002).*

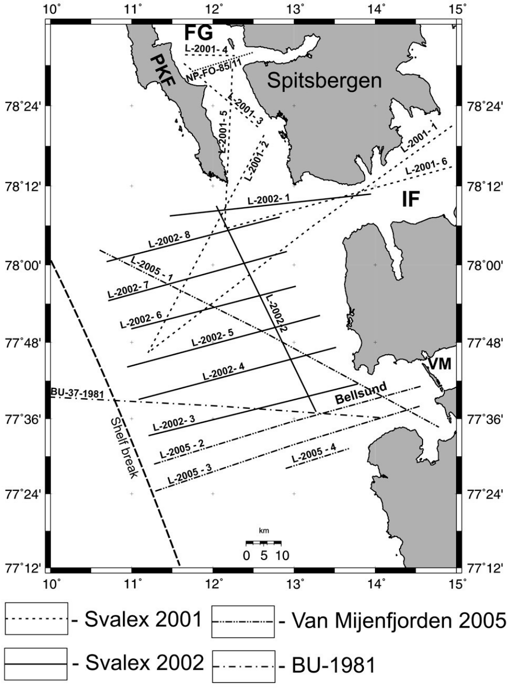

*Fig. 2. Survey map. Line NP-FO-85/11 published by Gabrielsen et al. (1992). IF – Isfjorden; VM – Van Mijenfjorden; PKF – Prins Karls Forland.*

(HFZ) which is parallel to it (Fig. 1; Faleide et al. 1991, 1996).

The area of investigation is located along the western hinterland zone adjacent to the uplifted, basement-involving West Spitsbergen Fold-and-Thrust Belt (WSFB, Bergh et al. 1997; Braathen et al. 1999; CASE Team 2001). The area is characterized by pre-Devonian crystalline basement rocks unconformably overlain by slivers of Tertiary sedimentary cover (Fig. 1) (Eiken & Austegard 1987; Gabrielsen et al. 1992; Gosen & Paech 2001).

The Pre-Devonian, crystalline basement of the Svalbard Archipelago comprises Precambrian to Early Silurian sediments and magmatites which have been deformed during the Paleozoic Caledonian and younger orogenies (Birkenmajer 1981; Worsley & Aga 1986). The Caledonian Orogeny was followed by a period of extensive erosion that brought about the deposition of Old Red molasse sediments in Svalbard in the Latest Silurian(?) - Late Devonian time. During subsequent Svalbardian deformation in the Early Carboniferous, the Old Red sedimentary strata were affected by the compressional west-directed folding and thrusting (McCann 2000; Piepjohn 2000; Piepjohn et al. 2000; Dallmann 2007). By the end of the Carboniferous period, the Svalbard area became part of a continental platform (Birkenmajer 1981). Since then, the development of the Svalbard area has been characterized by varying regimes - uplifting, erosion and subsidence with the accumulation of a thick succession of carbonates, evaporates and clastic sediments. Stable platform conditions predominated on Svalbard until the Cretaceous. During the Jurassic and lower Cretaceous, marine conditions prevailed in the area followed by regional uplift in Late Cretaceous time (Worsley & Aga 1986; Harland & Dowdeswell 1988; Faleide et al. 1991; Myhre et al. 1992).

Since the Late Cretaceous, the Spitsbergen continental margin has been affected by the evolution of the North Atlantic region. A brief summary of the evolution and its relation to the West Spitsbergen Fold and Thrust Belt development is presented below.

The North Atlantic evolution we can be divided into 3 stages:
*1) Paleocene (anomalies 27-24).* Before the opening of the Norwegian-Greenland Sea, Greenland belonged to the Eurasian plate and a land bridge existed between North Greenland and Svalbard (Talwani & Eldholm 1977; Tessensohn & Piepjohn 2000). According to a refined model of the evolution of the Labrador Sea (Chalmers & Pulvertaft 2001), the initiation of sea-floor spreading on the western side of Greenland took place in the Early Paleocene (anomalies 27, 61.3-60.9 Ma). Since that time Greenland moved to the northeast, oblique to Ellesmere Island with minor sinistral strike-slip motion along the Nares Strait, defined as the boundary between the North American plate and Greenland (Srivastava 1985; Tessensohn & Piepjohn 2000; Oakey & Stephenson 2008). During that time the Norwegian-Greenland Sea underwent rifting (Srivastava 1978), and dextral wrench movements along an old zone of weakness, the De Geer Zone (Faleide et al. 1993).

*2) Eocene (anomalies 24 – 13).* At the time of anomaly 24 a major reorganization of the plates took place in the North Atlantic and Arctic regions, beginning with of sea-floor spreading in Baffin Bay, the Norwegian-Greenland Sea and in the Eurasian Basin (Talwani & Eldholm 1977; Srivastava & Tapscott 1986; Eldholm et al. 1990; Tessensohn & Piepjohn 2000; Mosar et al. 2002; Oakey & Stephenson 2008). The spreading systems of the Labrador Sea/Baffin Bay and Norwegian-Greenland Sea were connected in a triple junction south of Greenland. Greenland started to move northward (Tessensohn & Piepjohn 2000) as a separate plate oblique to Ellesmere Island and to Western Spitsbergen, causing the main compressive deformation within the Eurekan and West Spitsbergen foldbelt systems north of Greenland (Birkenmajer 1981; Faleide et al. 1984; Tessensohn & Piepjohn 2000; Oakey & Stephenson 2008). During the later stages of WSFB development (possibly late Eocene), synsedimentary formation of graben structures followed or accompanied by compressive deformation took place along the western coast of Spitsbergen (Steel et al. 1985; Gabrielsen et al. 1992, Gosen & Paech 2001). More detailed development of the graben structures is described later in this paper. The De Geer Zone consists of the Senja Fracture Zone, the Hornsund Fault Zone and the Greenland Fracture Zone (Fig. 3) and appears as a broad dextral regional shear zone separating Svalbard from NE Greenland (Harland 1969; Talwani & Eldholm 1977; Srivastava & Tapscott 1986; Faleide et al. 1993; Tessensohn & Piepjohn 2000; Lundin & Doré 2002; Mosar et al. 2002).

*3) Oligocene – present (anomaly 13).* In the earliest Oligocene, spreading in the Labrador Sea – Baffin Bay system finished, and a transtensional regime took place along the De Geer Zone (Tessensohn & Piepjohn 2000), and both the Eurekan and West Spitsbergen Fold belts became inactive (Faleide et al. 1993). Generation of oceanic crust started between Svalbard and Greenland. The latter became part of the North American plate and began to move to the WNW relative to Eurasia (Talwani & Eldholm 1977; Srivastava 1985; Srivastava & Tapscott 1986; Eldholm et al. 1990; Tessensohn & Piepjohn 2000; Mosar et al. 2002). Oblique extension along western Spitsbergen since earliest Oligocene was responsible for normal faulting, collapse of the earlier compressional structures, down-faulting of blocks on the western side of Hornsund Fault Zone and formation of the final graben geometry (Eldholm et al. 1987; Harland & Dowdeswell 1988; Faleide et al. 1991; Myhre et al. 1992; Lepvrier 1994; Manby & Lyberis 1996). The extension of the area led to thinning of the continental crust of the western Svalbard margin, causing subsidence and accumulation of a thick pile of Cenozoic sediments on the outer part of the continental shelf.

In the Svalbard area the Cenozoic deposits are best developed south of Isfjorden within the central basin and as graben infill along the west coast of Spitsbergen (Fig. 1). The Tertiary strata in the Forlandsundet Graben are reported to be approximately 5 km thick (Gabrielsen et al. 1992). There are four small outcrops of Tertiary sediments observed along the west coast: Forlandsundet, Ny

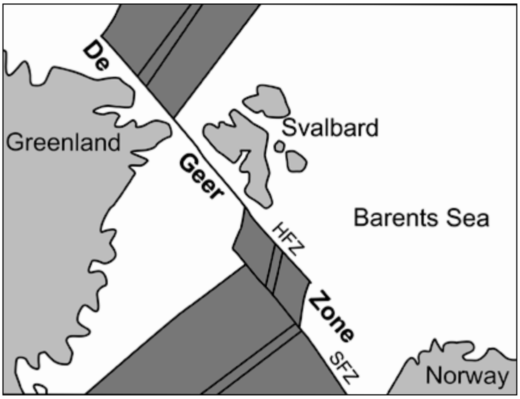

*Fig. 3. Sketch of De Geer Zone during Mid-Tertiary (from Faleide et al. 1993). SFZ – Senja Fracture Zone; HFZ – Hornsund Fault Zone.*

Ålesund, Renardodden, and Øyrlandet. The oldest formation of Tertiary sediments of the Central Basin are Early Paleocene, whereas the sediments outcropping in Forlandsundet are considered to be Late Eocene to Early Oligocene (Birkenmajer 1981; Manum & Throndsen 1986; Steel et al. 1985; Gabrielsen et al. 1992). The age of the oldest sediments in the Forlandsundet Graben is not known (Gosen & Paech 2001).

According to a recent publication by Knies et al. (In press) the first significant phase of Plio-Pleistocene glaciation in the Barents Sea – Svalbard region took place at 3.6-2.4 Ma. Glacial expansion beyond the coastline and/or on the shelf of the northern/western Barents Sea (including Svalbard) has been dated by the authors to ca. 2.7 Ma. Thus, the onset of glacially influenced sediment deposition in the area (previously dated by Faleide et al. (1996) to 2.3 Ma) may corresponded to the 2.7 Ma age.

The Upper Regional Unconformity (URU) identified within the sedimentary sequence along the Svalbard continental margin (Solheim and Kristoffersen 1984; Solheim et al. 1996) has been related to the general climatic shift dated at ca. 1.5 Ma (Knies et al. in press) and corresponded to the change in the depositional regime from net erosion to net accumulation (Faleide et al. 1996; Solheim et al. 1996).

Table 1 summarizes the evolution of the North Atlantic in relation to tectonic processes along western Spitsbergen. There are some disagreements in published articles about geological age determinations for tectonic events in the area. For example, according to new observations by Chalmers & Pulvertaft (2001) and Oakey & Stephenson (2008), the onset of sea-floor spreading in the Labrador Sea is related to magnetic anomaly 27 (mid Paleocene time), whereas Srivastava (1985) and Srivastava & Tapscott (1986) related it to anomaly 34 (Late Cretaceous). However, for the anomaly 27 and younger, Chalmers & Pulvertaft (2001) confirmed the general correspondence to that shown on the original map of Srivastava. The age of Eurekan compressive deformation may be controversial due to differences in event definition, while there is agreement on the existence of active tec-

| Age(Ma) | Epoch | Magnetic anomaly | Regional settings (North Atlantic) | | | Local settings (West Spitsbergen) |
|---|---|---|---|---|---|---|
| | | | West of Greenland (Labrador Sea/ Baffin Bay) | Greenland | East of Greenland (Norwegian-Greenland Sea) | |
| 25<br>30 | Oligocene | 7<br>8<br>9<br>10<br>11<br>12<br>13 | Sea-floor spreading in LS/BB is finished | Gr. moves WNW relative to Eurasia<br>Gr. is a part of North American plate | **Sea-floor spreading between Sv. and Gr.**<br>DGZ - transtensional transform zone. | Transtension in WSFTB: normal faulting, final graben developement<br>Crustal thinning and subsidence of the western margin of Spitsbegen |
| 35<br>40<br>45 | Eocene | 15<br>16<br>17<br>18<br>19<br>20<br>21 | Slowing or end of sea-floor spreading in LS/BB | **Eurekan and West Spitsbergen Compression**<br>Oblique movement of Gr. to Ellesmere Island and West Spitsbergen<br>N-ward movement of Gr.<br>Gr. became separate plate | DGZ - right-lateral megashear region, rift zone<br>**Sea-floor spreading in NGS**<br>Start of sea-floor spreading in NGS | **West Spitsbergen Compression**<br>Local extension, sedimentation and graben formation in Forlandsundet<br>Compressional deformation: folding and thrusting |
| 50<br>55 | | 22<br>23<br>24 | **Sea-floor spreading in LS/BB**<br>Change in spreading direction | | | |
| 60 | Paleocene | 25<br>26<br>27 | **Rifting in BB**<br>**Spreading in LS**<br>Start of sea-floor spreading in LS | Regional uplift NS-sinistral strike-slip<br>NE-ward movement of Gr. and Eurasia relative to North America | DGZ - dextral wrench movements<br>Rifting in NGS<br>Gr. belongs to Eurasian plate | Uplift<br>Sv. adjacent to northern Greenland |
| 65 | | 28 | Rifting in LS/BB | | | |

*Table 1. Summary of evolution in northern Atlantic during Cenozoic (Talwani & Eldholm 1977; Srivastava & Tapscott 1986; Faleide et al. 1991 & 1993; Tessensohn & Piepjohn 2000; Chalmers & Pulvertaft 2001; Oakey & Stepherson 2008). LS - Labrador Sea; BB - Baffin Bay; NGS - Norwegian-Greenland Sea; Gr. - Greenland; Sv. - Svalbard; DGZ - De Geer Zone; NS – Nares Strate; WSFTB - West Spitsbergen Fold and Thrust Belt.*

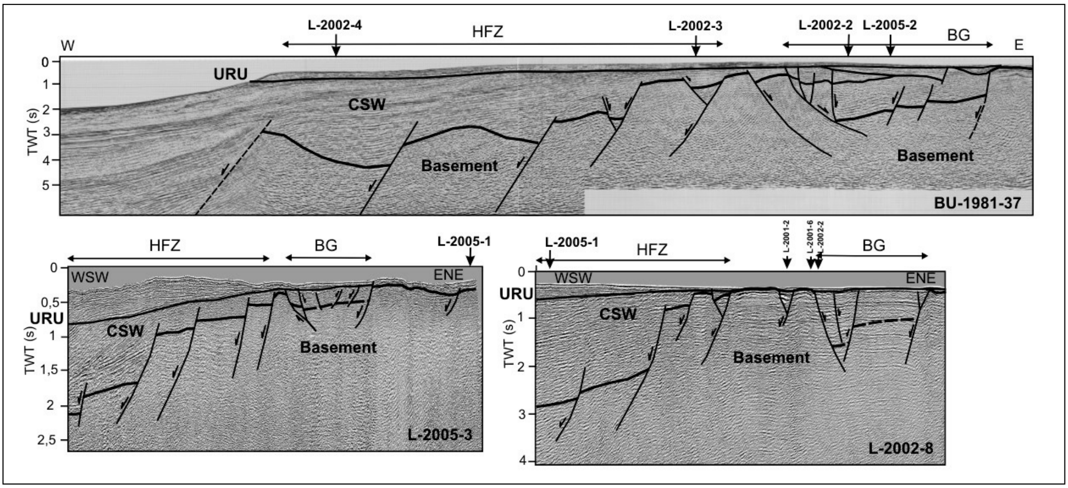

*Fig. 4. Interpretation along the seismic sections: BU-1981-37, L-2002-8 and L-2005-3. FG – Forlandsundet Graben; SS - Strike-slip fault; HFZ – Hornsund Fault Zone; CSW – Late Cenozoic Sedimentary Wedge; URU – Upper Regional Unconformity. Thick lines – interface between seismic units; thin lines – faults; dashed lines – uncertainties.*

tonism in the Innuitian Region in NW Greenland, the Nares Strait and Ellesmere Island from Late Cretaceous till the end of the Eocene. (Thorsteinsson & Tozer 1970, Oakey & Stephenson 2008). There are also some differences in age definition for the formation of the West Spitsbergen Fold-and-Trust Belt. For instance, Lyberis & Manby (1993) and Manby & Lyberis (1996) proposed the onset of the fold and thrust belt formation to be in Upper Cretaceous time and its termination it the Late Paleocene (anomaly 25), whereas most authors argue for an Eocene age for the fold-and-thrust belt development (Maher et al. 1995; Tessensohn & Piepjohn 2000; CASE Team 2001). In our review of the development of the North Atlantic we tried to follow the latest and most accepted models, when considering formation of the WSFB from anomaly 24 (Paleocene-Eocene transition) until the onset of the opening of the NGS (Norwegian Greenland Sea) at anomaly 13 (Early Oligocene) (Table 1).

## Results

The available seismic data along the west Spitsbergen shelf in the Forlandsundet and Bellsund areas have been interpreted with the aim of defining the main faults crossing the study region and to separate sections into seismic facies corresponding to the sedimentary sequences and underlying metamorphic basement. Identification of the seismic boundary between sedimentary strata and basement is difficult in most places, because of the absence of clearly defined reflectors and interference with noise and multiples. Nevertheless, we tried to define and correlate that interface along all seismic lines. The main criterion for identification of the top basement was a separation of strata with well-defined layering from parts below with more chaotic and weaker signals. Criteria for a main fault definition were a rapid depth shift of the top basement interface and/or a pronounced inclined reflector cutting a sequence.

The main structural features that have been observed in the MCS data were the Forlandsundet Graben with its southward continuation into the Bellsund Graben, and the Hornsund Fault Zone overlain by a thick sedimentary wedge. The greatest thicknesses of sedimentary cover occur along the shelf edge near the Hornsund Fault Zone (up to 3 s. twt) and within the Bellsund Graben (around 2 s. twt). An example showing the interpretation of the Hornsund Fault Zone and the Bellsund Graben is shown in Fig. 4. The sedimentary strata that cover the shelf area have been divided into two stratigraphic megasequences separated by a well defined unconformity (URU).

### *The Hornsund Fault Zone*

The Hornsund Fault Zone is defined as a zone of down-faulted blocks that extend along the central and outer continental shelf in a NNW-SSE direction, and are covered by the Tertiary sedimentary wedge (Eldholm et al. 1987; Myhre et al. 1992; Faleide et al. 1996; Solheim et al. 1996). The eastern boundary of the Hornsund Fault Zone is interpreted as the start of the westward-dipping down-faulted blocks of basement (Fig. 4). This boundary could be defined by a horst structure to the west of the Forlandsundet Graben and the Bellsund Graben. The horst along the Forlandsundet Graben is uplifted, forming Prins Karls Forland. To the south, the horst continues, but is not as uplifted as in the north, hidden below the water and the sedimentary wedge. The interpretation of the Hornsund Fault Zone is in agreement with published structural models along the seismic lines that cross the Spitsbergen shelf in the study area and in its vicinity (Sundvor & Austegard 1990; Faleide et al. 1991, 1996; Ritzmann et al. 2002, 2004).

*Sedimentary wedge*

In the study area the Cenozoic sedimentary wedge can be seen on the seismic profiles as a westward-dipping unit unconformably overlying the down-faulted basement blocks of the HFZ. The Cenozoic sedimentary wedge represents glacially dominated deposits accumulated during the last 2.7 my (Faleide et al. 1996; Solheim et al. 1996; Knies et al. in press). In some sections, it may be possible that Paleozoic and Mesozoic sedimentary strata are present between the Cenozoic sedimentary wedge (CSW) and the underlying basement. But any clear evidence for the presence of such strata is difficult to find along the seismic lines.

The sedimentary wedge can be divided into a number of sequences separated by unconformities (Faleide et al. 1996; Solheim et al. 1996). We can clearly define the most pronounced unconformity separating the relatively steep, westward dipping sedimentary unit from the overlying, relatively flat subparallel stratum (Fig. 4). According to Faleide et al. (1996) and Solheim et al. (1996) that surface corresponds to the URU. The upper part of the sedimentary succession has a relatively thin top sedimentary layer deposited unconformably over deformed sedimentary strata. The seismic reflectivity of the upper layer indicates horizontal layering or bedding subparallell to the relief of the URU surface. The layer has been interpreted along all of the profiles crossing the inner and outer shelf, with increased thickness seawards (Fig. 4).

*Forlandsundet Graben*

The Forlandsundet Graben extends in a NNW-SSE direction along the Spitsbergen continental shelf bordered by Prins Karls Forland to the west and the coastline of Spitsbergen to the east (Fig. 1b). Gabrielsen et al. (1992) described the major faults of the graben as a NNE-SSE striking, steeply dipping en echelon system of faults separating the Cenozoic sediments from basement rocks. The segments of the major faults terminate in some cases at NW-SE trending faults. The Forlandsundet Graben has been divided into four units along strike, and an interpretation of seismic sections acquired within different graben units shows shift in the polarity of the sedimentary fill (Gabrielsen et al. 1992).

Line drawings of interpreted seismic sections are shown in Fig. 5. The figure also includes a line drawing of line NP-FO-85/11 that crosses the Forlandsundet central

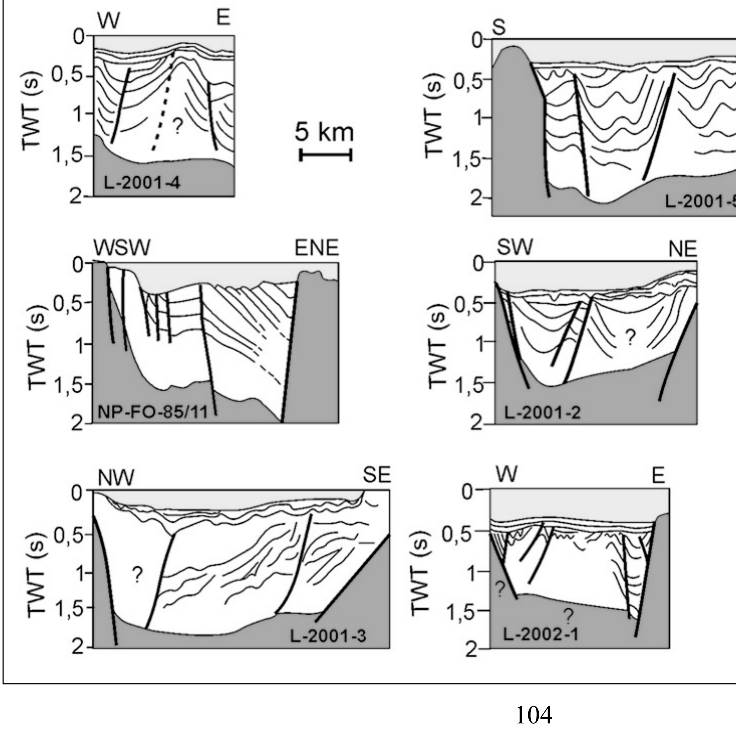

*Fig. 5. Visualization of the general character of seismic reflectivity within the Forlandsundet Graben. For location of profiles see Fig. 2. Thick lines – faults; thin lines – layering.*

area (Gabrielsen et al. 1992). Observations along lines L-2001-4 and NP-FO-85/11 show quite similar features as regards sedimentary structure, reflecting eastward tilting of sedimentary beds within the eastern part of profile. The eastern part of the section along L-2001-5 demonstrates relatively horizontal layering but with some signs of folding. The central part of L-2001-3 is characterized by westward dips, whereas central part of the L-2001-5 indicates deformation by folding.

### *Bellsund Graben*

Eiken & Austegard (1987) described graben structures with geometry similar to the Forlandsundet Graben further south of Prins Karls Forland. They also postulated the possibility of analogous shifting in polarity of sedimentary infilling between the different graben units along the coast.

The acquisition of additional MCS data allowed us to make a more detailed study of the shelf area between outer Isfjorden and Bellsund. Along seismic lines crossing the area, the reflectivity picture changes significantly from the outer to the inner shelf. The part of the shelf that is located to the east of the Hornsund Fault Zone reflects a graben structure, i.e. the Bellsund Graben. This graben corresponds to a southward continuation of the Forlandsundet Graben. An example of the Bellsund Graben reflectivity is shown in Fig. 6. The western boundary fault of the graben is generally well defined on most of the seismic sections. The identification of the eastern boundary fault on the seismic lines is limited by the short landward extension of the seismic profiles, except those lines extending into the fjord mouths (Fig. 2).

The seismic images of the sedimentary fill in the Bellsund Graben are generally characterized by a slight inclination of the layers due to normal faulting, reverse faulting and folding (Fig. 6).

Fig. 7 shows line drawings of the seismic interpretations within the Bellsund Graben. Observations along the northern lines (from L-2002-8 to L-2002-4) generally express a similar trend in the seismic structure, indicating a slight westward inclination within the central part of the sedimentary sequence. A shift in dip direction of layers within the graben occurs along the southern profiles, L-2002-3 and L-2005-2. Along the profile parallel to the coastline (L-2002-2), the area of intersection with L-2002-4 and L-2002-3 (southward from SP-900) is characterized by extensive faulting (Fig. 8). The sediment/basement boundary along L-2005-3 has been identified at depths no greater than 500 ms twt. The termination of the relatively thick sedimentary sequence could correspond to the southern end of the Bellsund Graben.

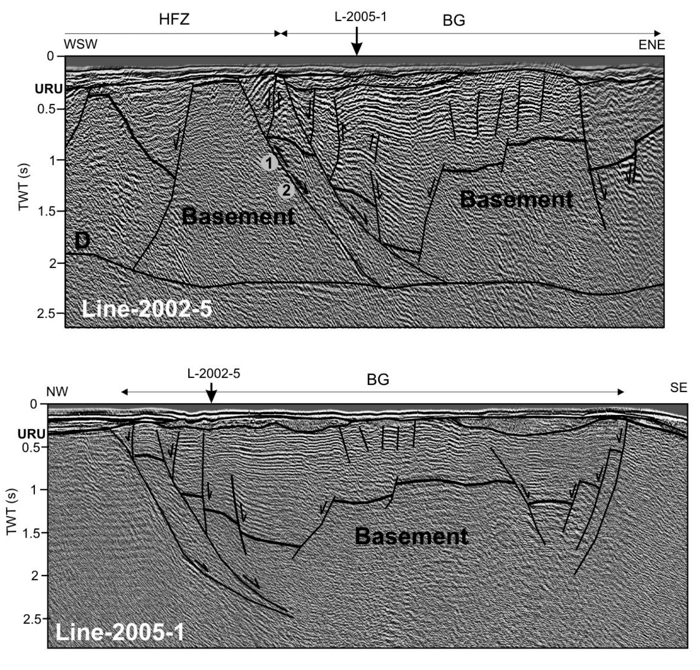

*Fig. 6. Interpretation along two seismic sections Line-2002-5 and Line-2005-1, Bellsund Graben. BG – Bellsund Graben; HH – Baement Hecla Hoek; D – Surface of detachment; URU – Upper Regional Unconformity; faults 1 and 2 (Line-2002-5) – first reverse (fault 1) and then normal faulting (fault 2).*

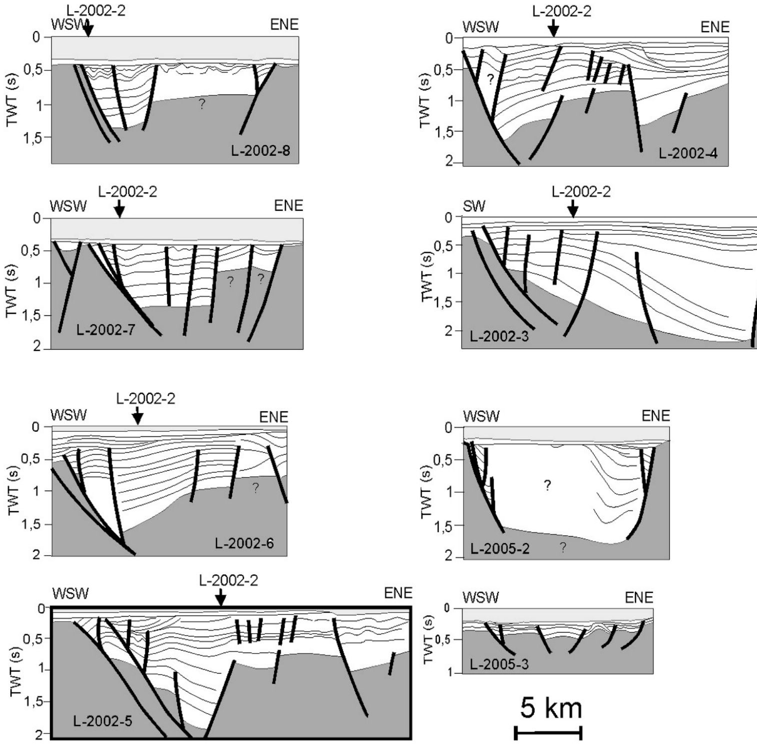

*Fig. 7. Visualization of general character of seismic reflectivity within the Bellsund Graben. SS – strike-slip fault. For location of profiles see Fig. 2. Thick lines – faults; thin lines – layering.*

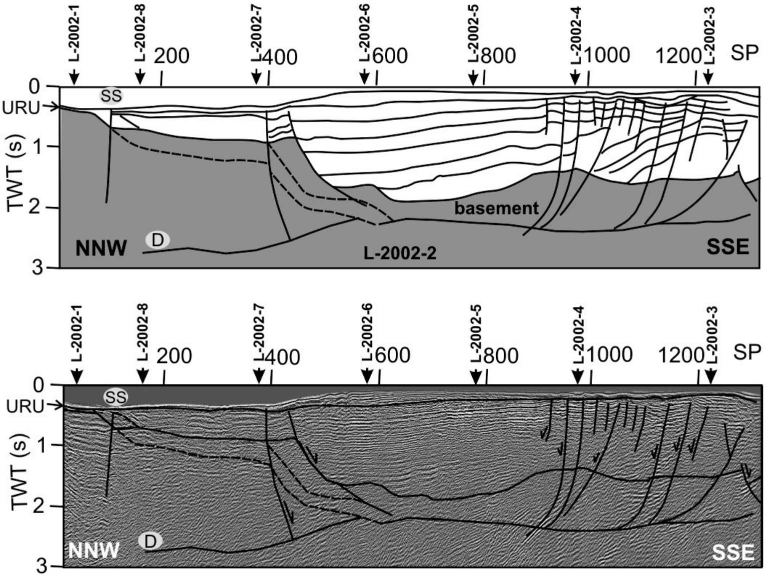

*Fig. 8. Figure above: visualization of general character of seismic reflectivity along the Line-2002-2 (Thick lines – faults; thin lines – layering). Figure below: interpretation along the Line-2002-2. For location of profiles see Fig. 2. D – interface of detachment; HH – interface of basement Hecla Hoek; SS – strike-slip fault; Dashed lines – faults crossing the line at a sharp angles.*

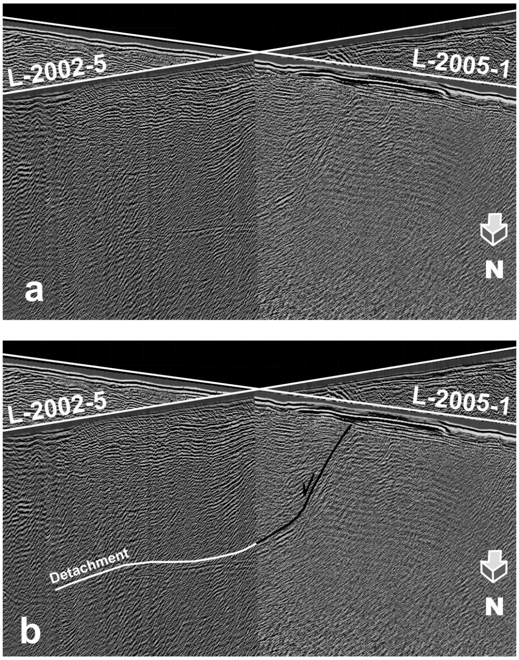

*Fig. 9. 3D view of the crossing sections L-2002-5 and L-2005-1 with example of fault soling out into detachment surface, with and without interpretation (figures a and b correspondingly).*

### *Detachment*

A sub-horizontal and slightly curved reflector at depths of about 2,5 s. twt has been observed along seismic lines covering the continental shelf between Isfjorden and Bellsund. Examples of the reflector interpretation are shown in Fig. 6 along L-2002-5 and in Fig. 8 along L-2002-2. We interpret the reflector as a thrust fault reactivated as an extensional detachment. Normal faults sole out into the detachment surface, as shown in 3-D view in Fig. 9b.

The detachment is found along seismic lines acquired during the survey Svalex – 2002. Along the SW-NE striking profiles, the reflector underlies the graben area, extends westwards, and dies out within the eastern part of the Hornsund Fault Zone. The observations along seismic section L-2002-2 (Fig. 8), striking along the shelf, show that the reflector underlies the graben and disappears towards the northern end of the profile. The lines of older surveys that cross the area of the detachment do not show the reflector, and this could be caused by the use of different parameters of data acquisition and processing flow.

# Discussion

### *The Hornsund Fault Zone and the Forlandsundet and Bellsund Grabens fault systems*

The locations of the interpreted major faults that correspond to the Hornsund Fault Zone, Forlandsundet Graben, and Bellsund Graben are shown in Fig. 10. On the map we observe an abrupt W-E trending offset between the faults bordering the Forlandsundet Graben and the Bellsund Graben in the areas outside Isfjorden and Bellsund. The right-lateral displacement of the graben fault system outside Isfjorden has been inferred in previous works by Eiken & Austegard (1987) and Gabrielsen et al. (1992). We relate this zone of displacement to an E-W trending transverse fault representing a borderline between Forlandsundet Graben and Bellsund Graben. The graben structures may have formed either as one structure prior to the area being transected by dextral strike-slip faulting or afterwards, developed independently on each side of the fault (Fig. 10). The same situation could be present in the southern part of Bellsund Graben (seaward of Bellsund), where we observe slight dextral displacements of the major faults, which might also reflect strike-slip movements. More likely, the dextral displacement indicates a transfer fault bounding

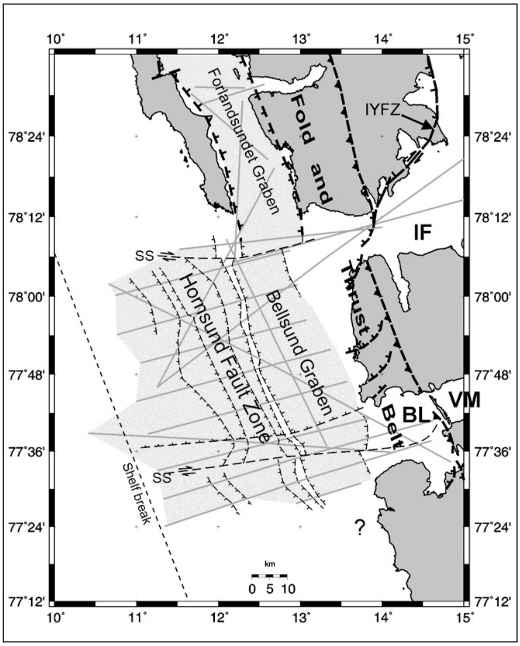

*Fig. 10. Map of main structural features within the study area. Dark grey area – Spitsbergen; Light grey area – main structural features: a) Forlandsundet Graben, b) Bellsund Graben, c) Hornsund Fault Zone; IYFZ – Isfjorden-Ymerbukta Fault Zone (Braathen et al. 1999; Bergh et al. 2000; Saalmann & Thiedig 2002); IF – Isfjorden; VM – Van Mijenfjorden; BL – Bellsund; SS – strike-slip faults (interpreted shear zones).*

graben structures that developed independently on each side of the fault, since the reflectivity pattern along lines on each side of the strike-slip faults is quite different (see Fig. 7, L-2005-2 and L-2005-3).

The transfer faults cutting Forlandsundet Graben and Bellsund Graben seaward of Isfjorden and Bellsund (Fig. 10) might signify transitions between zones with different intensity of deformation developed along the West Spitsbergen Fold and Thrust Belt. Reflectivity along the seismic lines in the Forlandsundet area shows more intense folding than that observed along the seismic lines crossing the Bellsund Graben (Figs. 5 and 7), while the reflectivity picture to the south of the transverse fault outside of Bellsund reflects the southern termination of the Bellsund Graben. A 3D view of the basement interface and the strike-slip faults is shown in Fig. 11.

### *Forlandsundet and Bellsund grabens*

There is no solid agreement for a hypothesis about graben structural evolution along the western part of WSFB. Due to the facts that the fold-and-thrust belt evolved during the time of dextral strike-slip movement along De Geer Zone (anomaly 24 -13), some authors relate its evolution to a transpressional regime (Harland 1969; Lowel 1972; Craddock et al. 1985). Thus, the mechanism for initiation of the Forlandsundet Graben formation was also correlated with the regional dextral transpression (Gabrielsen et al. 1992; Steel et al. 1995). CASE Team (2001) points out that the transpressional evolution of the WSFB based on observations of the principal geometry of the fold-and-thrust belt is not consistent with those of typical transpressively generated strike-slip zones. For instance, consistent tectonic transport to the ENE of the entire belt, lack of fold-belt parallel strike-slip faults and the extent of the fold-and-thrust belt to the east more than 100 km from the western continental margin (Dallmann et al. 1993) do not support evolution of the fold-and-thrust belt by transpression. The authors reviewed the evolution of WSFB and interpreted it as "ENE-directed, compressive intraplate foldbelt in the hinge area between Greenland and Eurasia" caused by the northward movements of the Greenland plate. The De Geer Zone was related to the initial zone of weakness in continental crust and evolved prior the formation of the fold-and-thrust belt.

According to Gosen & Paech (2001), the tectonic history of the Forlandsundet Graben could be divided into three stages. The first stage corresponded to the initial accumulation of thick sedimentary strata within Forlandsundet, probably in latest Paleocene to Early Eocene time. The sediments accumulated in broader basin than the present graben. This assumption is in agreement with Gabrielsen et al. 1992. The initial stage of synsedimentary extension was followed by compression with dextral strike-slip faulting. The final stage with development of normal faults bounding the present graben was related to post-compressional extension (post-Early Oligocene) (Gosen &Paech 2001).

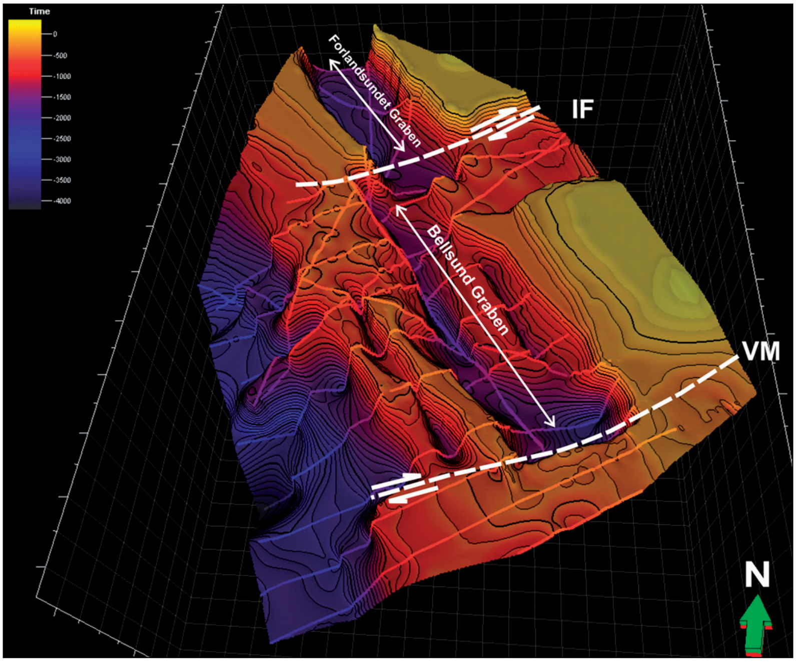

*Fig. 11. 3D view of the basement interface. Dashed lines – strike-slip (transfer) faults.*

Combining the interpretation of WSFB evolution (CASE Team 2001) with the tectonic history of the Forlandsundet Graben proposed by Gosen & Paech (2001), the evolution of WSFB and the adjacent graben can be outlined as follows:

1. Late Paleocene (anomaly 24): Onset of development of De Geer Zone as a major intracontinetal shear;
2. Latest Paleocene – Eocene: Compressive deformation on Spitsbergen and development of Forlandsundet area:

a. Latest Paleocene - Early Eocene (?): Onset of sedimentation in Forlandsundet. According to an observation that the Tertiary sediments unconformably overlie the Caledonian basement, the area underwent uplift and erosion during pre-latest Paleocene time (Gosen & Paech 2001). Thus, a development of local syn-sedimentary extensional structures could take place on top of the uplifted area during the main compressional phase.

b. Latest Eocene: Onset of transtensional movements (CASE Team 2001) and graben formation, possibly as a pull-apart structure during the dextral strike-slip regime and accompanied by the latest compressive movements in the WSFB (Gosen & Paech 2001).

c. Oligocene (anomaly 13): Onset of sea-floor spreading between Svalbard and Greenland, extensional deformation along the western Spitsbergen coast, normal faulting and final graben development.

This model of evolution along the western Spitsbergen coast is in accordance with observations of the sedimentary structure of the Forlandsundet Graben in our data and may explain the presence of compressional structures within the graben fill.

Folding and reverse faulting are also observed along seismic sections of the Bellsund Graben and may correspond to the same tectonic regime. This is reflected in signs of interplay between compressional and extensional regimes along the faults during graben formation. The example of deformation of the Tertiary infill against the basement rocks at the western boundary fault of Bellsund Graben is shown in Fig. 6. The signs of compression indicated in the very steep dip of the layers and different orientations of dip-directions (Line-2002-5) might reflect a push-up effect from the east related to a reverse fault (Fault 1, Line-2002-5, Fig. 6). During a subsequent extensional regime and the final stage of graben formation, the reverse fault was reactivated as a normal fault. It is marked in Fig. 6 as Fault 2.

A structural subdivision of the Forlandsundet Graben based on observation of shifting polarity in sedimentary infill has been described by Gabrielsen et al. (1992). They proposed a similar polarity shift and subdivision into graben units further south along the Bellsund Graben. We can support the proposal by observations made along seismic sections of survey Svalex-2002 crossing the Bellsund Graben, where the reflectivity pattern shows a change in polarity (Fig 7, Lines L-2002-4 and L-2002-3). According to our observations, we may conclude that the Bellsund Graben developed during the same tectonic regimes as Forlandsundet Graben, involving interaction of compressional and extensional forces. The initiation of sedimentation within the graben might be related to local extension during the regional compressional regime in (Early?) Eocene time, also responsible for development of the West Spitsbergen Fold and Thrust Belt.

*Detachment*

Braathen & Bergh (1995 a, b), Bergh et al. (1997) and Bergh et al. (2000) divided the West Spitsbergen Fold and Thrust belt into tectonic zones from west to east: a basement-involved fold-thrust stack along the west coast of Spitsbergen and a thin-skinned, foreland fold-and-thrust belt developed above a basal decollement in Permian gypsum in central areas.

Western Nordenskiøld Land (southern shore at the mouth of Isfjorden) has been described by Braathen & Bergh (1995 a,b) as an area with a Precambrian-Caledonian basement underlying Paleozoic, Mesozoic and Cenozoic sedimentary sequences, all involved in a major, NNW-SSE-striking basement uplift and fold-thrust complex. These authors describe three stages in the development of the fold-and thrust complex:

1) NNE-SSW crustal shortening and thrusting, following an early convergence between Greenland and Svalbard in Late Cretaceous (?);
2) Major deformation characterized by WSW-ENE shortening and generation of major fold complex in probable Middle Paleocene to Eocene time;
3) East-west extension, likely during post-Eocene time.

Based on these onshore studies we interpret the lowermost reflector, observed along most profiles of seismic survey Svalex-2002 (except lines L-2002-1 and L-2002-8), as a basal detachment. The detachment surface is shown in map view in Fig. 12 and in Fig. 13 (A) - our geo-seismic section based on observations along line L-2002-6 and from a geological model for the southern shore of Isfjorden (Faleide, unpublished) in combination with seismic data in Isfjorden. The detachment surface might represent a thrust fault that could be initiated in two ways:

1. As a continuation of WSW dipping thrusts of the major thrust complex (Braathen & Bergh 1995 a, b) into the basement (Fig 13, B). In this case the Bellsund Graben played the role of a westerly hinterland (analogous to the Forlandsundet Graben in Bergh et al. 2000) and was followed to the east by the basement-involved fold-thrust complex and by a zone of thin-skinned fold-thrust structures;
2. Or, it might be related to a decollement within a weak layer of gypsum-bearing Permian – Upper Carbonif-

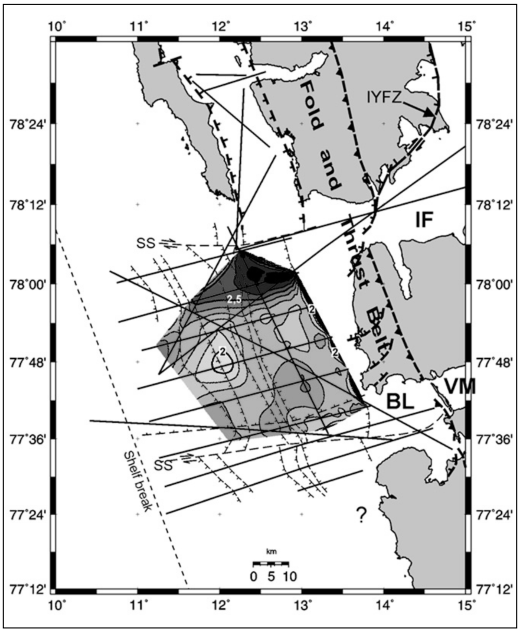

*Fig. 12. Map of the detachment surface. IYFZ – Isfjorden-Ymerbukta Fault Zone; IF – Isfjorden; VM – Van Mijenfjorden; BL – Bellsund. Contours on the detachment surface in twt (s).*

erous rocks (gypsum), over which the basement was thrusted during the compressional regime (Fig 13, C). The shortening in this model would be of greater magnitude than in the model described above.

During the subsequent regional transtension in Early Oligocene time, the thrust fault was reactivated as an extensional detachment, with normal faults in the graben area soling out in this zone (e.g. Fig. 9). Because of lack of data which might indicate whether the detachment evolved within the basement or a sedimentary layer, we left the nature of this surface with question marks (Fig. 13 A). The eastern major fault of the Bellsund graben may represent southward continuation of the Svartfjella, Eidembukta, and Daudmannsodden lineament (SEDL) that is located along the eastern Forlandsundet (Maher et al. 1997).

## Summary and Conclusions

Based on previous research and new, unpublished MCS data on the western continental shelf of Spitsbergen interpretations have been made with the aim of defining the main geological structures of the area. The Hornsund Fault Zone, Forlandsundet and Bellsund grabens have thus been mapped (Fig. 10).

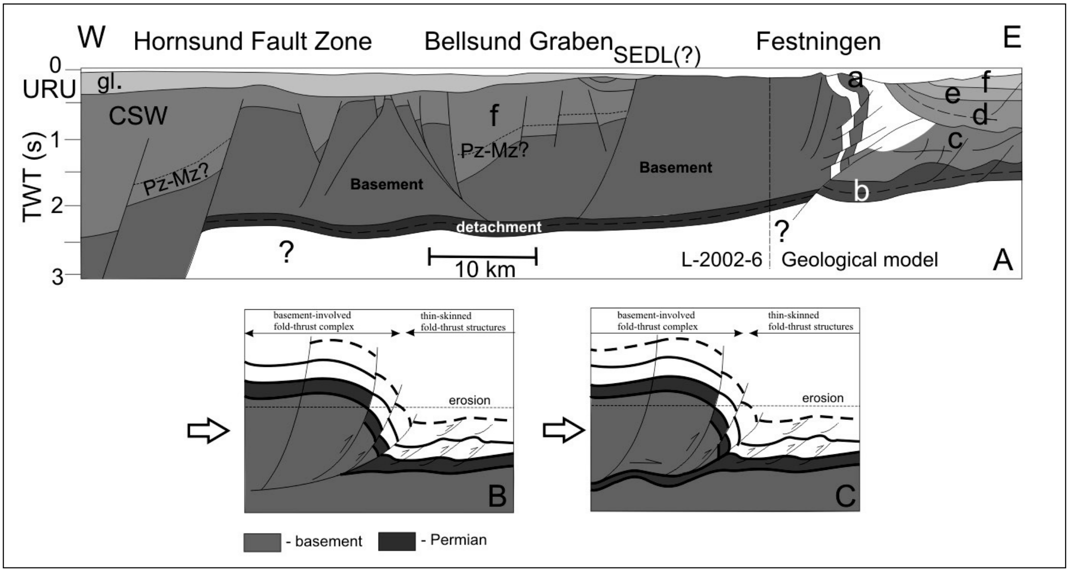

*Fig. 13. A) The geological model that represents a profile compiled from the observations along the line L-2002-6 (western part) and from the western part of geologic model for Isfjorden (Faleide (unpublished)). HFZ – Hornsund Fault Zone; CWS – Late Cenozoic Sedimentary Wedge; URU – Upper regional unconformity; SEDL – Svartfjella, Eidembukta, and Daudmannsodden lineament; a – Carboniferous rocks; b – Permian – U. Carboniferous; c – M. Jurassic – Triassic; d – L. Cretaceous – U. Jurassic; e – L. Cretaceous; f – Tertiary. Models of detachment evolution: B) Detachment surface as a continuation of WSW-ENE-dipping thrusts of the major thrust complex into the basement (Braathen & Bergh 1995 a,b). C) Detachment surface is related to a decollement within a weak layer of the Permian – Upper Carboniferous rocks (gypsum).*

The Bellsund Graben is interpreted as a southward continuation of the Forlandsundet Graben, separated and displaced westward by a dextral transverse fault off Isfjorden. Change in the reflectivity pattern and offset of the main strike of faults in the southern part of the Bellsund Graben may suggest the presence of a transverse fault off the Bellsund area and related to the southern termination of the graben. The west-east transverse faults were observed. The strike-slip faults that cut off the Forlandsundet and Bellsund grabens may be interpreted to be either younger than the graben formation or related to their simultaneous development.

The shift in polarity of layer geometry within the sedimentary fill of the Bellsund Graben, is also observed in the Forlandsundet Graben, and allows division of the graben into units. The signs of compression within the sedimentary fill of the Bellsund graben might reflect the initiation of its formation within a broader basin than the present one. Thus, the evolution of the Bellsund Graben could be related to three stages of development of the Forlandsundet area (Gosen & Paech 2001) and to regional compression and formation of West Spitsbergen Fold and Thrust Belt:

1. Latest Paleocene - Early Eocene (?): Initial sedimentation within the local synsedimentary extensional structures, possibly on the top of an uplifted area during the main compressional regime.
2. Latest Eocene: Graben formation due to initial transtensional movements in the area, possibly developed as a pull-apart structure during a dextral strike-slip regime accompanied by local compression.
3. Oligocene: Normal faulting and final graben development caused by a transtensional regime corresponding to sea-floor spreading between Svalbard and Greenland.

The lowermost reflector, underlying Bellsund Graben, is related to a thrust surface developed during the compression responsible for the formation of the West Spitsbergen Fold and Thrust Belt in Middle Paleocene to Eocene time. The thrust movements could be related to two different models. In the first case, the surface of detachment might represent continuation of thrusts of the major basement-involved thrust complex, and in the second case, it might correspond to a decollement within a weak layer of Permian – Upper Carboniferous rocks (gypsum).

During the following oblique extension, in post-Eocene time, the thrust plane became a surface of focused extension as a detachment. This period was characterized by reactivation of the old compressional structures and normal faulting took place. This transtensional event is reflected in the development of the down-faulted blocks of the Hornsund Fault Zone and in the main development of the Forlandsundet and Bellsund graben structures.

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## References

Bergh, S., Braathen, A. & Andresen, A. 1997: Interaction of Basement-Involved and Thin-Skinned Tectonism in the Tertiary Fold-Thrust Belt of Central Spitsbergen, Svalbard. *AAPG Bulletin 81*, 637-661.

Bergh, S., Maher, H.D.Jr. & Braathen, A. 2000: Tertiary divergent thrust directions from partioned transpression, Brøggerhalvøya, Spitsbergen. *Norsk Geologisk Tidsskrift 80,* 63-82.

Bergh, S. & Grogan, P. 2003: Tertiary structure of the Sørkapp-Hornsund Region; South Spitsbergen; and implications for the offshore southern extension of the fold-thrust belt. *Norwegian Journal of Geology 83*, 43-60.

Birkenmajer, K. 1981: The geology of Svalbard, the western part of the Barents Sea, and the continental margin of Scandinavia. *In* Nairn, A., Churkin, M. & Stehli, F., G. (eds.): *The ocean basins and margins. The Arctic Ocean. Volume 5*, 265-329. Plenum Press, New York and London.

Braathen, A. & Bergh, S. 1995(a): Structural outline of a Tertiary Basement – cored uplift/inversion structure in western Spitsbergen, Svalbard: Kinematics and controlling factors. *Tectonics 14*, 95-119.

Braathen, A. & Bergh, S. 1995(b): Kinematic of Tertiary deformation in the basement-involved fold-thrust complex, western Nordenskiøld Land, Svalbard: tectonic implications based on fault-slip data analysis. *Tectonophysics 249*, 1-29.

Braathen, A., Bergh, S., Karlsen, F., Maher, H. Jr., Anderesen, A., Hansen, A. & Bergvik, A. 1999: Kinematics of the Isfjorden-Ymerbukta Fault Zone: a dextral oblique-thrust ramp in the Tertiary fold-thrust belt of Spitsbergen. *Norsk Geologisk Tidsskrift 79*, 227-240.

CASE Team: Cepec, P., Gosen, W., Lyberis, N., Manby, G., Paech, H.,Y., Piepjohn, K., Tessensohn, F. & Thiedhelm, T. 2001: The evolution of the West Spitsbergen Fold-and-Thrust Belt. In Tessensohn, F. (ed.): *Intra-continental fold belts – CASE 1: West Spitsbergen.* Geologisches Jahrbuch B, 91, 733-773.

Craddock, C., Hauser, E., Maher, H., Jr.,Sun, A. Y., & Zhu Guo-Qiang, 1985: Tectonic evolution of the West Spitsbergen fold belt; *Tectonophysics, vol. 114*, p. 193-211.

Chalmers, J.A. & Pulvertaft, T.C.R. 2001: Development of the continental margins of the Labrador Sea: a review. In Wilson, R.C.L., Whitmarsh, R.B., Taylor, B. & Froitzhelm, N.: *Non-Volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea*, 77 – 105. The Geological Society of London.

Dallmann, W.K., Andresen, A., Bergh, S.G., Maher, H.D. & Ohta, Y. 1993: Tertiary fold-and-thrust belt of Spitsbergen, Svalbard: Compilation map, summary and bibliography. *Norsk Polarinstitutt Meddelelser, 128*. 46 pp., 3 plates.

Dallmann, W.K. 2007: Geology of Svalbard. In Sigmond, E. & Roberts, D.: Geology of the land and sea areas of Northern Europe. *Norges Geologiske Undersøkelse Special Publication 10*, 87-89.

Eiken, O. & Austegard, A. 1987: The Tertiary orogenic belt of West-Spitsbergen: Seismic expressions of the offshore sedimentary basins. *Norsk Geologisk Tidsskrift 67*, 383-394.

Eldholm, O., Faleide, J.I. & Myhre, A.M. 1987: Continent-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology 15*, 1118–1122.

Eldholm, O., Skogseid, J., Sundvor, E. & Myhre, A.N. 1990: The Norwegian-Greenland Sea. *In* Grantz, A. & Sweeney, J.F. (eds.): *The Geology of North America, Volume L, The Arctic Ocean Region* , 351-364. The Geological Society of America.

Faleide, J.I., Gudlaugsson, S.T. & Jacquart, G. 1984: Evolution of the western Barents Sea. *Marine and Petroleum geology 1*, 123-150.

Faleide, J.I., Gudlaugsson, S.T., Eldholm, O., Myhre, A.M. & Jackson, H.R. 1991: Deep seismic transects across the sheared western Barents Sea – Svalbard continental margin. *Tectonophysics 189*, 73-89.

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

Faleide, J.I., Solheim, A., Fiedler, A., Hjelstuen, B.O., Andersen, E.S., & Vanneste, K. 1996: Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. *Global and Planetary Change 12*, 53-74.

Gabrielsen, R.H., Kløvjan, O.S., Haugsbø, H., Midbøe, P.S., Nøttvedt, A., Rasmussen, E. & Skott, P.H. 1992: A structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard. *Norsk Geologisk Tidsskrift 72*, 105-120.

Gosen, W. & Paech, H.,J. 2001: Structures in the Tertiary Sediments of the Forlandsundet Graben. In Tessensohn, F. (ed.): *Intra-continental fold belts – CASE 1: West Spitsbergen.* Geologisches Jahrbuch B, 91, 475-502.

Harland, W.B. 1969: Contribution of Spitsbergen to understanding of the tectonic evolution of the North Atlantic region. In Kay, M. (eds): *North Atlantic: Geology and Continental Drift, a symposium, Memoir 12*, 817-851. American Association of Petroleum Geologists, Tusla, Oklahoma, U.S.A.

Harland, W. B. & Dowdeswell, E. K. 1988: Geological Evolution of the Barents Shelf Region. Graham and Trotman, 224 pp.

Kellogg, H.E. 1975: Tertiary stratigraphy and tectonism in Svalbard and Continental Drift. *AAPG Bulletin 59*, 465-485.

Knies, J., Matthiessen, J., Vogt, C., Laberg, J.S., Hjelstuen, B.O, Smelror, M., Larsen, E., Andreassen, K., Eidvin, T., & Vorren, T.O. In press: The Plio-Pleistocene glaciation of the Barents Sea–Svalbard region: a new model on revised chronostratigraphy. *Quaternary Science Reviews.*

Lepvrier, C. 1994: The origin of the West Spitsbergen fold belt from geological constraints and plate kinematics - implications for the Arctic - comment. *Tectonophysics 234 (4)*, 329-333.

Lundin, E. & Doré, A.G. 2002: Mid-Cenozoic post-breakup deformation in 'passive' margins bordering the Norwegian-Greenland Sea. *Marine and Petroleum Geology 19*, 79-93.

Lyberis, N. & Manby, G. 1993: The origin of the West Spitsbergen Fold Belt from geological constraints and plate kinematics: Implications for the Arctic. *Tectonophysics 224,* 371-391.

Maher, H. D., Jr., Braathen, A., Bergh, S., Dallmann, W., & Harland, W., B. 1995: Tertiary or Cretaceous age for Spitsbergen's fold-thrust belt on the Barents Shelf. *Tectonics 14(6)*, 1321–1326.

Maher, H.D., Bergh, S., Braathen, A. & Ohta, Y. 1997: Svartfjella, Eidembukta, and Daudmannsodden lineament: Tertiary orogen-parallel motion in the crystalline hinterland of Spitsbergen 's fold-thrust belt. *Tectonics 16 (1)*. 88-106.

Manby, G.M. & Lyberis N. 1996: State of stress and tectonic evolution of the West Spitsbergen Fold Belt. *Tectonophysics 267*, 1-29.

Manum, S.B. & Throndsen, T. 1986: Age of Tertiary formations on Spitsbergen. *Polar Research 4*, 103-131.

McCann, A., J. 2000: Deformation of the Old Red Sandstone of NW Spitsbergen; links to the Ellesmerian and Caledonian orogenies. *Geological Society, London, Special Publications 180*, 567-584.

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

Myhre, A.M., Eldholm, O., Faleide, J.I., Skogseid, J., Gudlaugsson, S.T., Planke, S., Stuevold, L.M., & Vågnes, E. 1992: Norway – Svalbard continental margin: structural and stratigraphical styles. *In* Poag, C. W. & Graciansky, P. C. (eds): *Geologic Evolution of Atlantic Continental Rises*, 157-185. Van Nostrand Reinhold, New York.

Oakey, G.N. & Stephenson, R. 2008: Crustal structure of the Innuitian region of Arctic Canada and Greenland from gravity modelling: implications for the Palaeogene Eurekan orogen. *Geophysical Journal International 173*, 1039–1063.

Piepjohn, K. 2000: The Svalbardian-Ellesmerian deformation of the Old Red Sandstone and the pre-Devonian basement in NW Spitsbergen (Svalbard). Geological Society, London, *Special Publications 180*, 585-601.

Piepjohn, K., Brinkmann, L., Grewing, A. & Kerp, H. 2000: New data on the age of the uppermost ORS and the lowermost post-ORS strata in Dickson Land (Spitsbergen) and implications for the age of the Svalbardian deformation. *Geological Society, London, Special Publications 180*, 603-609.

Ritzmann, O., Jokat, W., Mjelde, R. & Shimamura, H. 2002: Crustal structure between the Knipovich Ridge and the Van Mijenfjorden (Svalbard). *Marine Geophysical Researches 23*, 379-401.

Ritzmann, O., Jokat, W., Czuba, W., Guterch, A., Mjelde, R. & Nishimura, Y. 2004: A deep seismic transect from Hovgård Ridge to northwestern Svalbard across the continental-ocean transition: A sheared margin study. *Geophysical Journal International 157*, 683-702.

Saalmann, K. & Thiedig, F. 2002: Thrust tectonics on Brøggerhalvøya and their relationship to the Tertiary West Spitsbergen Fold-and-Thrust Belt. *Geological Magazine 139(1)*, 47-72.

Solheim, A., Andersen, E.S., Elverhøi, A., Fiedler, A. 1996: Late Cenozoic depositional history of the western Svalbard continental shelf, controlled by subsidence and climate. *Global and Planetary Change 12*, 135-148.

Solheim, A. & Kristoffersen, Y., 1984: The physical environment, Western Barents Sea; Sediments above the upper regional unconformity: thickness, seismic stratigraphy and outline of the glacial history. *Norsk Polarinstitutt Skrifter 179B*, 26 pp.

Srivastava, S.P. 1978: Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic. *Geophys. J. Roy. Astr. Soc. 52*, 313-357.

Srivastava, S.P. 1985: Evolution of the Eurasian Basin and its implications to the motion of Greenland along Nares strait. *Tectonophysics 114*, 29-53.

Srivastava, S.P. & Tapscott, C.R. 1986: Plate Kinematics of the North Atlantic. *In* Vogt, P.R. & Tucholke, B.E. (eds.): T*he Geology of North America, Volume M, The Western North Atlantic Region,* 379-402. The Geological Society of America.

Steel, R.J., Gjelberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A. & Rye Larsen, M. 1985: The Tertiary strike-slip basins and orogenic belt of Spitsbergen. *Society of Economic Paleontologists and Mineralogists, Special Publication 37*, 339-360.

Sundvor, E. & Austegard, A. 1990: The evolution of the Svalbard margins: synthesis and new results. *In* Bleil, U. & Thiede, J. (eds.): *Geological history of the Polar Oceans: Arctic versus Antarctic*, 77-94. Kluwer Academic Publishers.

Talwani, M. & Eldholm, O., 1977: Evolution of the Norwegian-Greenland Sea. *Geological Society of America Bulletin 88*, 969-999.

Tessensohn, F. & Piepjohn, K. 2000: Eocene compressive deformation in Arctic Canada, North Greenland and Svalbard and its plate tectonic causes. *Polarforschung 68,* 121-124.

Thorsteinsson, R. & Tozer, E.T. 1970: Geology of the Arctic Archipelago. *In* Douglass, R.J.W. (ed): *Geology and Economic Minerals of Canada, Economic Geology Report no.1*, 547-590, Geological Survey of Canada.

Worsley, D., (main author), Aga, O.J, (editor) 1986: The geological history of Svalbard: evolution of an arctic archipelago. Den norske stats oljeselskap a.s, Stavanger, 120 pp.