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Structural analysis along seismic profiles trough late-Paleozoic deposits in Billefjorden and Sassenfjorden, Svalbard and their relation to the Billefjorden Fault Zone

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Abstract

The focus of this thesis is structural analysis of the Billefjorden Fault Zone astride Billefjorden and Sassenfjorden in Spitsbergen, with the use of seismic interpretation combined/aided by geological and bathymetric maps, field observations and well data. The aim is to describe structures and the tectonic development of the study area. The focus is on large tectonic events from Devonian to Palaeogene.

The Billefjorden Fault Zone was described in detail by Harland et al. (1974). Since then, many studies have been made on the fault zone, with much focus on along-strike changes and a suggested reactivation history. Most published work is based on land observations from Austfjorden to Pyramiden. Much less work has been done on the offshore domain of the fault zone.

Marine seismic data from Billefjorden and Sassenfjorden were available for this thesis. In order to identify stratigraphic units in the seismic profiles, terrestrial seismics are used in combination with well data and a velocity survey from Reindalen. Furthermore, geological maps, published works and bathymetry are used for structural interpretation.

The seismic data are of very poor quality. This presents a challenge in locating stratigraphic units and identifying structures. No well-tie is available in the study area. Therefore, a well in Reindalen is used. The distance from the well to the study area is problematic since only part of the stratigraphy overlap. Another problem are significant geological changes along the tie-line. The problems with poor data quality is partially solved by combining the seismic data with geological maps and bathymetry.

The result is a number of interpreted seismic lines and bathymetry. The interpretation includes stratigraphic division and structural elements such as faults, folds, horst, graben and basins. Based on the seismic interpretation and bathymetry a suggested tectonic development is presented. The structures described in Billefjorden and Sassenfjorden span form post-Caledonian orogenic collapse, Devonian convergence, Carboniferous basin development, Cretaceous intrusive events and Palaeogene convergence.

Furthermore, a model for the offshore continuation of the BFZ in Billefjorden and Sassenfjorden is presented. The model differs from other published work in regard to the southward extent of the Balliolbreen Fault and Odellfjellet Fault. In this thesis it is suggested that the fault array is preserved between Pyramiden and the south coast of Sassenfjorden. An important along-strike change is the narrowing of a fault-bound horst that is bound by the two faults.

Analysis of the seismic data and bathymetry also suggest the existence of two NW-SE trending lineaments along Sassenfjorden. The two lineaments are suggested faults which have not been mapped previously.

Acknowledgments

A great deal of gratitude is owed to the people who put down the legwork out in the field defying the cold climate and famous predators of Svalbard, so that I can sit comfortably in my warm and dry office making my interpretations and writings.

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1. Introduction

1.1. Background and framework for the study

The map of Svalbard has been developed since the 17th century by early explorers. However, more recently, Svalbard has experienced an increased number of geological investigations since the 70´s; a credit to the discovery of hydrocarbons off the Norwegian coast. Consequentially, petroleum exploration and production companies, The Geological Survey of Norway (NGU) and NPI have invested in geological surveys; this due to Svalbard representing an exposed part of the Norwegian continental shelf. The shared geological origin between Svalbard and the Norwegian continental shelf allow correlation.

This wave of surveys added valuable insight to the geology hidden under the seabed. The more accessible geology of Svalbard allows more direct study of the lithology and the possibility to obtain otherwise unavailable information. The studies by oil companies have stagnated, but the presence of academic interest and studies is still strong. Scientists are still working on understanding the details of structures and evolution of Svalbard.

The history is far from unravelled and there are about as many opinions as there are scientists on the structures of this Arctic archipelago. The NPI has conducted systematic mapping with increasing scale over Svalbard. Many of which are used in this study to aid seismic interpretation and trace faults, structures and rock boundaries. This study aims to analyse and interpret structures and faults in Late-Palaeozoic sedimentary and underlying crystalline basement in Billefjorden and Sassenfjorden (Fig. 1.1 and 1.2) in order to understand the tectonic evolution of the Billefjorden Fault Zone (BFZ).

Decades worth of published work exist on the geology and structures of Svalbard. Far less is known on the structures and geometry of blocks and lineaments underlying the fjords. This has left a gap in our ability to map lineaments continuously over Svalbard, understanding of the geometry of blocks and deformation structures in Devonian-Carboniferous deposits. However, as datasets, covering offshore areas began to appear; more studies focus on the fjords.

In this study, I analyse Devonian to Carboniferous sedimentary strata that succeed the Caledonian Orogeny. The geology of Svalbard displays a multi-tectonic evolution, several of these larger events are discussed in this thesis. The main focus of this paper are Devonian-Carboniferous tectonic events. However, later events are considered as they left traces in the stratigraphy. In some cases, overprinting the Devonian-Carboniferous events and reactivating faults.

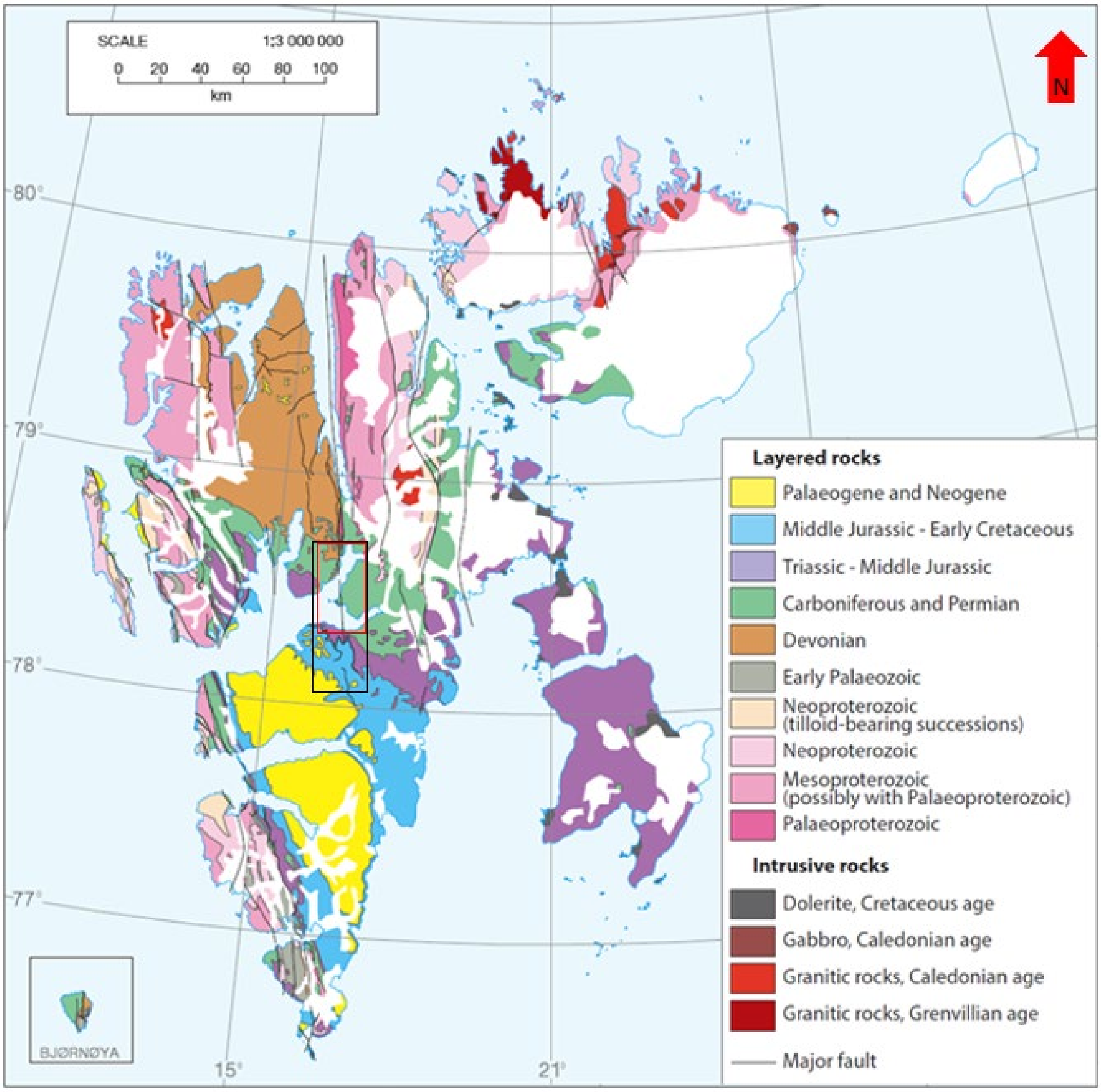
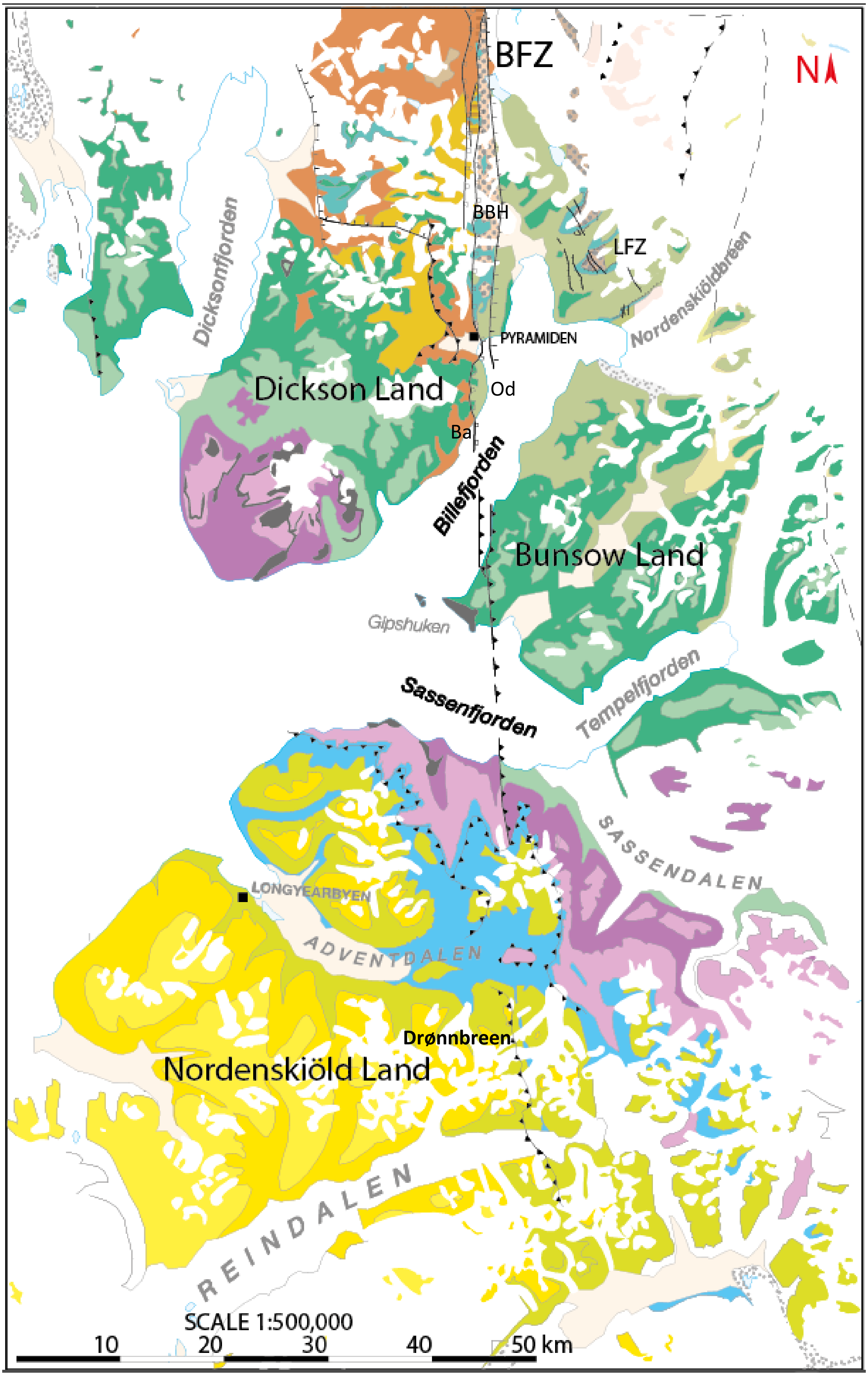


Fig. 1.1 Bedrock map of Svalbard. The red frame indicates the study area (Fig. 1.7) while the black frame includes study area and area with onshore seismic tie-line (Fig.1.2). Modified from (Dallmann et al. 2002)

Following the Caledonian Orogeny (Ordovician-Silurian), extensional forces in the Devonian (Haakonian Event and Monacobreen Event) resulted in denudation, erosion, basin formation and faulting. This extensional period was interrupted by the Svalbardian Event in Late Famennian to Late Tournaisian. The Svalbardian Event is part of the Ellesmerian Orogeny that affected Svalbard. This period was followed by Carboniferous extension and basin formation. Later, in the Palaeogene, convergence caused by the Eurekan Orogeny caused the formation of the West Spitsbergen Fold Belt (WSFB). The development of the WSFB is also called the West Spitsbergen Orogeny (Piepjohn et al. 2000). Traces of these tectonic events are studied and discussed in this thesis.


BFZ
N
BBH
LFZ
Dicksonfjorden
Nordenskiöldbreen
PYRAMIDEN
Dickson Land
Od
Ba
Billefjorden
Bunsow Land
Gipshuken
Sassenfjorden
Tempelfjorden
SASSENDALEN
LONGYEARBYEN
ADVENTDALEN
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Nordenskiöld Land
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SCALE 1:500,000
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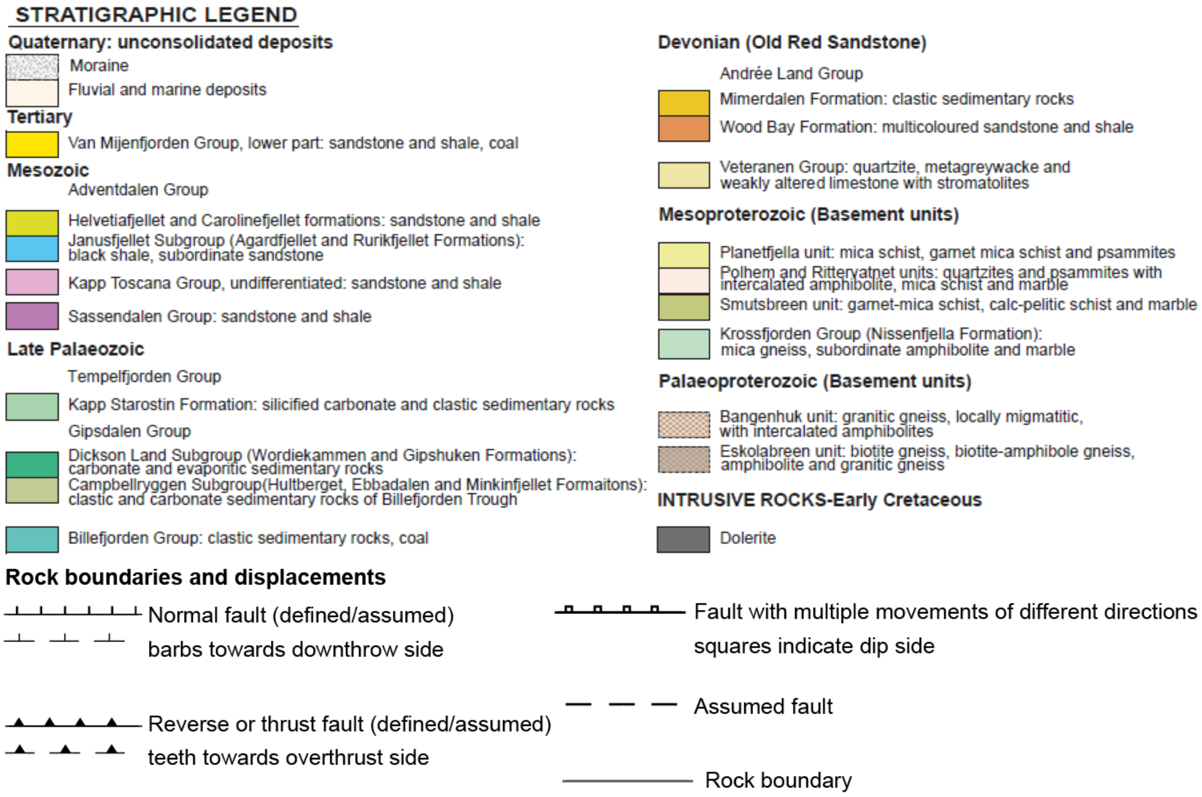


Fig. 1.2 Bedrock map over study area and Nordenskiöld Land. BFZ transects the area in a N-S orientation. The strata have a gentle south-west dip and progressively older rocks are exposed to the north. Past Sassenfjorden, the faults are horizontal thrust faults in Adventdalen Group. BBH = Billefjorden Basement High, Od = Odellfjellet Fault, Ba = Balliolbreen Fault. Edited from Dallmann et al. (2002).

The main goal for this project is to analyse offshore structures in Billefjorden and Sassenfjorden using seismics, bathymetry and field data. The focus is on the development of the BFZ (Bælum & Braathen 2012; Braathen et al. 2011; Harland et al. 1974; Lamar et al. 1986; McCann & Dallmann 1996) and its relation to Devonian-Carboniferous deposits (Blinova et al. 2013; Johannessen & Steel 1992; Steel & Worsley 1984).

Bælum & Braathen (2012) conducted a similar study using some of the same seismic data as used here. However, their study only presents lines from Sassenfjorden and Isfjorden omitting Billefjorden. Although, they include two-way travel time (TWT) maps of the basement and selected formations (Billefjorden Group, Wordiekammen Formation and syn-rift deposit thickness map) in Sassenfjorden and Billefjorden, no analysis of structures within the lithology in Billefjorden are presented. They use the TWT maps to trace the fault array of fault strands of BFZ.

There is yet to be made an adequate and systematic structural mapping of Billefjorden and Sassenfjorden. Such analysis and mapping is essential to understand the movement, geometry and evolution of fault strands of the Billefjorden Fault Zone and their relation to Devonian-Carboniferous deposits in the area.

This thesis is part of ARCEx work package 2.1. whose aim is to analyse petroleum systems and is a continuation of ARCEx work package 1. The 2.1 work package includes onshore and offshore basin analysis. It is a collaboration between UiT, Lundin Oil-Harstad and UNIS. This thesis is a continuation of previous studies conducted by UiT on Svalbard focusing on onshore-offshore tectonics of the Norwegian continental shelf and structural correlations in Isfjorden and Lomfjorden areas on Spitsbergen (Andresen et al. 1992; Bergh et al. 1994; Bergh et al. 1997; Braathen et al. 1999b; Johansen et al. 1994). In a greater context, this type of study helps to understand the development of The Western Barents Shelf and its structures today.

1.1.1. Abbreviations

The following table contains abbreviations that have been used in the text. For abbreviations in figures, see corresponding figure text.

Full name	Abbreviation	Full name	Abbreviation
Balliolbreen Fault	Ba	Nordfjorden High	NH
Below sea level	bsl	Odellfjellet Fault	Od
Billefjorden Basement High	BBH	Old Red Sandstone	ORS
Billefjorden Fault Zone	BFZ	true vertical depth	TVD
Billefjorden Trough	BT	Two-way travel time	TWT
Central Tertiary Basin	CTB	West Spitsbergen Fold Belt	WSFB

1.1. Thesis objectives

The main objectives for this paper are to identify, describe and illustrate structures caused by major tectonic events spanning from post-Caledonian to Palaeogene, including Devonian basin formation, The Svalbardian Event (Ellesmerian Orogeny), Carboniferous extension and Palaeogene compression (West Spitsbergen Orogeny/Eurekan Orogeny). The aim is to describe a relative time sequence in which the structures (deformation) appeared and its kinematics. Further, I aim to discuss the development of Billefjorden Fault Zone and to map the lineaments over the fjord connecting them to their onshore continuation.

To form a comprehensive understanding of lineaments and deformation structures in the study area I have formulated a number of objectives. The final aim is to present a complete summarised model for the tectonic evolution along the BFZ in Billefjorden and Sassenfjorden with a number of cross sections from seismic profiles and to compare it to the work of Bælum & Braathen (2012) and Smyrak-Sikora et al. (2018). I have defined the main project objectives as such:

1. Identify key stratigraphic horizons in the seismic data. Then to analyse and describe deformation structures in post-Caledonian sedimentary rock under the fjord seafloor in the study area. Presented with selected representative seismic profiles.

2. To map and analyse faults. Study the sense of movement and timing of various fault strands of the BFZ and present along-strike changes across Billefjorden and Sassenfjorden.

3. Investigate whether there is evidence to support a reactivation of fault strands of the BFZ as suggested by Harland et al. (1974). Further, I will investigate Carboniferous extensional reactivation and Palaeogene inversion as suggested by Bælum & Braathen (2012).

4. Based on the above objectives the final goal is to construct a model for the tectonic development of the study area and to compare it to other existing models including Bælum & Braathen (2012) and Smyrak-Sikora et al. (2018).

1.3. Geology

The Geology of Svalbard has been studied and described by various international scientific groups. Many stratigraphic units therefore have more than one name and the definitions are poorly defined or sometimes overlap. In the literature on Svalbard, I have come across different nomenclature and divisions of the stratigraphic units. For consistency, I am using the updated stratigraphic definitions from The Committee on the Stratigraphy of Svalbard (SKS) as described in the Stratigraphic Lexicon of Svalbard by Dallmann (1999). In those cases where the original source uses an older outdated name or division for a stratigraphic sequence, I have used the updated equivalent name and definition.

Svalbard hosts crystalline and sedimentary rock that holds a nearly continuous record from Precambrian to Cenozoic age (Steel & Worsley 1984). In this thesis, three structurally and temporally distinct units are considered: (I) The Pre-Caledonian Basement. This unit is defined as the rocks affected by the Caledonian Orogeny. The basement consists of both crystalline and sedimentary rocks that have been metamorphosed and deformed to various degrees (Ohta 1992). (II) Devonian to Palaeogene sedimentary successions, representing basin fill across Svalbard (Johannessen & Steel 1992). (III) Dolerite intrusions of Cretaceous age (125-78 Ma) (Nejbert et al. 2011). These units are further described in section 1.3.1.3.

1.3.1. Regional geology – Dickson Land, Bünsow Land, Nordenskiöld Land

The study area is offshore in Billefjorden and Sassenfjorden (Fig. 1.1). Adjacent coastal exposures are used to interpret stratigraphic horizons in the seismic data and to put the structures in a larger context. Billefjorden is located at the border between the land areas Dickson Land (to the north-west) and Bünsow Land (to the south-east). The old mining settlement Pyramiden is located in the area on the north-east coast of Billefjorden. The onshore seismic survey that is used as a tie-line for identification of stratigraphic units in the marine seismic profiles is located south of Billefjorden and Sassenfjorden in the north-eastern part of Nordenskiöld Land (Dallmann et al. 2002).

1.3.1.1. Structural geology

The BFZ (*see section 1.3.1.2.)* transects Spitsbergen and separates the basement into the North-West Basement Province and the North-East Basement Province (Fig. 1.3). Bünsow Land is located on the North-East Basement Province and Nordenskiöld Land includes both of the basement provinces while the basement underlying Dickson Land is debated (due to partially undefined boundaries between basement provinces). Palaeozoic and Mesozoic bedrock cover the Pre-Caledonian Basement. However, small exposures of the basement can be found, including a narrow horst within the BFZ just north of Pyramiden referred to as the Billefjorden Basement High (BBH) (Fig. 1.2 & 1.4). West of the BFZ, the basement is covered by early to late Devonian bedrock. To the east, younger late Palaeozoic to Mesozoic rock overlies the basement (Dallmann et al. 2004b; Dallmann et al. 2015).

The Central Tertiary Basin (CTB) covers roughly half of Spitsbergen including Dickson Land, Bünsow Land and Nordenskiöld Land (Fig. 1.3). The formation of the CTB basin is associated with the opening of the Atlantic and rifting in the Labrador Sea during the Paleogene (Harland et al. 1974; Steel et al. 1981). Exposed bedrock in the basin area is of Carboniferous to Paleogene age with the younger stratigraphy in the south and successively older to the north-east. The basin stratigraphy forms a gentle syncline and in Adventdalen, the bedrock has a gentle south-westerly tilt. Furthermore, in Adventdalen thrust faults are exposed in the Adventdalen Group (*see section 1.3.1.3.2.)* which parallel the stratigraphy (Fig. 1.3 cross section). These faults have been described as eastward-directed decollements, they bend upwards to the surface and interact with the BFZ between Adventdalen and Sassendalen (Dallmann et al. 2015; Major et al. 2000).

The basement of The Nordfjorden High (NH) (Fig. 1.3) is undefined due to the thick overlying Devonian cover. The Dickson Land peninsula makes the southernmost limit of the NH exposed on land. The NH is bound to the east by the BFZ and the Billefjorden Trough with the above mentioned BBH resting in between (Fig. 1.3 and 1.4). Elevation of the NH relative to the Ny-Friesland Block has varied over time as indicated by sediment records. During deposition of the Hørbyebreen Formation (Early Carboniferous), the NH was subsided in relation to the Ny-Friesland Block. Later in Mid Carboniferous (during deposition of the Hultberget Formation) the NH had uplifted (Cutbill et al. 1976). These relative movements between blocks along the BFZ caused Devonian stratigraphy to erode east of the fault zone and are only found on the NH in this region of Spitsbergen (Friend 1961; Piepjohn 2000; Vogt 1938).

Billefjorden Trough is a half graben that extends over Bünsow Land, Billefjorden and Sassenfjorden (Fig. 1.3). It is a middle Carboniferous asymmetric basin. The BFZ is the western margin of the Billefjorden Trough and the depocentre lies towards the fault zone. The development of the basin is directly influenced by the growth and geometry of the BFZ. East of the depocentre the N-S trending Løvehovden Fault Zone and Ebbabreen Fault Array cut across the basin (Bælum & Braathen 2012; Dallmann et al. 2004b; Smyrak-Sikora et al. 2018). The dimensions of the basin extend 110 km N-S along-strike and 20-30 km across. The depocentre of the BT reaches 2000m and grows shallower in the outer realm to 500m (Bælum & Braathen 2012).

1.3.1.2. Billefjorden Fault Zone

Billefjorden Fault Zone is one of several large N-S trending lineaments that cut across Svalbard. The fault zone extends 2-300 km from Wijdefjorden across Billefjorden-Sassenfjorden region towards Kjellströmdalen where is disappears under Mesozoic stratigraphy (Dallmann et al. 2002; Dallmann et al. 2004a, 2004b). However, a magnetic survey suggest it may continue offshore to The Barents Shelf

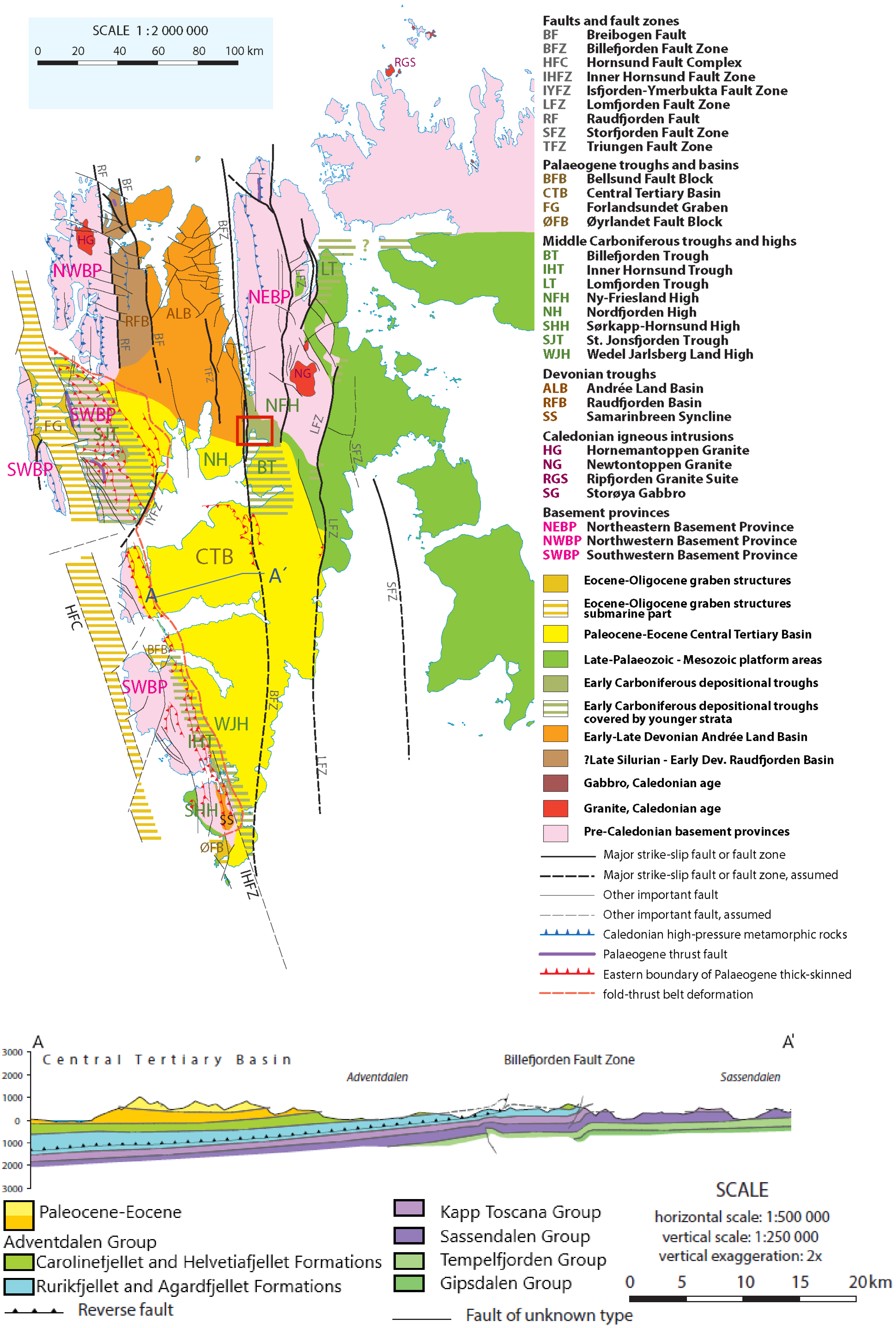


Fig. 1.3 Large structural elements of Spitsbergen. Transect A-A´ shows the geometry of the CTB and relation between Palaeogene thrust faults to BFZ. Edited from Dallmann et al. (2015). Red square see Fig. 1.8

(Skilbrei 1992). Balliolbreen Fault (Ba) and Odellfjellet Fault (Od) have been recognised by several well-established papers as the main lineaments of the BFZ (Gjelberg & Steel 1981; Harland et al. 1974; Manby et al. 1994). They are long 50-70° east dipping faults with implied reactivation history (Johannessen & Steel 1992; Manby et al. 1994; Steel & Worsley 1984) (Fig. 1.2). According to Bælum & Braathen (2012) The BFZ has three master fault strands: the Balliolbreen, Odellfjellet and Drønbreen faults, that are connected by two relay zones. However, the existence of relay zones and Drønbreen Fault is debated (see discussion). The full width of BFZ can be seen just north of Billefjorden (Harland et al. 1974). Harland et al. (1974) recognised the importance of the Billefjorden Fault Zone as it crosscuts central Svalbard where the most complete stratigraphic record is preserved. Thus, allowing interpretation of a long interval of history from a relatively small area.

The BFZ was initiated after of the Caledonian Orogeny and was later reactivated during several tectonic events. The Caledonian Orogeny was caused by the closing of the Iapetus Ocean and formation of Euramerica, it was during the earlier stages of this event that Svalbard's basement was assembled. Following the Caledonian Orogeny in early Devonian, post-orogenic collapse characterised by a regional extension lasted through the Devonian. Most of the Devonian is dominated by an extensional regime and the development of depositional basins for the Devonian Old Red Sandstone (ORS) across Spitsbergen. Svalbard moved northwards into an arid climate. This triggered massive erosion of the newly formed Caledonian mountain ranges. As terrestrial highlands disintegrated, the weathering material filled the Devonian basins (Dallmann et al. 2015; Harland et al. 1974; Harland & Wright 1979; Steel & Worsley 1984).

Harland et al. (1974) proposed that Billefjorden Fault Zone developed on a pre-existing Caledonian shear zone along a weakened basement after the post-orogenic collapse (Haakonian Event and Monacobreen Event). At the beginning of Carboniferous (Tournaisian), The Svalbardian Event (Kośmińska et al. 2020) caused the formation of major faults including the BFZ. During this time transcurrent and contractional movement is suggested. The Svalbardian Event is the tectonic phase of The Ellesmerian Orogeny that affected Svalbard. It was caused by the collision of Ellesmere Island and Svalbard with Laurasia (Piepjohn et al. 2015). During the Svalbardian Event, compression along the BFZ caused folding of the Devonian Andrée Land Group (Piepjohn Gosen et al. 2013). The Ny-Friesland Block bound to the east by BFZ was thrusted westward and elevated 10 km. The uplift caused Devonian sediments to erode and these are absent to the west of the BFZ. East of the BFZ Carboniferous rock unconformably overlay Devonian rock (Piepjohn 2000).

Much of the Carboniferous was characterised by rifting and widespread basin formation both on

Svalbard and on the Barents Shelf. A 110 km long and 20-30 km wide half graben called The Billefjorden Trough (BT) developed in central Spitsbergen as a result of the rifting (Bælum & Braathen 2012). During this period, the BFZ was reactivated with normal faulting and formed the easternmost limit of the newly formed Billefjorden Trough. The extension faulted the brittle ORS and the change in tectonic movements from Devonian convergence to Carboniferous extension caused and angular unconformity between the top of Devonian ORS and the base of Carboniferous stratigraphy (Manby & Lyberis 1992; Piepjohn & Dallmann 2014).

From late Carboniferous to Early Cretaceous only minor extensional movements took place across the Billefjorden Fault Zone, supporting the idea that rather stable platform conditions prevailed, as

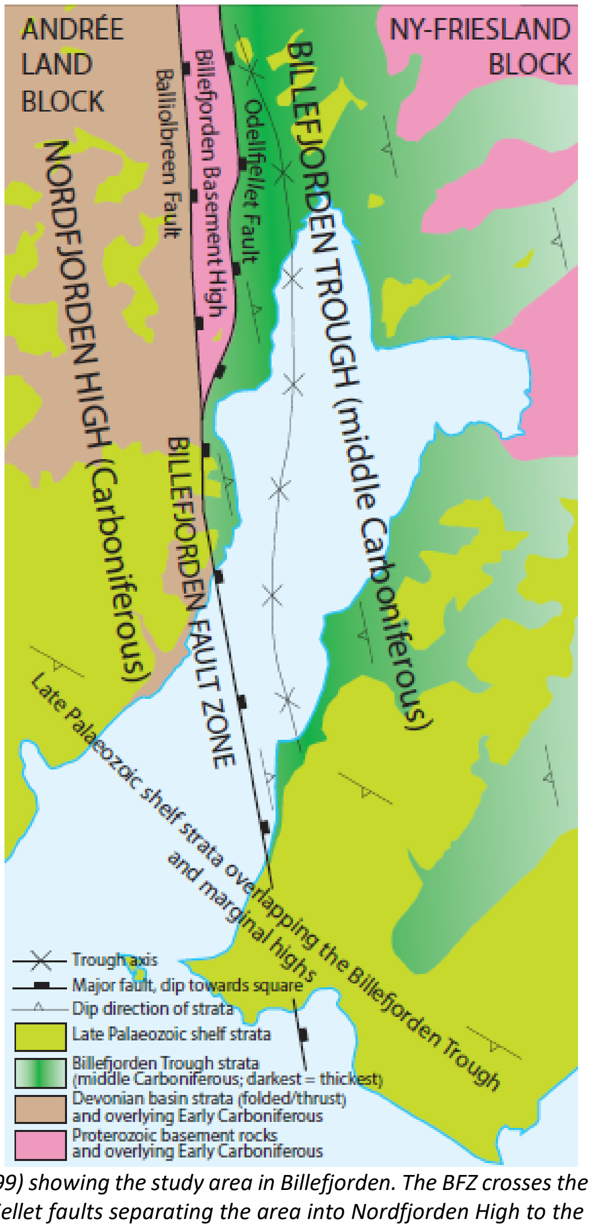


Fig. 1.4 Map from Dallmann (1999) showing the study area in Billefjorden. The BFZ crosses the area and the main fault strands here are Balliolbreen and Odellfjellet faults separating the area into Nordfjorden High to the west and Billefjorden Trough to the east. Devonian rocks are absent east of the BFZ. A narrow basement block, the Billefjorden Basement High is exposed between the two major fault strands

indicated by the sedimentary sequences present. Platform subsidence allowed substantial sediment accumulation (Cutbill & Challinor 1965; Harland et al. 1974).

This persisted until the Cenozoic when the opening of the North Atlantic caused new tectonic movements. BFZ reactivated under convergent motion due to the opening of the Atlantic. The Barents Shelf and Spitsbergen separated from Greenland along the transform De Geer Fault (Buchan 1965; Harland et al. 1974; Parker 1967; Steel & Worsley 1984). The West Spitsbergen Fold Belt formed at this time and the event is called the West Spitsbergen Orogeny (or in larger context the Eurekan Orogeny). Reversed faulting and decollement zones in Lower to Middle Triassic to Lower Cretaceous rocks are accredited to this Palaeogene convergence (Haremo et al. 1990). Palaeocene to Eocene (66-34 Ma) basin inversion caused by the West Spitsbergen Orogeny (Eurekan Orogeny) has been suggested (Andresen et al. 1992). It is suggested that fault stands of the BFZ reactivated under convergent forces (Braathen et al. 2011; Harland et al. 1974).

1.3.1.3. Lithology

1.3.1.3.1. Pre-Caledonian Basement

In the area of Billefjorden, the Pre-Caledonian Basement of Svalbard is folded, overthrust and faulted as a result of the Caledonian Orogeny (Orvin 1969). The metamorphic basement is overlain unconformably by the Devonian Old Red Sandstone (Harland & Wright 1979). Major events that have relevance for this study begin with the termination of the Caledonian Orogeny; a mountain building event that lasted from Early Ordovician to Early Devonian (approx. 480-400 Ma); caused by the collision of mainly Laurentia (North America) and Baltica (northern Europe). During this time, the basement of Svalbard assembled from several crustal blocks. The resulting mountain ranges from the Caledonian Orogeny still exist in Europe, North America and Greenland. Rocks affected by this mountain building event define the basement of Svalbard (Dallmann 1999; Elvevold et al. 2007; Park 2014). These metamorphosed pre-Caledonian rocks are frequently referred to as “Hecla Hoek” (Orvin 1969). However, Hecla Hoek has a diffuse definition (Dallmann et al. 2015, page 186) and is therefore omitted in this paper; instead, the basement is referred to as Pre-Caledonian Basement or simply basement.

The Pre-Caledonian Basement divides into three major provinces: The South-western Province, North-western Province and the North-eastern Province (composed of two separate terranes Nordaustlandet and Ny-Friesland) (Fig. 1.3) (Harland & Wright 1979). The three provinces represent crustal blocks of different tectonic settings, juxtaposed when Svalbard assembled (late Silurian) (Dallmann et al. 2015;

Gee 1986; Skilbrei 1992,). All three provinces are bound by large transcurrent north-south trending fault zones with suggested strike-slip kinematics (Witt-Nilsson et al. 1998).

On Svalbard, basement rocks are exposed in Ny-Friesland (North-eastern Province) and along the west coast of Spitsbergen (North-western Province and West Spitsbergen Fold Belt in the South-western Province). Dickson Land (hosting part of study area) lies at the boundary between the North-eastern Province and North-western Province. The basement of the North-western Province in Dickson Land is covered by post-Caledonian stratigraphy (Cutbill & Challinor 1965; Dallmann et al. 2002). Therefore, structures and petrology of the North-western Province in the study area are unknown. Bünsow Land and a narrow strip of Dickson Land (part of study area) lies on the North-eastern Province and exposures north of the study area allow better descriptions.

In western Ny-Friesland, the basement rocks are composed of gneisses, metamorphosed supracrustal rock and granitoid intrusive rocks. They include both metamorphosed and unmetamorphosed rocks of low to high metamorphic facies. The three provinces have very different grade of metamorphism and diverse deformation structures. The variation is attributed to the separate tectonic evolution and geologic setting prior to the assembly into Svalbard (Dallmann et al. 2015, page 186).

The North-western Province is mostly composed of metasedimentary units from Late Mesoproterozoic to Neoproterozoic intruded by Tonian granitoids. In broad terms, both the North-western and North-eastern Provinces show high amphibolite metamorphic facies in the lower units (and gneissose granites) and decreasing metamorphic grade upwards in the upper units. Slates and phyllites compose the upper low-grade facies rocks in the North-eastern Province (Dallmann et al. 2015; Gee 1986).

In the North-eastern Province, the basement includes a high-grade metamorphic complex including amphibolite and blueschist. The upper units of Ny-Friesland are phyllites and schists. Neoproterozoic units in the North-eastern Province are low-grade to unmetamorphosed (Witt-Nilsson et al. 1998). Here we also find the oldest rocks of Spitsbergen, a 2.7Ga quartz-monzonite. In addition, the North-eastern Province has a >5km thick sequence of quartzite, slate and carbonate formations. The North-eastern and North-western Provinces host Caledonian migmatite complexes, which compose the younger units of the basement. The basement is deformed by folding and thrusting related to the Grenvillian Orogeny (boundary Meso-/Neoproterozoic) (Ohta 1992). Structurally, western Ny-Friesland of the North-eastern Province is dominated by the north-south trending Atomfjella Antiform (Dallmann et al. 2015, page 186; Witt-Nilsson et al. 1998).

Strong deformation is also present in the South-western Province which is characterised by several superimposed orogenies including the WSFB (Gee 1972; Harland & Wright 1979). However, this province is outside the scope of this study and will not be described in further detail.

1.3.1.3.2. Post-Caledonian sedimentary rocks

Seven stratigraphic groups overlying the basement are present in the area around and in Billefjorden and Sassenfjorden. These represent sediments deposited on top of the basement after the Caledonian Orogeny. The Post-Caledonian rocks in the study area are of Devonian to middle Cretaceous age. The stratigraphic groups are from base to top: (I) Andrée Land Group, (II) Billefjorden Group, (III) Gipsdalen Group, (IV) Tempelfjorden Group, (V) Sassendalen Group, (VI) Kapp Toscana Group and (VII) Adventdalen Group (Fig. 1.5). Each group reflect different depositional environments and show deformation from the tectonic evolution of Svalbard (Dallmann 1999).

(I) The Devonian Andrée Land Group was deposited in an extensional regime, which succeeded the Caledonian Orogeny. The unit is exposed in a large area of the Andrée Land basin. These sediments are a part of the Old Red Sandstone which are eroded material of Euramerica (which formed during the Caledonian collision) deposited in a continental molasses basin. At the end of the Caledonian Orogeny (Early Devonian), Svalbard was located at equatorial latitudes north of the Caledonian mountain range on the northern boundary of Euramerica. At this time, a dry and arid climate prevailed, yielding a thick sequence of red coloured terrestrial sedimentary deposits during the Devonian. Due to the appearance of these deposits, Euramerica is often called the Old-Red Continent (thus the name Old Red Sandstone) (Dallmann 2015). The ORS marks accumulation areas such as extending lowlands, troughs and grabens in an arid climate, it accumulated up to 8000m thickness (Friend & Moody-Stuart 1972; Hjelle 1993). Outcrops of Devonian ORS are limited to central northern Spitsbergen and Sørkapp Land (Harland & Wright 1979). Where Devonian beds are absent, it is either because they were never deposited or because they have been removed by erosion. In those cases, the Carboniferous rocks lie directly on the basement (Hjelle 1993).

The Andrée Land Group is composed of terrestrial Wood Bay Formation, Mimerdalen Subgroup and Grey Hoek and Wijde Bay formations with marine components. Mimerdalen Subgroup is exposed outside the study area west of Pyramiden and Mimerdalen and is therefore not described further.

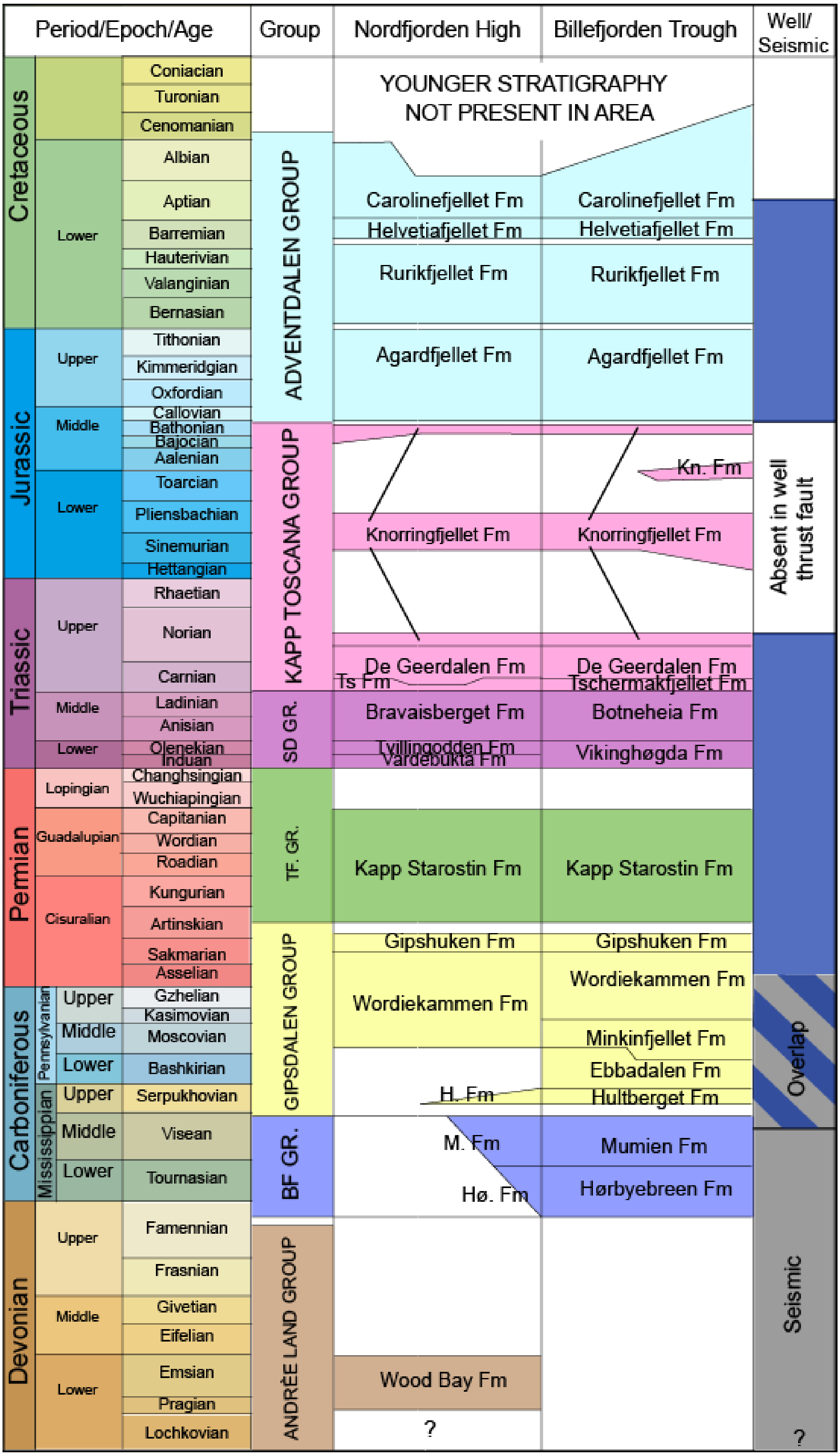


Fig. 1.5 Post-Caledonian stratigraphy of the HN and BT based on and edited from Dallmann (1999). Kn. Fm- Knorringfjellet Formation, Ts. Fm- Tschermakfjellet Formation, H. Fm -Hultberget Formation, M. Fm–Mumien Formation, Hø. Fm- Hørbyebreen Formation. The right column shows the depth of the well in Reindalen and seismics in Billefjorden and north-western Sassenfjorden.

Wood Bay Formation is composed of conglomerate, sandstone, siltstone and shale with accumulated thickness of 3000m. These are fluvial deposits from various river systems and show cyclic deposition. Primary structures include channels after old river systems (Friend & Moody-Stuart 1972). It has normal grading (fining upwards) and is folded and faulted. Locally there are beds of marl in the Wood Bay Formation and these are interpreted to be remnants of lake beds (Friend & Moody-Stuart 1972). Devonian lithology ends in late Famennian with a hiatus due to erosion during the Svalbardian Event. Uplift during the Svalbardian Event (Tournaisian) caused Devonian sediment to erode and are absent the east of BFZ (Dallmann et al. 2015; Harland et al. 1974).

(II) Overlying the Andrée Land Group is the Billefjorden Group. Billefjorden Group was deposited on a peneplain including alluvial fans, braided and meandering rivers, lakes and swamps (Dallmann et al. 2015). The strata consist of clastic sediments of greyish sand- and siltstones with occurrences of conglomerates, shales and coal beds. Billefjorden Group includes Hørbyebreen Formation and Mumien Formation of Famennian (end of Devonian) to Viséan age (Mississippian).

The sediments of Billefjorden Group are best preserved in middle Carboniferous troughs and reach a cumulative thickness of up to 300m and have a gentle south plunge (Cutbill & Challinor 1965). The Hørbyebreen Formation reaches up to 200 m of sandstone, conglomerate and coal. According to Dallmann (1999), it´s lower boundary is described as an angular unconformity with underlying folded basement or folded or tilted Wood Bay Formation. The overlying Mumien Formation reaches 100 m thickness. The lower part of the Mumien Formation is mainly composed of sandstone, while the upper unit is shale and coal deposits. A hiatus during Serpukhovian exist between Billefjorden Group and the overlying Gipsdalen Group. The two groups are separated by an angular unconformity (Dallmann 1999; Douglass 1995).

(III) Sediments of the Gipsdalen Group form a transition from a terrestrial to marine depositional setting with a total maximal thickness of 1800 m. The age of the Group spans from middle Carboniferous (Serpukhovian) to Early Permian (Artinskian) and is subdivided into Hultberget, Ebbadalen, Minkinfjellet, Wordiekammen, and Gipshuken formations. Red beds of the Hultberget Formation reflect terrestrial fluvial and alluvial environments which transition to marginal and open marine clastic, carbonate and evaporate strata of Ebbadalen and Minkinfjellet formations. Ebbadalen Formation includes western conglomerate facies (Odellfjellet Member) close to the BFZ (Dallmann 1999; Dallmann et al. 2015).

With the exception of Hultberget Formation, these formations are only developed in the Billefjorden Trough. Outside the trough, on the NH, sedimentation of the Gipsdalen Group started later with Hultberget (locally) and Wordiekammen formations. At the time of Wordiekammen Formation deposition, marine conditions prevailed partially due to global rise in sea level and partially due to subsidence and faulting. Wordiekammen Formation composes an up to 300 m thick carbonate platform (Steel & Worsley 1984). Deposits of Gipshuken Formation (the youngest of the Gipsdalen Group) are evaporites and algal mats from marginal marine lagoons, mudflats, sabkhas and collapse breccias. Maximum thickness is 280m and the sediments are characterised by interbedding carbonates anhydrite/gypsum and marl. There is a hiatus between Gipshuken Formation and the overlying Kapp Starostin Formation of the Tempelfjorden Group in mid Artinskian (Dallmann 1999). Gipsdalen Group includes syn-rift sequences (Fig. 1.6) (Braathen et al. 2011).

(IV) On Spitsbergen only the Kapp Starostin Formation (middle to end of Permian) of the Tempelfjorden Group is present. At Isfjorden the formation measures 380m and thins out to the south. It includes open marine siliceous and black shales, cherts and intercalations of sandstone and silicified limestone. The shift from the carbonate platform of Wordiekammen Formation to silicic Tempelfjorden Group is interpreted to be a shift to deeper, but mainly colder marine environments. At the end of Permian (Lopingian) there is a regional hiatus. The sedimentary record does not continue until the beginning of the Triassic (Dallmann 1999).

(V) The Triassic record begins with the Sassendalen Group, which is subdivided into Vardebukta, Tvillingodden and Bravaisberget formations in western Spitsbergen and Vikinghøgda and Botneheia formations in central and eastern Spitsbergen. The depositional age for the group starts at the beginning of the Triassic (Induan) and continues through the middle Triassic (Ladinian). A succession of 350 m thick Sassendalen Group shales and siltstones indicate coastal to shallow marine environments in central Spitsbergen, while the west is dominated by sandstone-prone deltaic coarsening upward sequences (Dallmann 1999).

In Sassendalen, the Vikinghøgda Formation represents open shelf deposition. At the base it is characterised by grey- and silty shales with minor siltstone. Upwards the unit grades into mudstone and siltstone. The upper lithology is composed of dark grey mudstone and dolomite beds. The formation measures 250m in central Spitsbergen (Dallmann 1999). The overlying Botneheia Formation measures 168 m in Nordenskiöld Land and thinning northwards. The lower part of the unit is characterised by coarsening upwards mudstone to siltstone. Upwards the lithology is dominated by organic rich black shale with phosphate nodules. The unit reflects deltaic and regressive shelf deposits with locally restricted water circulation. Carbonaceous siltstone occurs trough unit (Dallmann 1999; Krajewski & Woźny 2009; Mørk et al. 1989).

The lithologies of this time interval is characterised by a transgressive regime (lower and middle Triassic) with marine and deltaic progradation from middle to late Triassic. Large thickness variations in the lithology are attributed to fault-related downwarping, that controlled sediment transport. Triassic up until late Middle Jurassic deposits reflect stable shelf conditions which is reflected in both the Sassendalen Group and the overlying Kapp Toscana Group lithologies (Mørk et al. 1982).

(VI) The Kapp Toscana Group records a transition to shallower conditions in a condensed inner shelf environment with shales, silt- and sandstones and with erosive surfaces within the stratigraphy. Kapp Toscana deposition begins directly after the Sassendalen Group ends, from the Late Triassic (Carnian) to Middle Jurassic (Bathonian). In central Spitsbergen, the sediment accumulates to 350 m (Dallmann 2016).

The base of the Kapp Toscana Group is the Tschermakfjellet Formation pro-deltaic shales (Dallmann 1999; Dallmann et al. 2015). It´s reported to have a reddish concentration due to weathering siderite nodules and a thickness of 30-65m in central and eastern Spitsbergen. The sediments are laminated and have reversed grading (Buchan 1965). The overlying unit is the De Geerdalen Formation, which is described as non- to shallow marine and deltaic deposits. It is marked by a transition from the Tschermakfjellet Formation shales to sandstone units. It reaches 320m thickness in outer Isfjorden but narrows towards central and eastern Svalbard. Dallmann (1999) summarises the unit as made of mainly two types of sandstone; one reversely graded argillaceous sandstone and the second as a normally graded sandstone with mud conglomerates or gravelstones.

The topmost formation of the Kapp Toscana Group is the Knorringfjellet Formation which records deposition in a shallow marine environment. Thickness varies from 3-75m and the lithology is highly condensed with conglomerate at the base which is followed by shale and sandstone at the top. There is a big regional hiatus in Knorringfjellet Formation from late Norian to Aalenian (Middle Jurassic) with an exception of a preserved sequence in the lower Jurassic (Dallmann 1999; Dallmann et al. 2015).

(VII) The youngest stratigraphic group is the Late Jurassic (Callovian) to middle Cretaceous (Albian) Adventdalen Group. Adventdalen Group is subdivided into four units, from base to top they are: Agardhfjellet Formation, Rurikfjellet Formation, Helvetiafjellet Formation and Carolinefjellet Formation. Short hiatuses separate Agardhfjellet, Rurikfjellet and Helvetiafjellet formations (Dallmann 1999; Parker 1967).

On Svalbard the Adventdalen Group reaches a thickness of 750-1600 m and the main lithologies are shale, siltstone and sandstone. Agardfjellet Formation is an organic rich shale silt and mudstone offshore this unit is equivalent to the main hydrocarbon source rock Hekkingen Formation. It has a thickness of 90-350 m. The overlying Rurikfjellet Formation is a 110-400m thick, organic rich coarsening upwards unit of dark shale, siltstone and sandstone deposited in an open marine shelf. The next unit

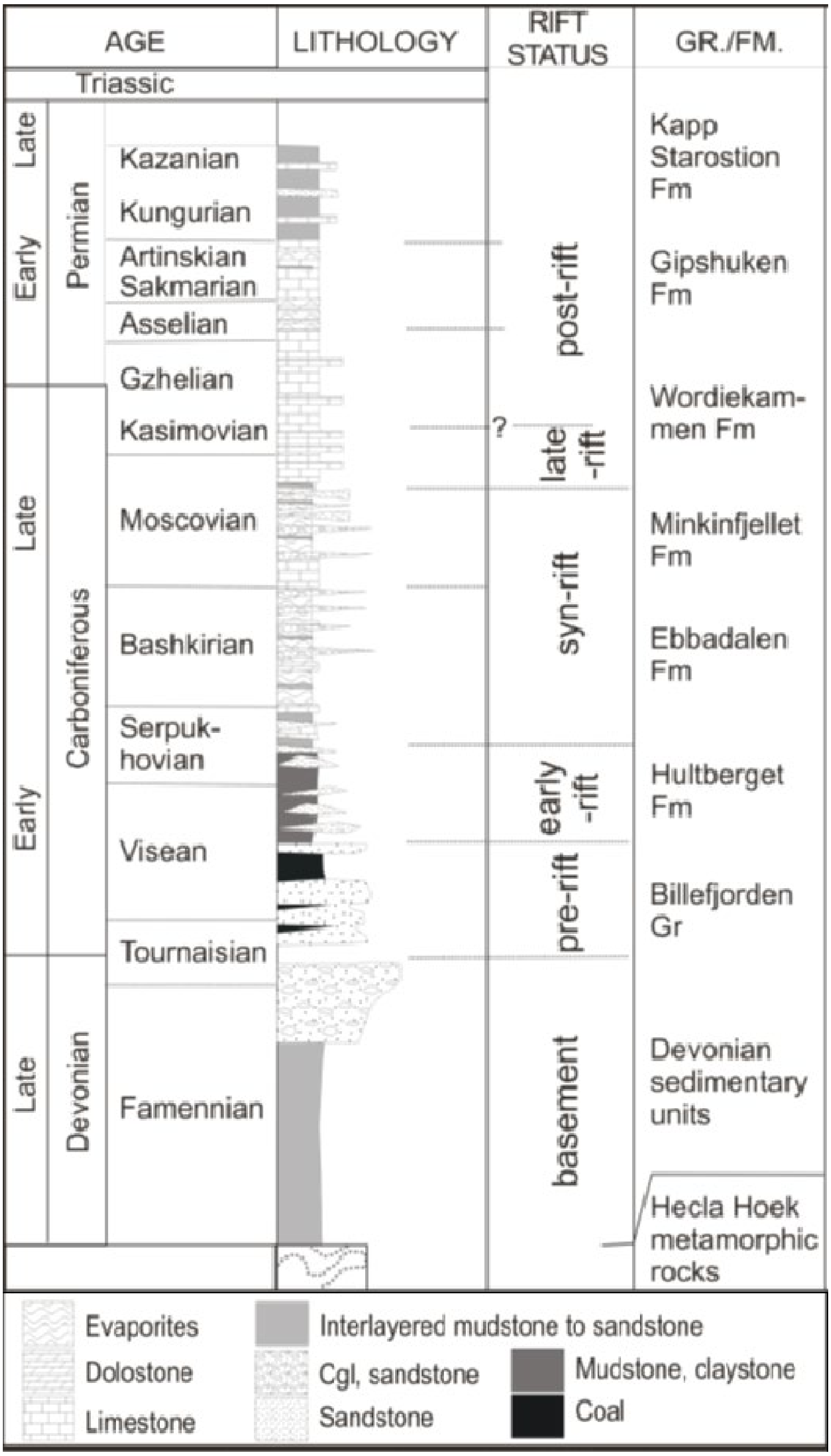


Fig. 1.6 Stratigraphic column indicating lithology in relation to Carboniferous rifting. Covering pre-rift basement and Billefjorden Group and syn- to post-rift formations of Gipsdalen Group (Edited from Braathen et al. 2011).

in the stratigraphy is the Helvetiafjellet Formation which consists of 40-155m thick sediments deposited in a transgressive regime (fluvial and delta related facies). The base is marked by coarse pebbly sandstones. The lithology is mostly sandstone and shale laminated with coal seams (Harland et al. 1976; Parker 1967). The youngest stratigraphic formation of the Adventdalen Group and the whole stratigraphy in the area is the Carolinefjellet Formation. It reaches 190-1200(?) m thickness and is increasing to the south-east. The main lithologies are shale, siltstone and sandstone deposited in a pro-delta, distal marine environment. The Carolinefjellet Formation is composed of units alternating between sandstone dominated and siltstone dominated beds (Parker 1967).

Palaeogene deposits are absent in the study area and will not be described further. Except for some glacial Quaternary sediments, the geological record in the study area ends with Adventdalen Group.

1.3.2. Study Area

The study area covers Billefjorden and Sassenfjorden (Fig. 1.7A). The two fjords lie in the north-east corner of the CTB. The old mining site Pyramiden lies in inner Billefjorden. There, the BFZ meets the coast. The Paleoproterozoic Billefjorden Basement High north of Pyramiden is bound by the Balliolbreen Fault to the west and the Odellfjellet Fault to the east. Additional shorter fault segments cut the basement and Billefjorden Group on the BBH. Together the BBH and faults form a distinct N-S structure between the NH and BT. Onshore the horst and bounding faults terminate at Mimerbukta but are expected to continue into the offshore domain (Dallmann et al. 2004b).

The Balliolbreen and Odellfjellet faults are the main fault strands of the BFZ in the study area. The Balliolbreen Fault is a 60-72^{o} eastward dipping Upper Devonian reverse fault. It most apparent feature is displacing Precambrian basement over Devonian rocks (Bergh et al. 2011; Harland et al. 1974; Lamar et al. 1986). According to Lamar et al. (1995), since the fault does not cut the Carboniferous Hørbyebreen Formation further north, no later displacement along the fault occurred. Smyrak-Sikora et al. (2018) however, suggests Carboniferous reactivation as a normal fault that resulted in a 200-300 m down throw in the Billefjorden Group further south towards Pyramiden.

The Odellfjellet Fault reaches Billefjorden by the eastern slope of Pyramiden (Fig. 1.8) (Dallmann et al. 2004b). It initiated as a Carboniferous normal fault and had a major control on the BT basin geometry and development. During this time, east of Odellfjellet Fault, the basin accumulated thick sedimentary deposits. Meanwhile west of the fault on the NH there was no sediment deposition at this time. The dip of the basin stratigraphy towards the fault is further indication of extension. Odellfjellet Fault may have been reactivated as a reverse fault (Johannessen & Steel 1992; Manby et al. 1994; McCann & Dallmann 1996).

West of Pyramiden coastal stratigraphy exposes the Gipsdalen (Ebbadalen and Gipshuken formations),

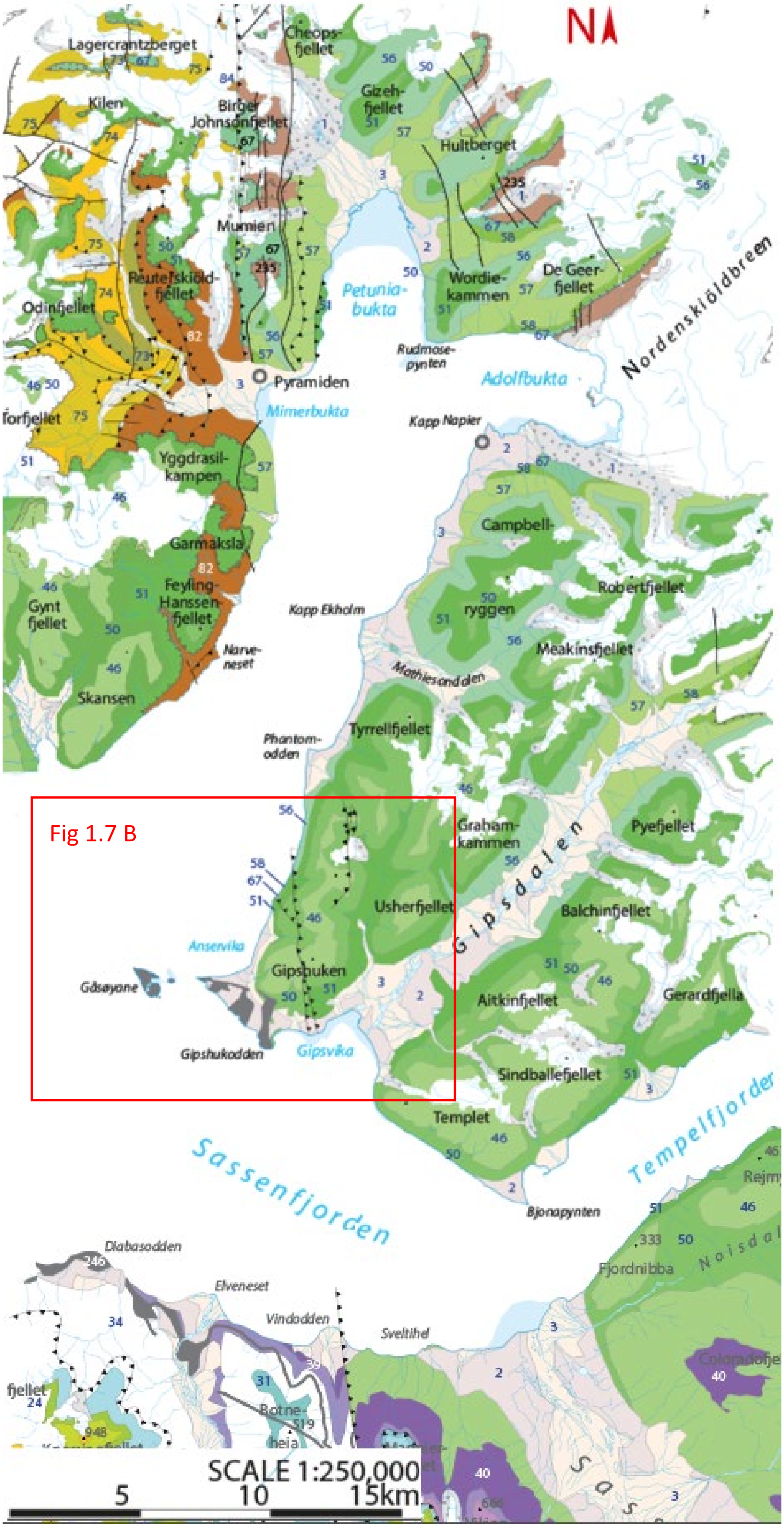


Fig. 1.7 A Detailed map of study area. See Fig. 1.7 C for map legend. Edited from Dallmann et al. (2009) and Major et al. (2000)

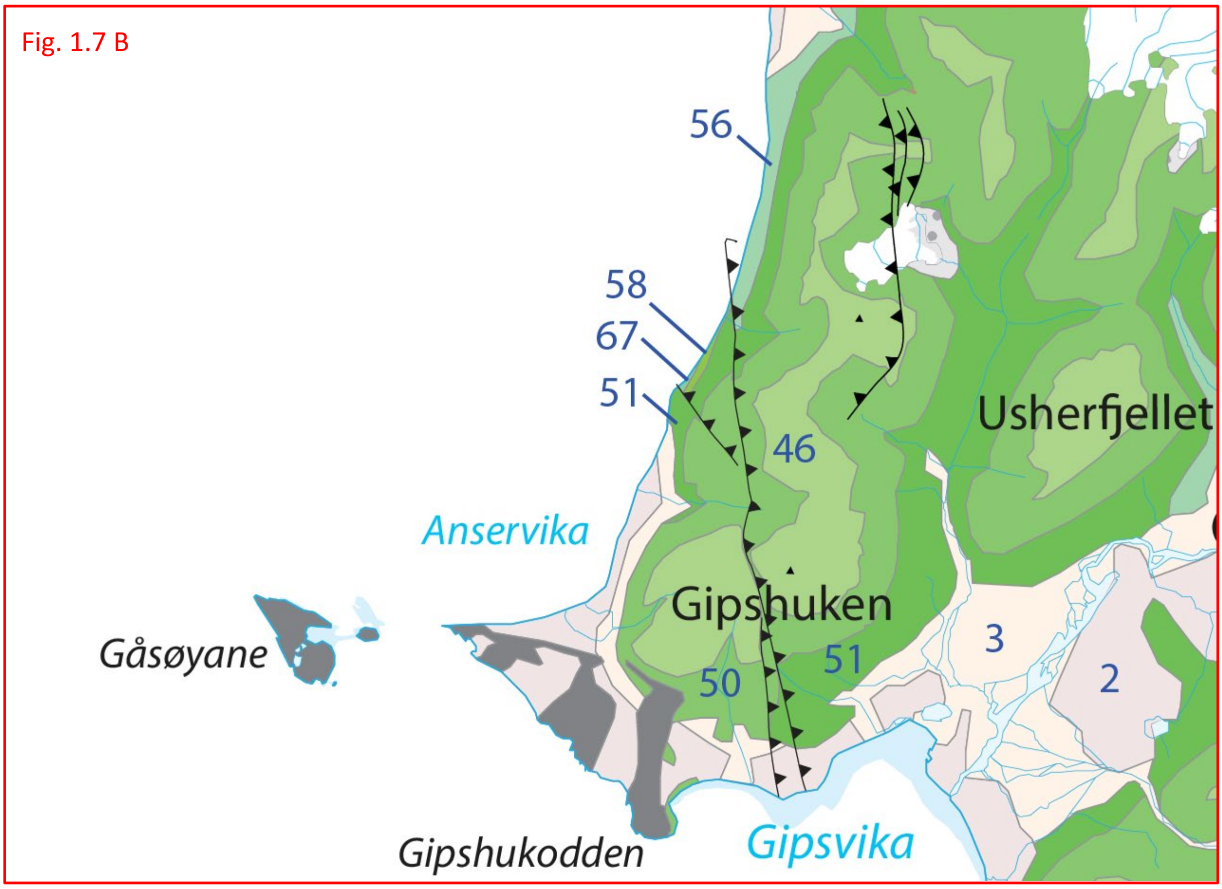


Fig. 1.7 B Detailed map of lineaments and geology at Gipshuken. See Fig. 1.7 C for map legend. Edited from Dallmann et al. (2009) and Major et al. (2000)

Billefjorden and Andrée Land groups (Dallmann et al. 2004b). East of Pyramiden the entire shoreline exposes the basin (BT) infill Gipsdalen Group rocks. Therefore, in Petuniabukta and Adolfbukta the offshore stratigraphy is assumed to continue with rift to pre-rift sequences. At Anservika the coastline is dominated by the late-rift Wordiekammen Formation. Continuing north, the coastal rocks get progressively older down to syn-rift Ebbadalen Formation to pre-rift Billefjorden at Petuniabukta and Adolfbukta (Braathen et al. 2011; Dallmann et al. 2004b). Between Adolfbukta and Anservika late- to syn-rift units of the BT half graben are expected.

A narrow elongate exposure of the Billefjorden Group lies in the inner part of Adolfbukta. It unconformably overlies basement rock. Further south-east the exposure disappears under the Nordenskiöldbreen, but to the north it can be traced through several E-W trending valleys (Dallmann, Piepjohn et al. 2004b). Seismic line NH8706-402 terminates towards this unconformity and is expected to show the structure in the offshore seismic profile. The youngest rock on the coast of Billefjorden is the Kapp Starostin Formation, while the oldest is the Wood Bay Formation. However, its base is not exposed in the study area.

LEGEND

Line symbols

Normal boundary between stratigraphic units
Normal fault
Reverse fault, or shear zone in high-grade metamorphic rocks
Strike-slip fault, dextral / sinistral (both may occur at the same fault)
Fault of unknown type
Angular unconformity

Stratigraphy and lithology

Quaternary
Unconsolidated material (Pleistocene - Holocene)
1 Moraines
2 Marine deposits
3 Glaci-fluvial deposits

Carboniferous - Permian
Tempelfjorden Group (Permian)
46 Kapp Starostin Formation (Artinskian - Tatarian): silicified carbonate rocks, chert and sandstone

Gipsdalen Group (Late Carboniferous - Early Permian)
50 Gipshuken Formation (Sakmarian - Artinskian): dolomite and limestone
51 Wordiekammen Formation (Moscovian - Sakmarian): dolomite and limestone
56 Minkinfjellet Formation (Moscovian): sandstone, dolostone, limestone, dolomite breccia
57 Ebbadalen Formation (Bashkirian): mudstone, sandstone, coaly shale
58 Hultberget Formation (Serpukhovian): red sandstone and shale

67 Billefjorden Group (Early Carboniferous): sandstone, conglomerate

Devonian
Andrée Land Group (Pragian - Eifelian)
73 Plantekløfta Formation: conglomerate, sandstone and shale
74 Planteryggen Formation: sandstone, siltstone and conglomerate
75 Tordalen Formation: sandstone, siltstone and shale
82 Wood Bay Formation (Pragian - Emsian):

Palaeoproterozoic (>1600 Ma)
235 Part of Atomfjella Complex, Ny-Friesland

Intrusive Rocks
Dolerite (Diabasodden Suite, Early Cretaceous)

Fig. 1.7 C Map legend for Fig. 1.7 A and B. Edited from Dallmann et al. (2009) and Major et al. (2000).

At Gipshuken, the N-S trending Gipshuken reverse faults cut the headland (Fig. 1.7 B). This fault array lies along and parallel to the BFZ. The Gipshuken and Cowantoppen faults are short fault segments exposed at Gipshuken (Fig. 1.7 B). They are both vertical, footwall to the west reverse faults. The Gipshuken fault cuts through Gipshuken and Kapp Starostin formations. The Cowantoppen Fault juxtaposes Ebbadalen Formation onto Gipshuken Formation on the north coast of Gipshuken and southwards disappears under the Kapp Starostin Formation where the stratigraphy forms a monocline (Dallmann et al. 2004; Harland et al. 1974). This flexure is formed by Palaeogene convergent reactivation of the BFZ at Gipshuken (Dallmann et al. 2015). Gipshukodden and Gåsøyane are composed of Cretaceous dolerite intrusions (Dallmann et al. 2004b; Nejbert et al. 2011). Seismic profiles show they continue offshore in the fjord.

1.4. Previous work related to study

Bælum & Braathen (2012) study on fault array and basin geometry from offshore seismic data in Sassenfjorden and Isfjorden is directly related to this study. The same well in Reindalen and onshore seismic data (line NH8802-32) is used to identify key stratigraphic horizons, which are extrapolated to the offshore domain. They present seismic lines from Sassendalen and Isfjorden and topographic maps based on seismic data, thus this study is meant to fill the gap northwards in Billefjorden by presenting the seismic data which is only described but not presented by Bælum & Braathen (2012).

Apart from the terrestrial seismics, overlapping study area includes line NH8706-206 south of Gåsøyane. The same approach as used by Bælum & Braathen (2012) to locate stratigraphic horizons in the TWT domain of seismic profiles is applied largely in this paper. This includes the use of check shots (velocity survey) and well data in Reindalen, the use of land seismics and field observations on land. In addition, this thesis presents supplementary methods in identifying stratigraphic units in the seismic data since only part of the stratigraphy overlap from Reindalen to Billefjorden (Fig. 1.5). This method is based on land observations along the coast of Billefjorden and on existing maps (see Methods). Conclusions of the Bælum & Braathen (2012) paper include the presence of two relay zones along the BFZ where the Balliolbreen, Odellfjellet and Drønbreen faults overlap and replace one another as master faults. Furthermore, they discuss the reactivation history of the BFZ. These are described further in the discussion. The study area here extends further north than Bælum & Braathen (2012).

Inner Billefjorden lies just south of the Smyrak-Sikora et al. (2018) study. Smyrak-Sikora et al. (2018)

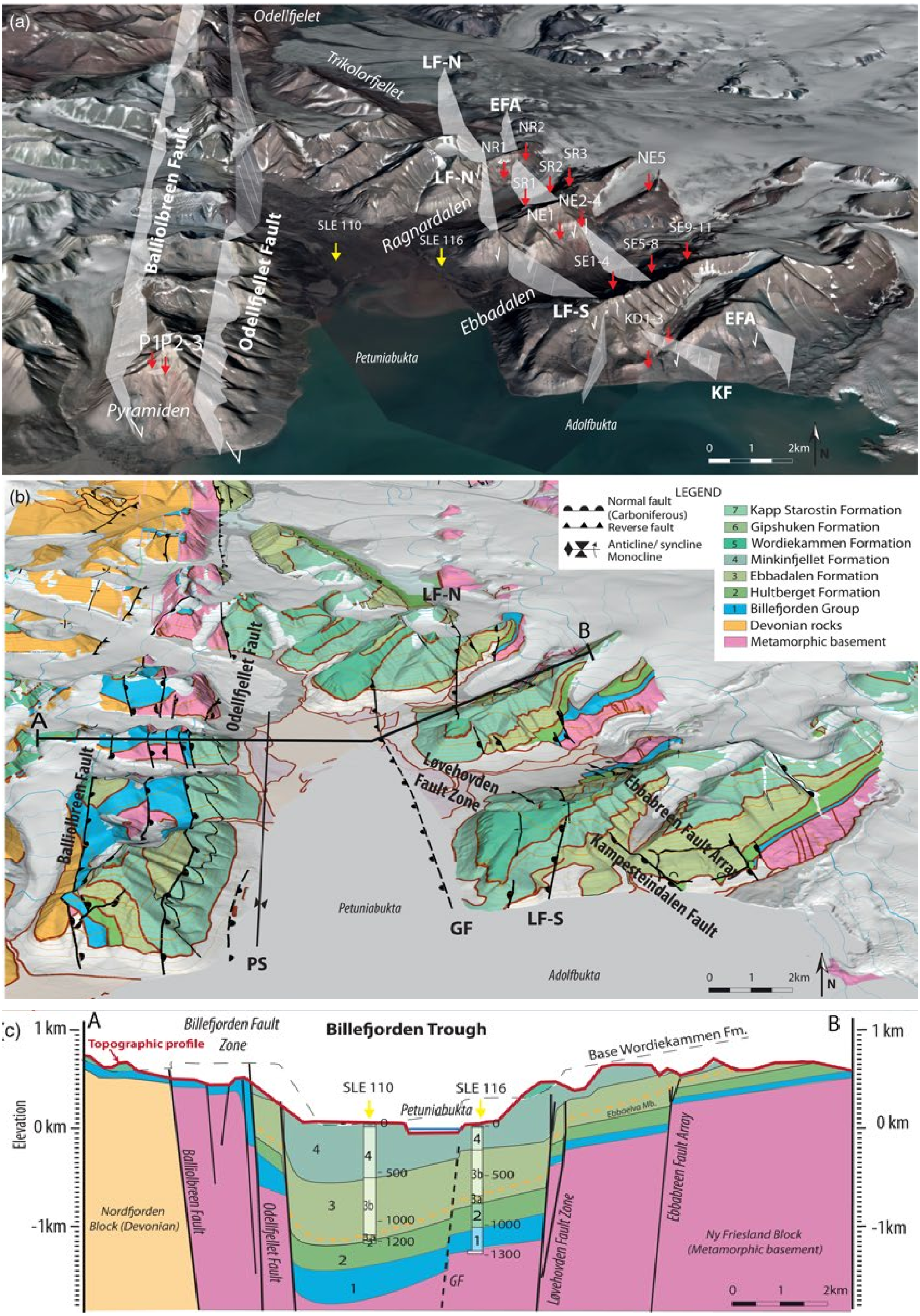


Fig. 1.8 3D illustration of Pyramiden and Petuniabukta. Top figure shows terrain model with faults. Middle figure shows geological map over terrainmodel. Bottom figure shows cross section A-B over Billefjorden Trough (Smyrak-Sikora et al. 2018)

collected terrestrial field data and used published borehole core logs to comply stratigraphic columns for their study in Pyramiden and north of Adolfbukta. Both the Bælum & Braathen (2012) paper and Smyrak-Sikora et al. (2018) claim that the BT has more symmetrical basin character in the north, by Odellfjellet and Løvehovden faults. Southwards the basin adopts a more asymmetrical shape. Smyrak-Sikora et al. (2018) further discusses the fault control on the BT basin development. They suggest that the basin initially developed as a symmetrical basin and later developed the asymmetrical character. However, this seems unlikely since outcrop patterns show that the basin stratigraphy attenuates further east past the Løvehovden Faults, while it ends abruptly against Odellfjellet Fault in the west (Dallmann et al. 2009; Dallmann et al. 2015, pages 202-205; McCann & Dallmann 1996). Should the basin initially have developed as a symmetrical basin, it would be expected to have more uniform thickness across the basin and the units to end abruptly both to the east and to the west. Same as the Bælum & Braathen (2012) survey, Smyrak-Sikora et al. (2018) discuss a relay ramp at Pyramiden connecting Balliolbreen and Odellfjellet faults. This study is thus meant to fill the gap between the two surveys and highlight structures in subsurface units, which cannot be studied on land.

2. Methods

This study used marine seismic data to study the subsurface geology of Billefjorden and Sassenfjorden. A number of marine seismic profiles were selected from available data sets to represent the offshore geology of Billefjorden and Sassenfjorden (described in section 2.1.2.). These profiles were interpreted in Petrel and Adobe Illustrator and are presented in section 3. In order to correlate stratigraphic units to the seismic profile, a seismic well-tie is used. A seismic well-tie is made by using a velocity survey from a borehole near or directly overlapping the seismic line. Depth (m) and travel time (s) measurements are made and paired down the borehole. A stratigraphic log from gamma measurements and drill cores pinpoints the geological units at specific depths. Combining this information, it is then possible to locate stratigraphic units in the TWT domain of the seismic profile.

The closest well to the study area with a velocity survey is well 7816/12-1 onshore in Reindalen (Fig.2.1). In order to use the well-tie a tie-line was used. The tie-line is a composite line of terrestrial seismic data which follows a transect from the well to the offshore domain in Sassendalen where it can be coupled to the marine seismic surveys (onshore seismics and well-tie are described in section 2.1.1.). The long distance from Reindalen to the study area is problematic since the geology changes significantly over the distance.

Due to the distance and only partly overlapping geology (right column, Fig. 1.5) between Reindalen and Billefjorden other approaches were used to locate key horizons in the marine seismics from the study area. This included extrapolating information from near onshore areas around Billefjorden and Sassenfjorden from geological maps and published articles (section 2.2). Exposed coastal units, their measured thickness and seismic velocity calculations were used to locate unit boundaries in the seismic data. In addition, seismic signatures (section 2.3) of the geological units and bathymetry data (section 2.4) were utilised to interpret the marine seismic profiles.

This multi-tool approach is necessary when there is no well-tie available directly at the seismic survey. The magnetic survey was not used. It reflects local igneous units, not the geometry of the basement. Much of the basement is not magnetic (Gee 1986; Harland et al. 1966), thus does not reflect in magnetic surveys. To summarise; the first step was locating the geological units in the seismic profiles using Petrel and the above mentioned multi-tool approach (well-tie, tie-line and map information). Then, interpretation of subsurface structures was done in Adobe Illustrator. These figures are presented and described in results.

2.1. Seismic data

2.1.1. Onshore seismic data and Reindalen well

The onshore seismic data is from two terrestrial campaigns conducted by Norsk Hydro in 1988 and 1989. Seven lines from the NH8802 campaign and one line from the NH8903 campaign are combined into one composite tie-line. The tie-line runs from well 7816/12-1 in Reindalen to the marine seismic survey at Sassenfjorden. Fig. 2.1 shows an overview of both terrestrial and marine seismic lines and the location of well 7816/12-1. The terrestrial composite section has total length of 55 km and includes four gaps or "jumpers" where the seismic lines did not overlap, including the transition from onshore to offshore seismic lines. The gaps vary between 0.5 and 1.6 km (Fig. 2.2).

The well in Reindalen is drilled by Norsk Hydro A/S and is 47km away from Gåsøyane at outer Billefjorden. It is located in the BFZ domain and in the vicinity of Paleogene thrust faults. At this point and southwards, the BFZ is poorly constrained. The depth of the well only reaches the Sveenbreen Formation of the Billefjorden Group at 2305m true vertical depth (TVD) (Norsk-Hydro A/S 1991). Thus, limiting the ability to link seismic horizons to stratigraphic units from Late Carboniferous to Devonian strata and the basement, which are important for studying the movements along BFZ. The main lithological unit from the well is therefore the Gipsdalen Group, which could be traced continuously from the well to south-east Sassenfjorden. The basement is poorly constrained both in the onshore and offshore seismics (see section 2.3. for seismic well-tie and seismic signature).

The acoustic source was generated by Dynacord (detonating cord) dynamite charges with 2-4 kg/shot. The source array was pulled by a snowmobile and charges were triggered every 50 m (Bælum & Braathen 2012). The source array produces an acoustic signal by triggering the dynamite charges. The acoustic signal is a pressure wave (p-wave) which propagates through the subsurface. If the p-wave hits a surface with different acoustic impedance (acoustic velocity) then part of the p-wave will be reflected back to the surface. This reflected acoustic signal is then recorded at the surface by geophones. The strength of the reflected signal will partly depend on the difference between acoustic properties of the subsurface materials. This is used to interpret material properties and structures of the subsurface lithological units. The signal was recorded by geophones with 25m receiver spacing. The dominant frequency was 25 Hz (Anell et al. 2014; Bælum & Braathen 2012; Bælum et al. 2012). The receiver (geophone) obtains and converts the p-wave signal into an electric signal which is recorded by a recording device (located on the bandwagon) through a channel. The geophones and channel are installed in a snowstreamer, a long cable which connects to the

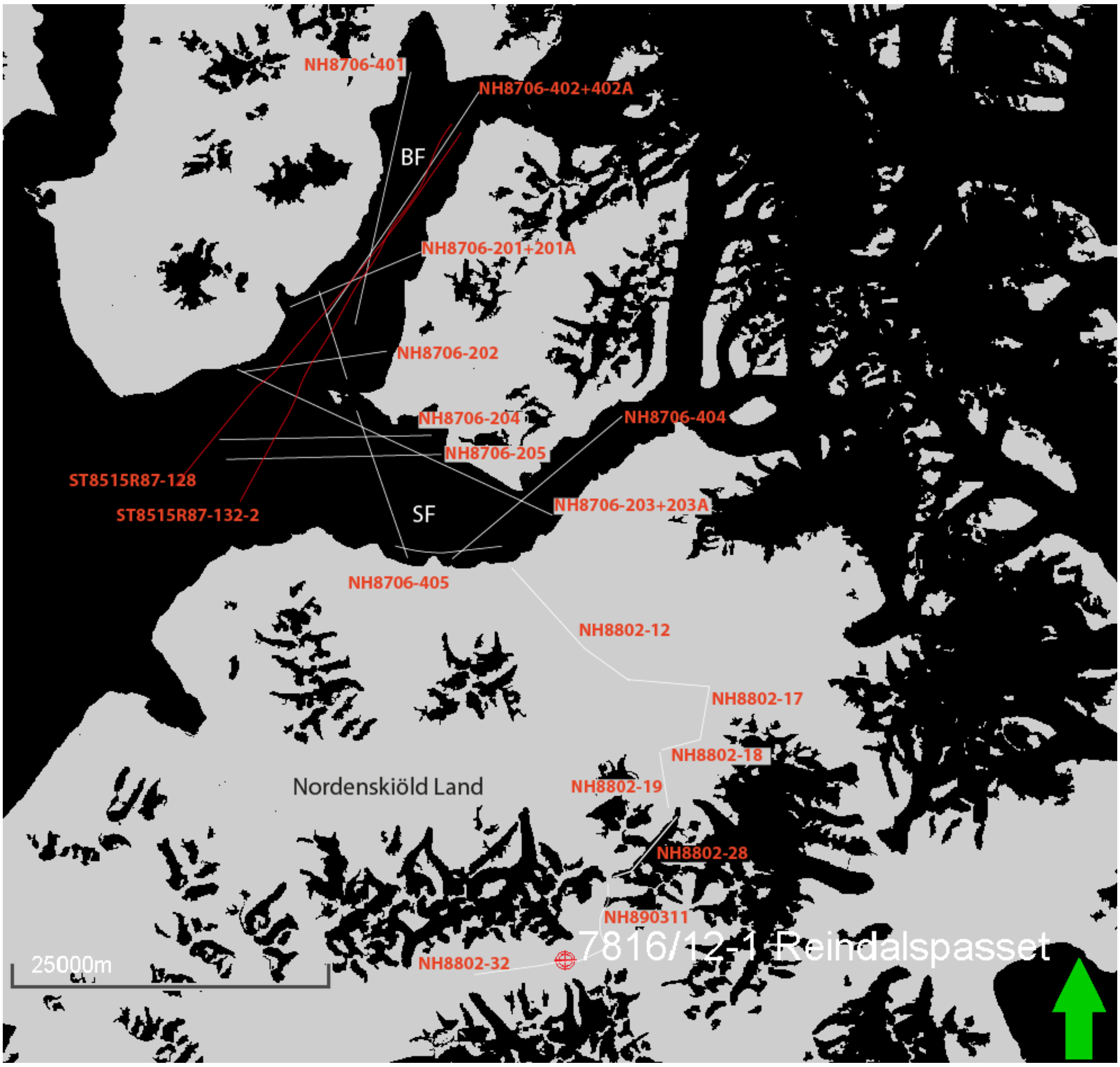


Fig. 2.1 Map generated in Petrel with overview over seismic lines and well 7816/12-1. BF- Billefjorden, SF- Sassenfjorden.

recording device. For the NH8802 and NH8903 campaigns a 60 channel, 1500m snowstreamer pulled by a bandwagon was used. It was driven with 50 m source offset behind the source array (Bælum et al. 2012; Rygg et al. 1993). Fig. 2.3 presents an overview of the seismic campaigns and the seismic lines which were selected for interpretation.

The recorded raw data has to be processed before interpretation. The processing converts the data into a format which can be imported into an interpretation program (Petrel) (Senger et al. 2013). The ST8515, NH8706 (terrestrial) and NH8802 dataset was fully processed and migrated when attained for this project. No further processing has been made. The only seismic line used from campaign NH8903 was raw, this had some effect on working with the tie-line but impact negligible on the final

Marine seismic lines	Length (km)	Composite tie-line (terrestrial)	Length (km)
ST8515R87-128	35.4	NH8802-32	10.5
ST8515R87-132-2	33.7	NH8903-11 raw mig	5.2
NH8706-201 + NH8706-201A	10.8	Jumper	0.5
NH8706-202	11.2	NH8802-28	6.8
NH8706-203 + NH8706-203A	26.8	Jumper	1
NH8706-204	16.5	NH8802-19	4.5
NH8706-205	16.9	NH8802-18	3.5
NH8706-211 + NH8706-211A	21.6	NH8802-17	4.3
NH8706-401	20.3	NH8802-12	18.4
NH 8706-404	10	Jumper	1.6
Considered but excluded		NH8706-405 (marine)	7.5
NH8706-402 + NH8706-402A	20.8	**Total lenght**	63.8

Fig. 2.2 Overview over seismic lines used in the study. The length of each line is stated. All lines except NH8903-11 were migrated.

Campaign	**ST8515**	**NH8706**	**NH8802**	**NH8903**
Year	1985	1987	1988	1989
Type	Marine	Marine	Land	Land
Area	Billefjorden	Sassenfjorden/Billefjorden	Nordenskiöld Land	Nordenskiöld Land
Number of lines	22	21	29	13
Length (km)	517	292	291	101
Raw/migrated	mig	mig	mig	raw
Streamer lenght (m)	2400	2000	1500	1500
Source	Airgun	Airgun	Dynamite	Dynamite
Positioning system	SATNAV	Microfix	n.a.	n.a.
Interpreted lines	ST8515R87-128	NH8706-201	**NH8802-12**	**NH8903-11**
	ST8515R87-132-2	NH8706-202	**NH8802-17**	
		NH8706-203 + NH8706-203A	**NH8802-18**	
		NH8706-204	**NH8802-19**	
		NH8706-205	**NH8802-28**	
		NH8706-211 + NH8706-211A	**NH8802-32**	
		NH8706-401		
		NH8706-402 + NH8706-402A		
		NH 8706-404		
		NH8706-405		

Fig. 2.3 Overview over seismic campaigns with technical specifications. Interpreted lines; blue are tie-line, black are marine seismics from Billefjorden and Sassenfjorden. Edited from Bælum & Braathen (2012).

interpretations in Billefjorden and Sassenfjorden. The seismic data are not depth converted. All seismics are in seconds (s) two-way time.

2.1.2. Offshore seismic data

The marine seismic data are from the ST8515 and NH8706 campaigns. Fig. 2.1. shows an overview of the selected seismic lines and their identifying numbers which were used from geological interpretation. Both surveys used an airgun for p-wave generation and the signal was collected with a 2400m and 2000m streamer respectively (Fig. 2.3) (Bælum & Braathen 2012). The available data from Billefjorden are 2D-seismic lines. The huge disadvantage of 2D seismics is that it does not show the orientation of structures and their 3D geometry in space. Information about true dip, curvature and connecting faults is lost compared to a 3D seismic survey. All seismic lines are presented in seconds (s) TWT. Two lines form the ST8515 campaign and eight from the NH8706 were selected for interpretation (Fig. 2.2). They vary in length from 10-35.4km. Overall, the resolution is the same for the marine data as for the terrestrial surveys. However, different datums are used for the onshore and offshore data which had to be considered when tracing horizons form the terrestrial tie-line to the marine domain.

Seismic surveys are susceptible to noise which can mask the signal reflected from stratigraphic structures. In the same way as for the terrestrial surveys this noise cause artefacts in the seismic data which are difficult to remove in processing. These artefacts have to be recognised when interpreting the seismic profiles, otherwise there is the risk of wrongful interpretation, mistaking noise generated artefacts as real geological structures (Mougenot 2018; Shearer 2009).

2.1.3. Seismic data quality

The most important parameters which control the quality of seismic data can roughly be divided into three components, namely: the technical limits of the recording instruments, the local geology of the survey area and lastly, the processing of the raw data. The technical aspects are related but not limited to the sensitivity of the recording instrument, number of traces and the recorded main frequency (Mougenot 2018; Liner & McGilvery 2019; Sheriff, 1975).

The various seismic campaigns used in this project are produced with different seismic traces. A common date was not set during the processing of the data causing a miss-tie between the surveys. This was considered during seismic interpretation and tracing horizons between crossing lines from different surveys. This is also problematic for producing amplitude maps but not for fault interpretation and structural analysis within the survey or seismic profile. The seismic data have normal polarity and minimum phase. Thus, the beginning of a peak represents an increase in acoustic impedance and the beginning of a trough in turn represents a decrease in acoustic impedance (Schlumberger 2020).

Seismic resolution is divided into vertical and horizontal. The vertical resolution is a function of the dominant frequency and velocity of the soundwave. It therefore varies with depth. It tells us the lower limit for when a structure can be individually detected and distinguished from another. Similarly, the horizontal resolution determines the minimum lateral extent and separation between structures in order to be detected as a single unit. The horizontal resolution is determined by the Fresnel zone which increases further from the acoustic transmitter and thus with depth. The narrower the Fresnel zone the better the resolution is (Berg & Woolverton 1985; Liner & McgGilvery 2019).

There was no processing report available and the exact resolution cannot be given. An estimation based on other publications and own estimations suggest vertical and horizontal resolution in the range of 20-40m (Bælum & Braathen 2012; Lubrano-Lavadera et al. 2019). However, the importance of the exact resolution diminishes since the error margin caused by the lack of a well-tie in the study area and poor processing is assessed to be greater than the resolution. The quality of the data and errors are discussed further in chapters 4 and 5.

Acquisition of seismic data in Billefjorden has proven problematic. The narrow fjord with steeply sloping seafloor causes the soundwaves from the sonar to bounce of the sides of the fjord. This causes so called side sweep which manifests as horizontal structures in the seismic image. Furthermore, glacial erosion of the fjords cause accumulation of a thick sedimentary cover on the sea floor. These sediments are dominated by clay rich moraines. Overburden from ice sheets compact the sediments which lead to high acoustic velocities. Cemented bedrock at the seafloor is known to cause sea floor multiples in the image and mask the acoustic signal from deeper levels (Johansen et al. 2003; Liner et al. 2019). The multiples are difficult to remove in processing (Kneib & Bardan 2003; Watson 1965).

These factors are in part the cause for the marine seismic data to be of worse quality than the terrestrial. Onshore permafrost can increase P-wave velocities up to 80–90% compared to unfrozen water saturated sediment. In an area like Svalbard this is a constant issue. Comparable to the effect of a thick cemented seabed it can have a problematic effect on the reflectivity from the stratigraphic boundaries (Johansen et al. 2003). This kind of artefacts are collectively termed coherent noise. Random noise is associated with artefacts caused by wind, airplanes, cars and other “loud sources”. Coherent noise is thus associated with reflected waves from the sound array which are not a representation of the actual geological structures and random noise is associated with sound waves generated by other sources in the area. Random noise is easier to filter out during processing. Strong topography, very shallow or deep water depth can have a negative effect on the seismic data quality. Other aspects, such as rapid deposition of sandstone can result in weak seismic reflections (Liner & McGilvery 2019; Sheriff & Loyd 1995).

An important function of data processing is removal of noise. Noise is any sound recorded which is not a direct reflection from the subsurface. Noise can come from the vehicles pulling the source array and snowstreamer, wind, airplanes and double reflections or side sweep from geological features. This will generate so called artefacts in the seismic image. Processing is meant to remove as much of these artefacts as possible, however it is often impossible to eliminate noise entirely (Gardner et al. 1974; Liner et al. 2019). Both the terrestrial and marine data used in this study are of medium to poor quality and have high noise to sound ratio. Much of the seismic interpretation was identifying artefacts in the seismic images and distinguishing them from geological structures, data quality and artefacts are further described in results, chapter 3.

Processing of seismic data also, has the function of converting the raw seismic data into a coherent seismic image which is a good representation of the actual geology in the survey area, this is called seismic migration. Seismic migration and processing are tricky. How well the processing is executed has significant effect the appearance of the final seismic image (Liner et al. 2019). All seismic data used in this project was fully processed, and no additional seismic processing was undertaken in this study. Both migration and removal of noise for the seismic data available is inadequate and proved very problematic for seismic interpretation.

2.2. Geological and isopach maps

Successful identification of stratigraphic units in the seismic image is essential in seismic interpretation. If key horizons are placed incorrect in the image, then our understanding and ability to reconstruct geological event is compromised. This is especially true for pinpointing the timing of events and correlating to events observed outside the area on a regional scale. Ideally, this is obtained with a well-tie in the study area where a drill core and velocity survey from a bore hole is used to locate the top and bottom boundary of stratigraphic units in the seismic image. As mentioned above the closest well-tie in Reindalen is insufficient to locate the entire stratigraphic column in Billefjorden and the units which could be traced from the well are likely to have a significant error margin. This problem was solved by extrapolating information about coastal geology into the offshore domain by use of geological and isopach maps and field observations (section 2.5).

All geological maps are from the Norwegian Polar Institute (Dallmann et al. 2000, 2002, 2004a, 2004b; Major et al. 2000). The isopach maps are taken from a report for UNIS Project 920040 (Dallmann 2016). Isopach maps show the thickness of selected stratigraphic units over an area and can provide valuable information on subsidence during deposition and sometimes fault movement. They are based on a compilation of data which is extrapolated over the mapped area with ArcGIS (Dallmann 2016). The accuracy of the thickness map depends on the spatial resolution and precision of datapoints. Isopach maps were used to predict the thickness and regional structure of units in the seismic image. The thickness of units are given in meters. A velocity model (section 2.3) was used to convert the thickness into a time-domain. This was necessary since all seismic images are in TWT. This method assumes that due to the proximity, the onshore and offshore geology is comparable in terms of thickness and structures of stratigraphic units.

2.3. Well-tie and velocity model

Since there is no well-tie for the seismic lines in Billefjorden, a well further away in Reindalen was used to pinpoint the stratigraphic units in the seismic image. The first step was to use the borehole, velocity survey and terrestrial seismics to create a well-tie in Reindalen. This made it possible to place seismic horizons in the seismic image from Reindalen and trace the stratigraphy across the tie-line in a traverse from Reindalen, Sassendalen to inner Sassenfjorden. However, the distance between the well and Billefjorden, faulted geology and miss-tie between seismic surveys cause uncertainty in the placement of horizons the further one moves from the well.

Key horizons represent boundaries of selected stratigraphic intervals that are traced horizontally along the seismic profiles during interpretation in Petrel. They represent the base of chosen stratigraphic units or time intervals. The placement of key horizons identifies stratigraphic units in the seismic profile, thus giving an age indicator for structures seen in the seismic data. This allows correlation between seismic lines and different areas within and outside Billefjorden and Sassenfjorden. It also allows to trace the stratigraphy across areas to study its continuity and thickness variation. Key horizons are chosen based on relevance to the study area. Another criterion is the resolution of the data set and thickness of the units, i.e. the unit needs to be detectable and be able to be delineated in the seismic image.

Measurements from the borehole are collected in a completion log (Norsk-Hydro A/S 1991). This log was used to complete a stratigraphic log with the geological units, their thickness and depth in the well. After an initial overview of the well log data from Reindalen 7816/12-1 it was clear that:

1) The 1991 completion log is outdated in regard to the division of stratigraphic units, many units have been merged, some names are out of use entirely while sub-units have been given a higher rank (e.g. a member is now a formation) (Dallmann 1999) First, the completion log had to be converted into the new lithostratigraphic division (Fig. 2.4). Second, selected key horizons are presented in the table with the new stratigraphic names, and location in the seismic profile in TWT (s), thickness of unit at well.

Janusfjellet Formation with Rurikfjellet and Agardfjellet Members in the completion log have been raised to subgroup and formation ranks in the new division. Wilhelmøya Formation has also been raised to subgroup rank with Knorringfjellet as a formation. Tschermakfjellet/De Geerdalen are combined in the completion log most likely due to difficulties in distinguishing between the two.

In the completion log, Sassendalen only has Barentsøya Formation consisting of Botneheia, Sticky Keep and Deltadalen Members. In the new division, Sassendalen Group in Central Spitsbergen consists of Botneheia Formation (equivalent to the Botneheia Member in completion log) and Vikinghøgda Formation (replacing Sticky Keep and Deltadalen Members). While on the NH, Sassendalen Group is Bravaisberget, Tvillingodden and Vardebukta formations.

2) The well in Reindalen is east of the main lineaments of the BFZ, this is indicated by the stratigraphy presented in the completion log. It shows the Botneheia Formation (footwall of a thrust fault in the well log, Middle Triassic - Anisian-Ladinian, 865-680 TVD m, 0,380-0,469 TWT s) and Minkinfjellet Formation (Upper Carboniferous- roughly Moscovian, 1900-2018 TVD m, 0,838-0,874 TWT s) and Ebbadalen Formation (Carboniferous- roughly Bashkirian, 2018-2251 TVD m 0,874-0,958 TWT s).

3) The exact subdivision of the Early Carboniferous Billefjorden Group is unclear from the Completion log. The old name Sveenbreen Formation is used in the well log. However, this Formation has since been divided into three sub-units. It is most likely a thin layer of Hultberget Formation as it is the underlying unit to Ebbadalen Formation and is also present in the BT stratigraphy and as have been previously determined, the well is East of the BFZ main lineaments as reflected by the lithology. It would be reasonable to assume that the remainder of the lithology would continue to the south.

1991 Completion Log Units	Updated Equivalent Stratigraphy	Base of Unit	
		TVD (m)	TWT (s)
No update needed	Cretaceous	396	0.283
	Jurassic	600	0.34
	Triassic	1030	0.546
	Tempelfjorden Gr		
	Kapp Starostin Fm	1332	0.659
Gipsdalen Gr	**Gipsdalen Gr**		
Gipshuken Fm	Gipshuken Fm	1599	0.745
Nordenskiöldbreen Fm	Wordiekammen Fm		
Tyrrellfjellet Mb		1900	0.838
Cadellfjellet Mb			
Minkinfjellet Mb	Minkinfjellet Fm	2018	0.874
Ebbadalen Fm	Ebbadalen Fm	2251	0.958
Billefjorden Gr			
Sveenbreen Fm	Hultberget Fm	2305?	0.98?
	Billefjorden Gr		
	Mumien Fm	?	?
Older units are deeper than maximum depth of well	Hørbyebreen Fm?	?	?
	Andrée Land Group (Wood Bay Fm)?	?	?
	Pre-Caledonian Basement	?	?

Fig. 2.4 Conversion table for stratigraphic units from the core log for well 7816/12-1 to updated as presented in Dallmann (1999).

In addition, there is no note of fault boundaries to overlying units, thus indicating a continuous stratigraphic record. The compilation log describes this interval as sandy, shale and coal, which is in accordance with lower members of Hultberget Formation. The exact boundary between Hultberget Formation, Mumien Formation, Billefjorden Group and Andrée Land Group are unknown at the well and have been assessed based on thickness maps (Dallmann 2016).

The acoustic velocity for each formation was calculated from the time intervals and thickness from the completion log from Norsk-Hydro A/S (1991). It was calculated by taking the thickness of the unit (in km) divided by the time interval in seconds and then divided by 2 (to correct from TWT to one way). The calculated velocities for each unit is presented in results.

2.4. Bathymetry

The available bathymetry was made by sonar. The vertical resolution is 10m and horizontal resolution is 10x10m. Global Mapper was used to view the topographic image. Bathymetric surveys generate topographic maps of the seafloor. These maps reveal the location of highs and lows in the survey area.

This can be an indication of horsts, grabens and faults. Although, some reservation has to be taken into account due to heterogeneous erosion (different rock types can have various resistance to erosion) and denudation. This is especially true for very old structures. The seismic data has many artefacts which need to be separated from real sub-surface features. Artefacts can often look very similar to real geological reflections; therefore, the available bathymetric data were used to investigate the nature of details in the seismic image. For example, features which were interpreted as faults in the seismic image could be confirmed by crosschecking with linear depressions in the bathymetry. It's important to note that many structures on the bathymetric dataset relate to Quaternary processes, namely glacial movements and deposits. These are however not the structures related to the geological events which are relevant in this survey.

2.5. Field observations

Field work lasted two days in September 2018. The first day consisted of walking along a transect at Anservika on the east coast of Billefjorden. The second day Pyramiden and the western coast of the fjord were visited by boat. Due to very short notice, sufficient preparation for the field work was not possible. The purpose of the field work was to see the exposed stratigraphy along Billefjorden. The two main focuses were first, to identify faults and associated kinematic markers. Second, to study the geometry of structures in the stratigraphy, namely folding, stretching, tilt, etc. This information on stratigraphic structures is used for interpretation of structures present under the fjord seafloor. Due to the close relation between the onshore and offshore geology, the exposed structures on land can be used as analogues for the offshore geology. In the absence of a well-tie which includes the stratigraphic interval of the seismic survey and due to the poor quality and migration problems of the seismic data set, it was necessary to combine all accessible information on the geology of the study area during interpretation.

3. Results

3.1. Interpretation of seismic data

Poor data quality resulted in high uncertainty during interpretation of the seismic images. To surpass this problem a type of "iteration-method" was used. In mathematics, iteration is using a function repeatedly. This repetition generates a number that is closing into the correct answer. In this fashion, several approaches were combined and often repeated to place stratigraphic horizons and interpret structures and although the result has high uncertainty, it is considered a "best fit" interpretation. These approaches included a well bore completion log (lithology and velocity survey, calculated acoustic speed for stratigraphic units), geological and isopach maps, photographs from coastal areas and a bathymetric survey.

Stratigraphic boundaries (horizons) were traced based on their characteristic seismic signature (combined from well and other sources), expected thickness, and acoustic speed for each formation (calculated from check shot data and other publications). Since the stratigraphic reflectors could not be traced continuously west of the BFZ at Sassenfjorden, these additional methods had to be used to identify the stratigraphy north-west of Sassenfjorden. Isopach maps gave an approximate thickness of geological units across the area. Geological maps were used to identify the units at the coast and calculate their subsurface depth based by subtracting the thickness above sea level, the water depth from the bathymetry survey (at the location of the seismic line) from the total thickness given by the isopach map. The remaining thickness was then converted into the TWT domain with use of the acoustic velocity (for the specific unit) calculated from the check shot survey.

The base of the formation was marked by a stratigraphic horizon, which represents the geological boundary between the unit in question with the underlying unit. The underlying unit was then added in a similar fashion, but this time using the total thickness from isopach maps (no subtraction was necessary for unit who are entirely below the sea floor) and conversion into TWT domain. The resulting time interval was then added to TWT of the base of the overlying unit. This process was repeated for the whole stratigraphy down to Devonian André Land Group which thickness is undefined but can reach 4km (Dallmann & Piepjohn 2020) which is below the resolution of the seismic data.

Furthermore, it proved impossible to differentiate between the basement and Devonian units due to small contrast in acoustic impedance between the units and similar (folded) internal structures. Geological maps provided information about geological boundaries between stratigraphic units but most importantly the fault array of BFZ. Individual faults around the study area were mapped out and combined with elongated highs and lows in the bathymetric map. Many faults, which are mapped on land, continue offshore as indicated by the topography. It was then possible to interpret structures in the seismic image as faults with higher confidence. The bathymetric survey proved crucial for the seismic interpretation and are the best quality data available for this study. Since this process was done for each line individually, the horizons sometimes ended up at different TWT on crossing lines. Therefore, each horizon had to be adjusted to coincide on crossing lines.

3.1.1. Data quality and artefacts

The terrestrial seismic data are of medium to poor quality. Coupling with the ground during terrestrial data acquisition is likely the reason why the terrestrial data still are better than the marine data. The water depth in the fjords reaches over 200 m. Seismic data acquisition can be problematic in deep water, especially with highly varied sea floor topography. In deep water, the water column is likely to show heterogeneity in seismic velocities (due to thermoclines, haloclines and water currents). This can increase the noise to sound ratio and generate artefact like jitter or multiple reflections. It also weakens and negatively affects the resolution and reflections from deeper depths in the subsurface (Hall 2003). A strong topography with steep slopes cause pull-up and push-down of the seismic signal. It happens when the reflected waves are delayed to various degrees causing stack degradation. The effect is seen as misaligned reflectors pulling up toward the topographic highs or lows (Samson & West 1992).

In the seismic data used in this survey, artefacts caused by water depth and strong topographic variations appear as seafloor multiples, jitter, hyperbolas, parabolic curvatures, pull-up and push-down reflectors. Reprocessing the data and better-applied migration algorithms can remove many of these artefacts. However, it is a difficult task and it´s often impossible to remove all noise. Reprocessing was not possible for this study, but neither was it considered since the focus is on seismic interpretation and structural interpretation of the study area, not seismic processing.

Specific criteria have been used to identify multiple reflections. One is that they appear at specific time intervals relative to the original primary wave, i.e. they appear at 2 times or 3 times etc. seconds TWT. Other characteristics used to identify multiples in this survey are that they cross- cut other reflectors and usually display a stronger angle on slopes than the primary. The difficulty with the latter is that pull-up and push-down effect, which is prominent in all of the seismic lines, has a similar effect. Thus, making it more difficult to differentiate between primary reflectors affected by distortion and the multiples. A hard and cemented seafloor is also problematic for the marine seismic data. It has caused sea floor multiples. Layers with a strong contrasting acoustic impedance are known to generate multiple reflections.

3.1.2. Seismic signatures and velocities

Upper Triassic to Cretaceous units are traced in the seismic tie-line although they do not belong to the studied stratigraphy in Billefjorden and Sassenfjorden. They are interpreted in the onshore tie-line in order to confirm an accurate horizon interpretation (by comparison with maps) and thus eliminating a potential error.

The youngest unit on top of the slopes above Billefjorden is the Kapp Starostin Formation of Tempelfjorden Group. Minkinfjellet and Wordiekammen formations of Gipsdalen Group are the youngest units at the coastlines and continuing below sea level thus being the youngest and topmost units in the seismic profiles from Billefjorden (Dallmann et al. 2004b). Therefore, most attention has been put to accurately identify, locate and trace Gipsdalen and Billefjorden groups from the Reindalen 7816/12-1 well to offshore Billefjorden and Sassenfjorden. In addition, due to Cretaceous tilting of stratigraphic beds, only some of the units overlap from Reindalen to Billefjorden (see right column fig 1.5). The youngest units (down to Triassic) which are present in Reindalen, are absent in Billefjorden. In turn, Billefjorden is expected to locally host the Devonian Andrée Land Group (which, if present, is not reached in Reindalen).

The well-tie (Fig. 3.1) and tie-line was applied to Gipsdalen Group. This unit could be traced from Reindalen to Billefjorden. Furthermore, seismic profiles and velocity models were made from the well-tie. These helped to interpret and locate the stratigraphy in Billefjorden. Errors are expected due to wrongful placement of horizons along the seismic profile and during transition between crossing or connecting seismic lines. It is problematic to trace stratigraphic horizons across faults. Since, studies show that the blocks and basins developed independently after faulting, the stratigraphy is likely to be different on either side of a fault. Without a well, further interpretation is based on land observations and not on direct measurements. The errors are likely to add up and increase the farther the seismic interpretation is from the well.

Sedimentary rocks in Svalbard are consolidated and have low porosity (Eiken 1985; Kurinin & Harland1970) The result is high-density rock with fast p-wave velocities (Breivik et al. 2005; Faleide et al. 1991; Sellevoll et al. 1991). P-wave velocities often exceed 6 km/s which for sedimentary rock only occurs in high density dolomite, limestone and anhydrite (Gardner et al. 1974).

The Adventdalen Group (Cretaceous to Early Jurassic) which is located from the surface down to 600m and 0.340s (TWT) at the 7816/12-1 well completion log. The calculated average acoustic velocity is 3.5km/s (Fig. 3.1). This value is the lowest of all units and is within the lower range of published 3.5-4.2km/s (Bastesen & Braathen 2010; Bælum & Braathen 2012; Eiken 1985). The seismic signature for

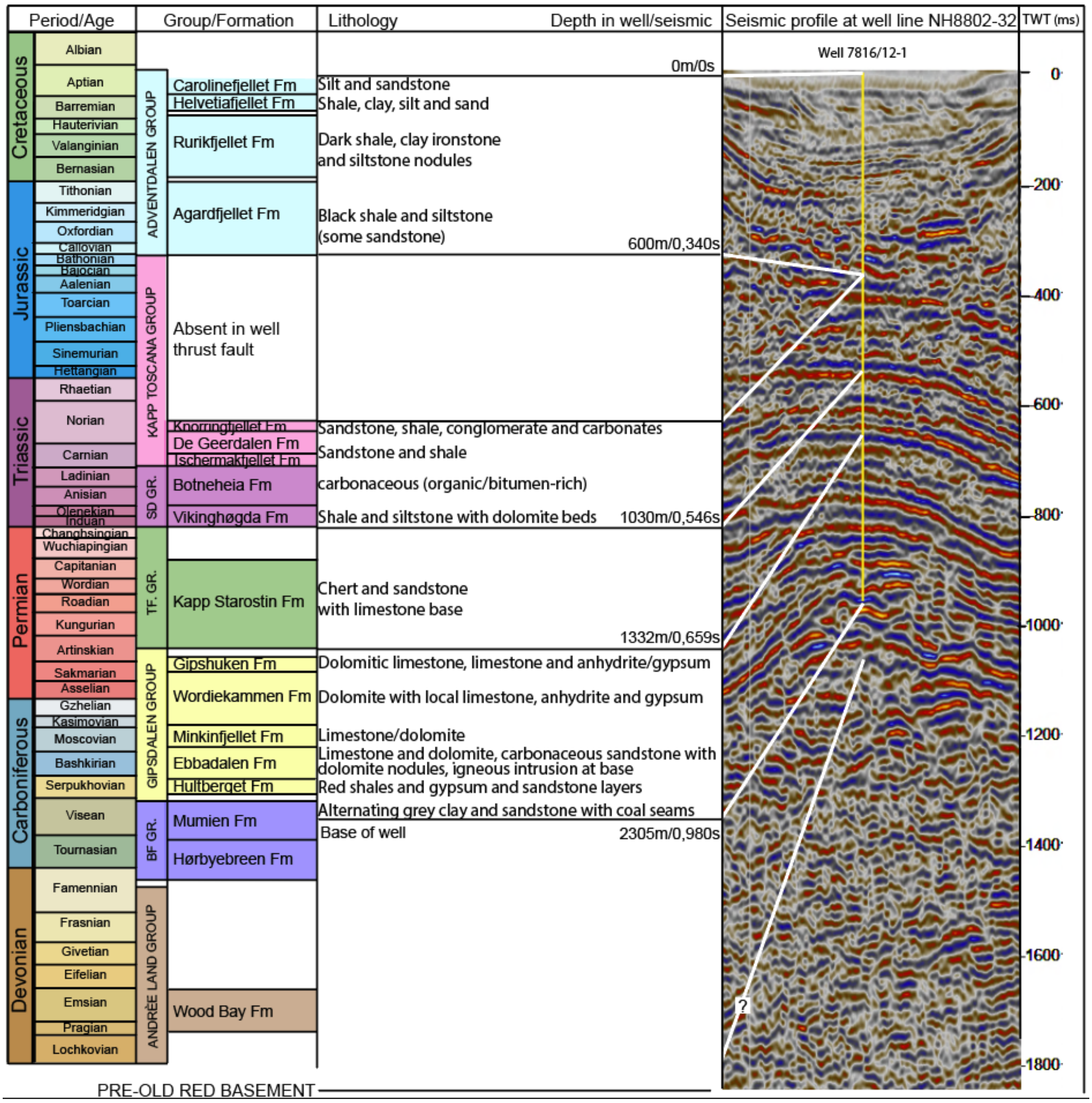


Fig. 3.1 Stratigraphic column linked to the seismic profile at Reindalspasset with well bore data. The position of stratigraphic boundaries is form Norsk Hydro completion log (Norsk-Hydro A/S 1991). Stratigraphic column and lithology are from Dallmann et al. (2015) and Norsk-Hydro A/S (1991)

this unit is partially masked by deformation; however, reflectors are of intermediate strength and locally disrupted by folds and faults.

The Triassic encompasses the **Kapp Toscana** and **Sassendalen Groups** which are located between 600-1030m depth and 0.34-0.546 s (TWT) at the well in Reindalen according to the completion log. The seismic reflectors are characterised by strong top and bottom reflectors and weaker disrupted reflections in between. The average acoustic velocity for the interval for the Kapp Toscana Group is 4km/s and 4.2km/h for the Sassendalen Group. Which is in the range of Bælum & Braathen (2012) 3.5-4 km/s The upper limit of the unit is placed just below a local synform (limited to the near well area) and a decollement, which are visible on the Adventdalen map and cross section for the area, thus confirming the correct placement of key horizons. According to maps a decollement at the base of the Adventdalen Group is underlying a synform between two mountain tops Bergmannshatten and Tronfjellet (Major et al. 2000). However, the Triassic units are unaffected by the deformation associated with the decollement.

Tempelfjorden Group (Kapp Starostin Formation) is located between 1030-1332 m depth and 0.546-0.659 s (TWT) at the Reindalen well 7816/12-1 as indicated by the completion log. The formation was traced along the composite line from the well to the southern extent of Sassendalen where it reaches the surface (line NH8802-17). This was confirmed by geological maps of the Adventdalen area (Major et al. 2000), which show that the point where the unit surfaces according to seismic interpretation corresponds to a contact between the Kapp Starostin Formation and the overlying the Sassendalen Group. In the seismic profiles the unit is identified as strong, continuous reflectors locally interrupted by deep seated faults. The top of Tempelfjorden Group defines the beginning of Triassic silicic development of intracratonic basin. The resulting chert/flint silicic and carbonate mix of the Kapp Starostin Formation is a strong seismic reflector (Dallmann 1999).

Calculations of acoustic speed is in accord with those published by Bælum & Braathen (2012) and are 5.35 km/s compared to 5 km/s from the published data. Tempelfjorden Group reaches 334m thickness on the slopes west of the seismic line in Adventdalen (Dallmann 2016). The Adventdalen map shows in cross section how the stratigraphy thins in the valley (due to erosion) where the seismic line is located, thus the formation is considerably thinner in the seismic profile and reaches a thickness of 80 m as measured both from velocities and TWT in the seismic data and thickness presented in the map. This indicates that the offshore data begin where the Gipsdalen Group is the topmost unit in Sassenfjorden. Indeed, there is a small exposure of Gipsdalen Group at the coast which indicated that the offshore stratigraphy begins with the Gipsdalen Group.

Gipsdalen Group is a heterogeneous group with some compositional variation between its formations.

Although significantly masked by high noise to sound ratio and problematic migration, the variations are reflected in the seismic data. It is the only group, which is divided into formations in the interpretation. Gipshuken Formation is composed of an alteration of dolomite, limestone and dominated by anhydrite/gypsum in the lower half (Norsk-Hydro A/S 1991). The incompetent gypsum and anhydrite layers are locally deformed and reflect weaker than over- and underlying units. The unit is characterised by intermediate and locally disrupted reflectors. The base of the Gipshuken Formation is picked at a speed increase which has good continuity, but with varying amplitude and character.

P-wave velocities for the Gipshuken Formation at Reindalen is 6.21 km/s. Acoustic speed for the Wordiekammen Formation is 6.47 km/s at Reindalen. As all of the Gipsdalen Group, the velocity is very high, but still lower than 6.8km/s published by Eiken (1985). Seismic signature is characterised by strong reflectors with variations due to lateral differences in composition across the study area. The Wordiekammen Formation has continuous distribution over the BFZ. The Minkinfjellet (6.56 Km/s) and Ebbadalen (5.55 km/s) formations have similar seismic appearance. They have intermediate to strong reflectors with variations due to compositional differences across the basins. Minkinfjellet Formation has slightly stronger and more continuous reflectors than Ebbadalen Formation. Sandstone layers and dolomite nodules within Ebbadalen Formation (Norsk-Hydro A/S 1991) generate local variations in amplitude. Hultberget Formation has continuous intermediate to weak reflectors.

Billefjorden Group; Calculations from the Reindalen 7816/12-1 well completion log show velocities of 4.9km/s in the upper 50 m of Mumien Formation. Which is lower than velocities presented by Eiken (1985). They report high velocities above 6 km/s. The difference is likely due to the fact that Eiken (1985) calculated velocities on the whole Group while Reindalen only allowed calculating for the top of Mumien Formation. Billefjorden Group's high acoustic velocity is attributed to highly competent sandstone layers. Assuming a max thickness of 250 m at the well and a uniform velocity for the unit (due to relatively homogenous lithological composition), the base of Billefjorden Group is placed at 1.060s (TWT). This coincides to a change in the seismic data, below this depth reflectors are more diffuse, disrupted and folded.

Due to lacking exposures of the group in Adventdalen it is not possible to make accurate estimations of the thickness of the unit with direct observations. Isopach maps are well constrained in the Billefjorden area (but not so much in Adventdalen) and these indicate thicknesses from 50-250 m. The trend in thickness variation according to the isopach maps for the unit reveal maximum thickness in the depocenter of the BT and pinching out towards the Odellfjellet Fault and to the eastern basin margin (Dallmann 2016). Assuming a similar thickness trend in Adventdalen the unit could reach its maximum thickness of 250m at the well in Reindalen. Seismic signatures include strong uninterrupted reflectors, which are expected to have continuous thickness towards Odellfjellet Fault.

Andrée Land Group Is only present west of the BFZ in the seismic data. It is characterised by internal deformation that stands in contrast to the flat lying post-Devonian sedimentary rock. Folds and crosscutting layers can be seen in seismic profiles from Billefjorden and Sassenfjorden. P-wave velocities exceeding 6 km/s are recorded in Devonian rocks (Eiken 1985; Sellevoll et al. 1991).

The Pre-Caledonian Basement cannot be defined in the majority of the seismic profiles. The unknown thickness of overlying Andrée Land Group makes it difficult to estimate the top pf the basement west of the BFZ (Dallmann & Piepjohn 2020). To the east the base of the layered sedimentary basin defines the top of the basement. In addition, weak contrasts in acoustic impedance between the units does not generate a strong reflection. Both units have internal deformations and the basement is likely deeper than the resolution of the seismic data.

3.2. Tie-line (interpretation)

The tie-line runs a total of 64 km combined of seven terrestrial and one marine line. Fig. 3.2 shows an overview of the line, which had to be divided into three sections (Fig. 3.2A, B and C) and enlarged for sufficient resolution. The well in Reindalen is drilled in the BFZ (Fig. 3.2 A). The stratigraphy in the seismic profile spans form the basement and Devonian to middle Cretaceous units. At the maximum TVD of 2305 m, the well in Reindalen does not reach past the top of Billefjorden Group. The base of Billefjorden Group and boundary with the basement is therefore estimated to be at -1035 ms TWT based on the assumed thickness and acoustic velocity for Billefjorden Group.

The line shows two profiles of the same basin (due to the changing direction of the line). This is a segment of the Central Tertiary Basin that spans over a large area in central Spitsbergen. There are local thrust duplexes (1 & 2, Fig. 3.2 A & B) on one of the profiles. Although the exact shortening direction is impossible to determine from a 2D profile it appears to coincide with Palaeogene shortening and parallel with larger detachments in the area. Thus, they are likely related to the same event.

Glacial icecaps cause shadows (3, Fig. 3.2 B) in the seismic image. They appear as blank spots at the top of the profile and mask underlying reflectors. Resolution is decent to about -1200ms TWT. Below this limit, reflectors are chaotic. High anomaly areas (4 & 5 Fig. 3.2 B &C) are interpreted as artefacts

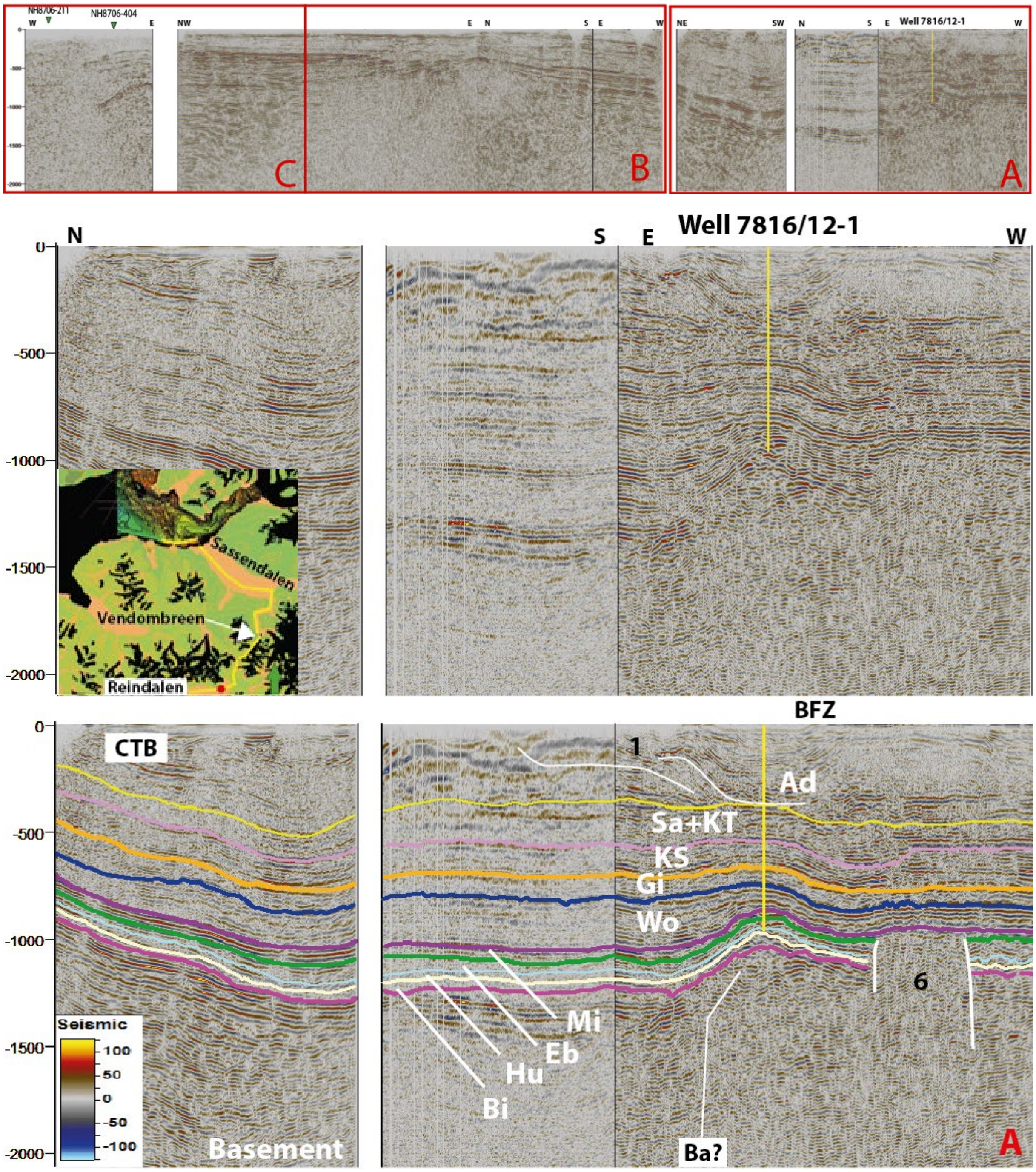


Fig. 3.2 A Top image shows an overview of the entire composite line. Enlarged areas are marked in red rectangles. Abbreviations: Ad-Adventdalen Group, SA-Sassendalen Group, KT-Kapp Toscana Group, KS-Kapp Starostin Formation, Gi-Gipshuken Formation, Wo-Wordiekammen Formation, Mi- Minkinfjellet Formation, Eb-Ebbadalen Formation, Hu- Hultberget Formation, Bi-Billefjorden Group, Ba-Balliolbreen Fault, CTB- Central Tertiary Basin, BFZ-Billefjorden Fault Zone. The coloured lines mark the base of each unit. White lines (1 and 6) are faults. The yellow vertical line shows the position of the well in the seismic profile. The yellow line on the map shows the location of the seismic line. Red circle is the location of well 7816/12-1.

caused by multiple reflections from the basin stratigraphy. It was considered if they are reflections of the basement. However, the area does not resemble the chaotic and folded appearance of the basement as seen under the well. Instead the area is characterised by reflectors which resemble the

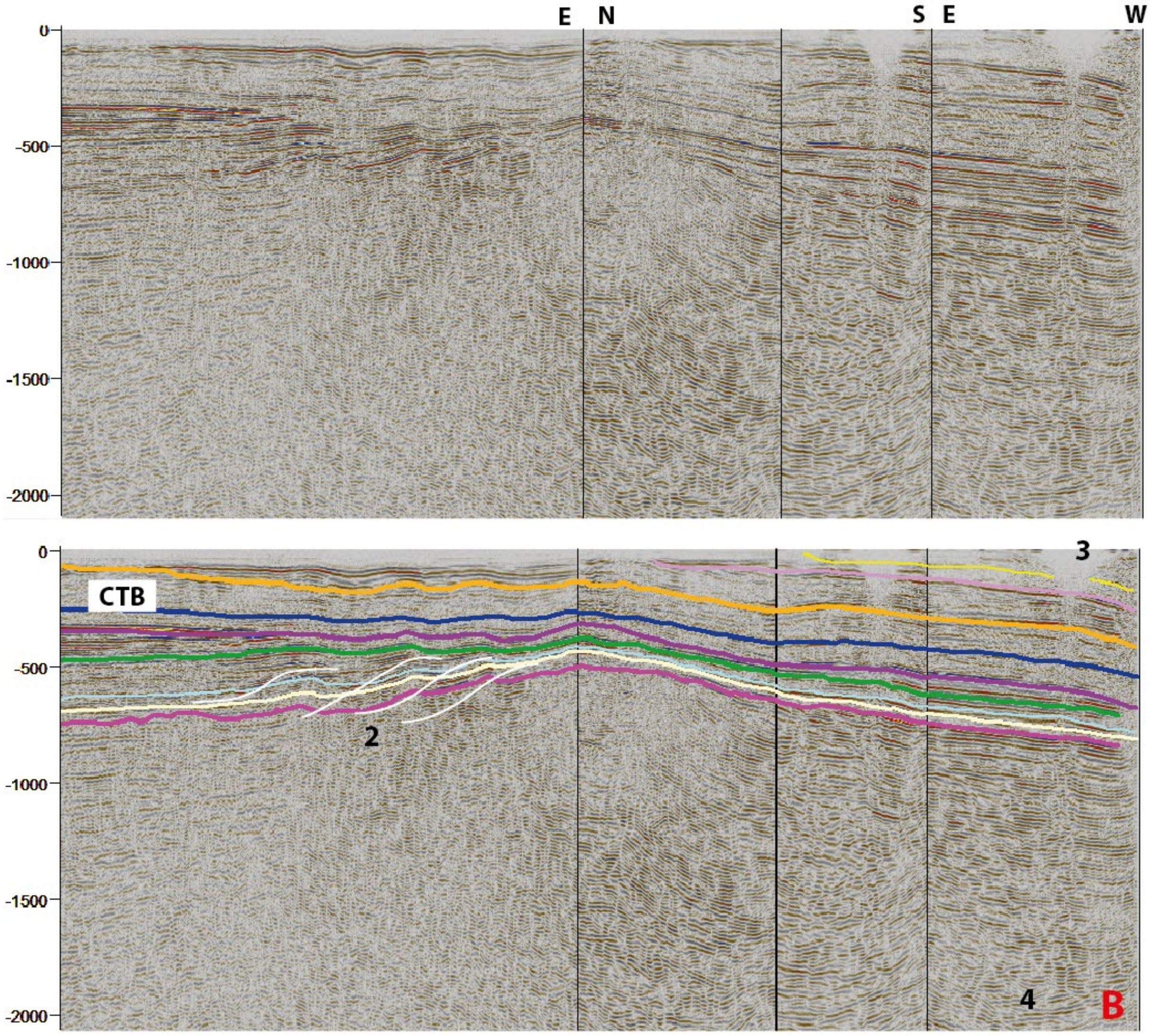


Fig. 3.2. B Section B from composite tie-line. Horizons mark the base of units. Colour-unit allocation and abbreviations are the same as Fig. 3.2A. The profile shows basin stratigraphy overlying basement (4). Note that the lines change direction. (2) Thrust faults cut from the basement to Ebbadalen Formation. (3) Shadows from overlying snow cover.

basin stratigraphy but located much deeper than is expected for the basin. The Adventdalen Group seen as a unit of folded stratigraphy pinching out to the north-east, terminates towards the surface at some point below Vendombreen (Fig. 3.2 B), which is located right between Reindalen and Sassendalen. This coincides with geological boundaries on maps. Crosschecking the interpretation with surface geology gives confidence to the interpretation. The composite line passes the BFZ at the well and offshore in the northern most section (Fig. 3.2 C). At the well, the BFZ appears to create a compression structure with folded monoclines overlying a basement high. Overlying thrust faults are likely a later development, not associated with the deep seated faults (Ba? and 6, Fig. 3.2 A). This deep seated fault reflect very poorly and there is high uncertainty to the interpretation, but it seems that the BFZ consists of at least one main fault (possibly Ba) and two horst bound faults (6, Fig. 3.2 A) which cut through Minkinfjellet Formation. In the north, the BFZ consists of a normal east dipping fault (Od, Fig. 3.2.C) displacing basin stratigraphy against basement and a steep, possibly reverse fault (Ba?, Fig. 3.2.C). The basin thickens towards the fault, indicating syn-rift sedimentation of Hultberget, Ebbadalen and Minkinfjellet formations.

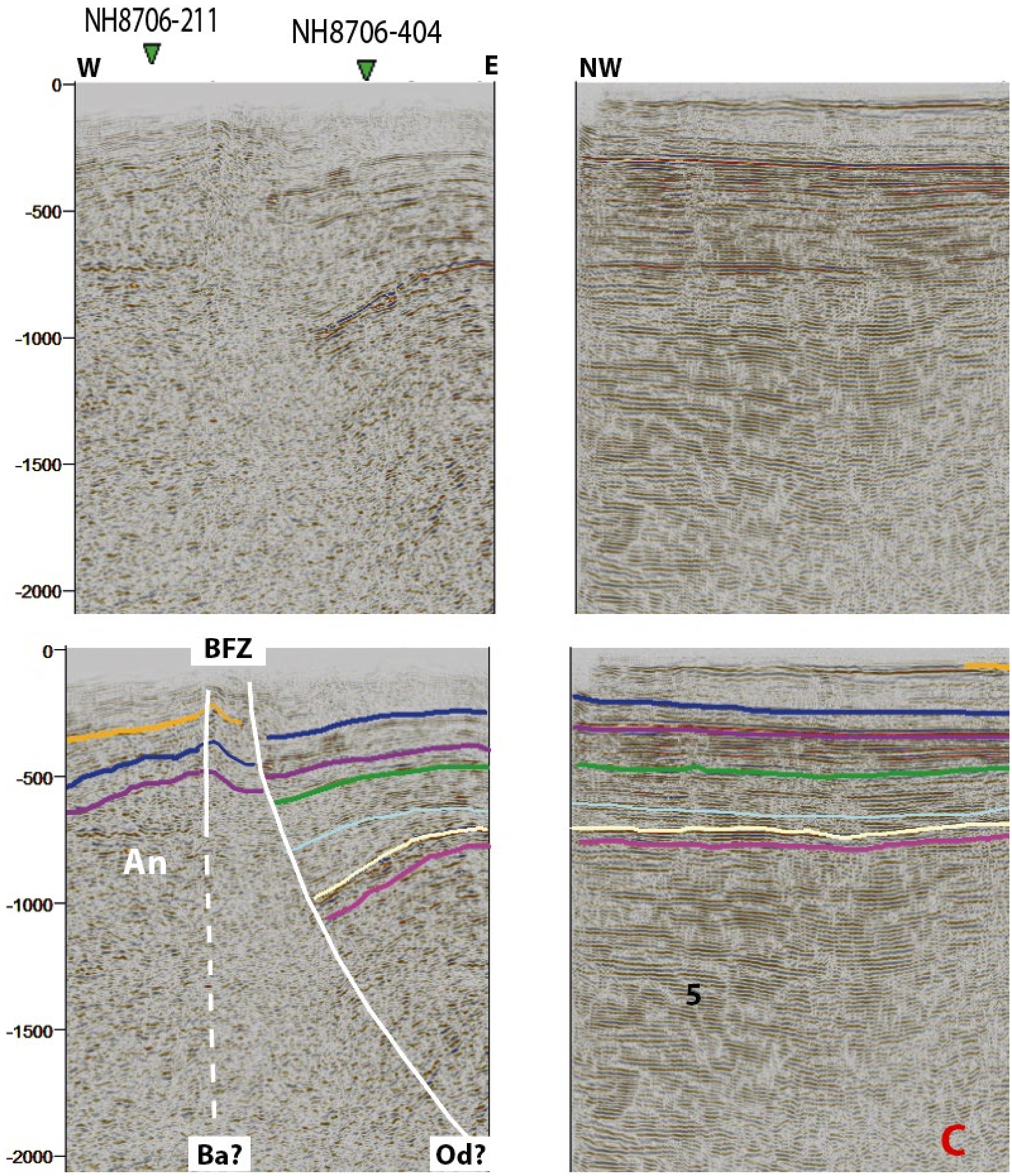


Fig. 3.2 C Section C from composite tie-line. Horizons mark the base of units. Colour-unit allocation and abbreviations are the same as Fig. 3.2A. Od- Odellfjellet Fault. The segment shows the transition from terrestrial (right) to marine (left) seismic lines. Basin stratigraphy (continuation from section B) ends towards a normal fault. Hultberget, Ebbadalen and Minkinfjellet thicken towards the fault. West of the fault, the stratigraphy is from Kapp Starostin to Wordiekammen overlying Andrée Land Group (An). A steep reverse (?) fault is traced west of the normal fault. Green arrows at top of section show location and number of crossing lines. High anomaly areas (5) appear towards the NW end of the terrestrial line.

3.3. Marine Seismics (interpretation)

3.3.1. Sassenfjorden

3.3.1.1. NH8706-404

Line NH8706-404 has a total length of 10 km (Fig. 3.3). It is a part of the tie-line, the line itself is outside of the study area. The purpose was to trace horizons from the terrestrial tie-line over to the offshore domain via crossing line NH8706-203 and into the study area. The line shows an asymmetric basin stratigraphy with its depocentre and termination towards the BFZ to the west.

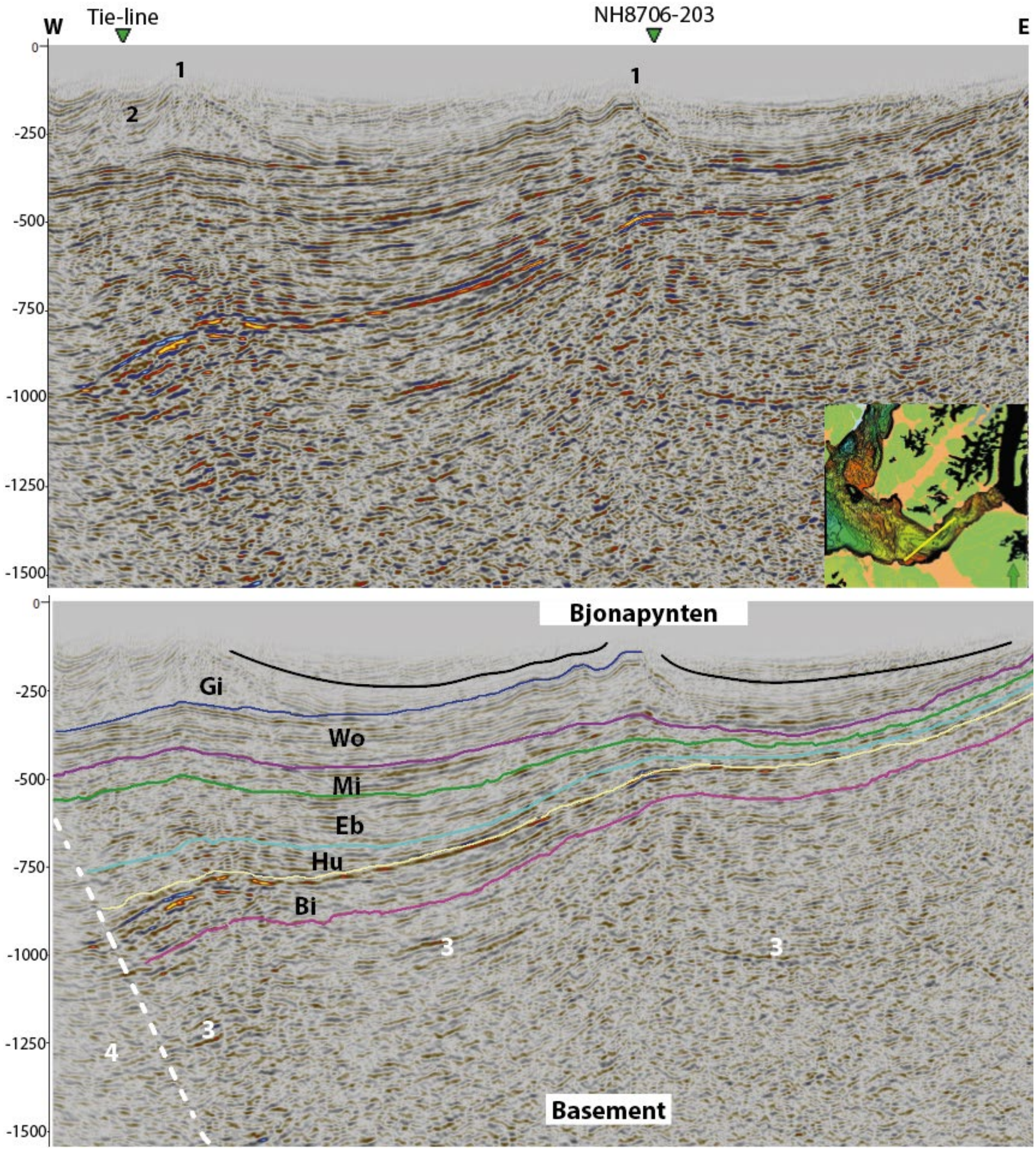


Fig. 3.3 Seismic line NH8706-404. Abbreviations and colours are described in Fig. 3.2. west dipping basin with Carboniferous to early Permian sedimentary rock. Undulations are pull-up effects from the seafloor.1- pull-up, 2 and 3 multiples, 4-fault shadow?

The basin fill is composed of stratigraphic units spanning from Famennian to Artinskian with pre-rift Billefjorden Group to post-rift Gipsdalen Formation. The base of the basin is the Pre-Caledonian Basement, which lies at about 1 s TWT near the interpreted fault. The profile shows an undulating stratigraphy with two peaks (1, Fig. 3.3). This is interpreted as an artefact caused by a pull-up effect from the seafloor. This interpretation is based on direct observation of coastal stratigraphy during fieldwork. The photograph (Fig. 3.4) shows a flat-lying, unfaulted stratigraphy over Bjonapynten where the seismic line shows strong pull-up. The coastal mountainside along the seismic profile lies flat and unfaulted. The assumption is therefore that is much more likely that the subsea stratigraphy also lies flat rather than drastically changing its horizontal style and therefore the undulations are artefacts. First reflectors (at about 175 ms TWT, Fig. 3.3) represent the seafloor. Velocity calculations further support the idea of pull-up at Bjonapynten and Sassendalen. Sediment accumulation (evident at Bjonapynten) and a strong topographic relief are likely causing this distortion of reflectors.

At the top of Gipsdalen Formation (2, Fig 3.3) there are seafloor multiples. In addition, there are weak reflectors (3, Fig. 3.3) under the base of Billefjorden; these are interpreted as multiple reflections. They lie at about 1250 ms TWT in the west. This is an unrealistic depth for the basin stratigraphy at this location. Thickness maps (Dallmann 2016) and velocity profiles indicate a much shallower base. The arrival times for these deep-seated reflectors below the base of Billefjorden group indicate that they can possibly be multiples from Billefjorden Group reflected at Wordiekammen Formation.

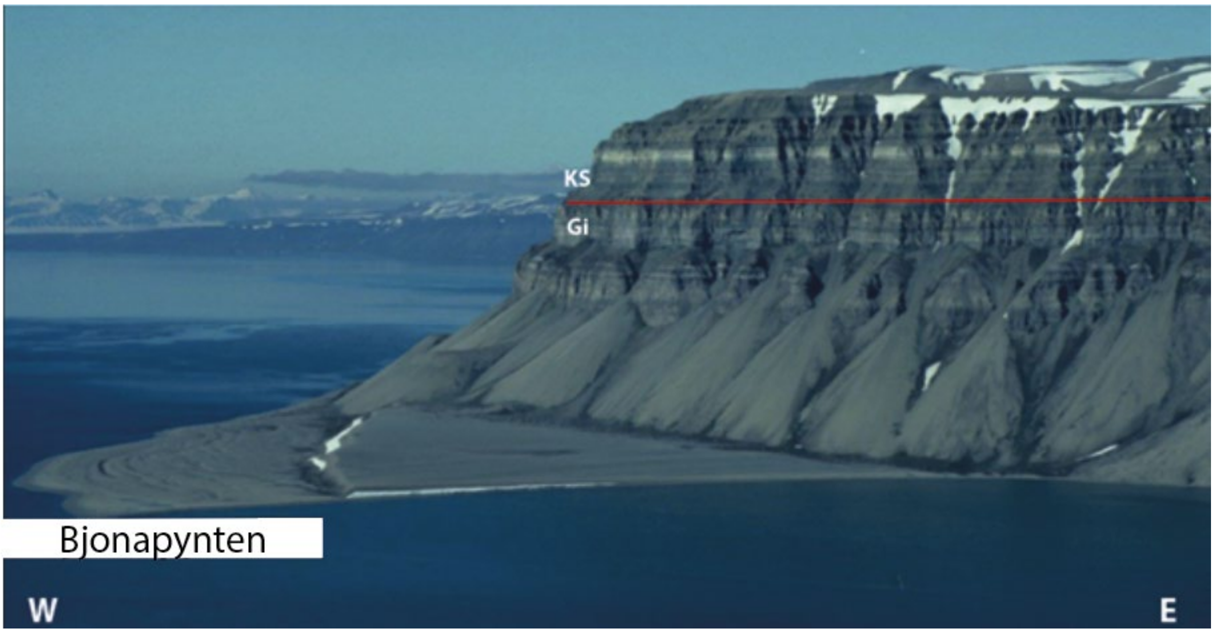


Fig. 3.4 Photograph of Templet and Bjonapynten. The bedding orientation is straight and horizontal.Gi-Gipshuken Formation, KS-Kapp Starostin Formation (Photo: W. Dallmann).

A possible local fault was considered. Located at an angle to the Balliolbreen Fault it is indicated with a dashed white line. In the bathymetric data, there is a steep slope with a SW-NE orientation (down to the NW) parallel to the potential fault, which could either be a surface expression of the fault or sediment accumulation from Sassendalen. All things considered it is more likely an artefact than a fault. The seismic reflectors are unclear and the overall issues with the data quality leave room for doubt. In addition, there are no other faults with similar orientation mapped in the area nor is there evidence for displacement of the stratigraphy on local maps. However, the Interrupted stratigraphy "disappears" (4, Fig. 3.3) west of the indicated fault, which may be a fault shadow on the footwall side.

1.3.1.2. NH8706-203

Seismic line NH8706-203 runs 26.8 km in a SE-NW direction along the coast from Templet to Gipshuken and across the mouth of Billefjorden towards Rundodden (Fig. 3.5). The SE extent of the line shows a profile of the Carboniferous Billefjorden Trough. Geological maps show that Gipshuken Formation surfaces along Templet (Dallmann et al. 2004b). In the seismic image, the reflector marked as the base of the unit is undulating and creating a synform. Photographs of Templet show a flat lying stratigraphy (Fig. 3.4). These land observations suggest that a synform boundary to underlying Wordiekammen Formation is unrealistic and a caused by pull-up from the seafloor surface.

The entire seismic profile is affected by multiple reflections from both the seafloor and dolerite intrusions. The multiples cut the stratigraphic reflections (1, Fig. 3.5) making it difficult to trace reflectors continuously and delineate the basin stratigraphy correctly. This problem is most prominent from the seafloor down to -600 ms TWT. As a result, the thickness of Wordiekammen Formation is exaggerated in the interpretation.

Overall, the stratigraphy shows a pre-rift Billefjorden Group underlying syn-rift units Hultberget, Ebbadalen a Minkinfjellet formations that appear to thicken towards the fault. The basin terminates to a steep east dipping normal fault (Od, Fig. 3.5) which may be a southward continuation of Odellfjellet Fault. A reverse fault (Ba, Fig. 3.5) runs west of the normal fault. These faults lie along a line offshore from the Gipshuken reverse faults. The Gipshuken fault array lies along the strike of BFZ and is likely a surface expression of offshore faults. They are characterised by east dipping steep reverse faults. Reverse kinematic indicators are also observed at the top reflectors of the seismic line (2, Fig. 3.5), but they are diffuse and may be altered by noise. There are no kinematic indicators deeper in the seismic image (such as relative displacement of stratigraphic boundaries). The notion of reverse movement is also based on similarities in configuration of the BFZ north of Gipshuken (reverse Balliolbreen Fault west of extensional Odellfjellet Fault).

If the assumption is correct, the fault may be either be the Balliolbreen Fault or a new fault strand with similar timing and movement. Gipshuken reverse faults and the seismic image suggest there is reverse movement above Carboniferous normal faults. However, as there are no reflectors to mark the base of the unit, the section remains undefined.

The high amplitude reflectors at the top centre of the profile are dolerite intrusions. Extensive intrusions are exposed at the coast across Anservika, Gipshuksletta and Gipshukodden. The Gåsøyane Islands are entirely composed of dolerite. The intrusions in the seismic image and the dolerite onshore are likely one unit. Extrapolating the geology from maps to the offshore area indicate that Wordiekammen Formation is the topmost unit in this area. However, its base along with underlying stratigraphy remains undefined in the interpretation since the dolerite is creating a shadow on all underlying structures. The two reflectors (3, Fig. 3.5) underlying the dolerite are interpreted to be multiples from the intrusive sills. A small pull up structure (4, Fig. 3.5) is located midway across the sill. It is not clear from the seismic weather is a small fault or a topographic artefact. Other lines in the area show similar features indicating that this may be local reverse faults which are reflected in the seismics. They may be associated with Palaeogene contraction.

A section of the Central Tertiary Basin lies at the NW end of the profile. Stratigraphy has a westerly dip and spans form Sassendalen to Devonian Andrée Land Group. The basement cannot be defined NW of the Gipshuken reverse faults. The top of the basement is likely below the depth of resolution in this profile. The eastward extent of the CTB terminates towards steep NE dipping thrust faults (5, Fig. 3.5). The faults cut the top of Permian Kapp Starostin Formation and the dolerite intrusions and are therefore formed after both the deposition of the strata and intrusion of the dolerite.

1.3.1.3. NH8706-204

Line NH8706-204 shows a W-E 16.5 km profile (Fig. 3.6). A large part of the image is chaotic. There are few reflectors and the ones that show are masked by multiples and misleading due to pull-up and push down from the seafloor. The main features identified in this section include the Billefjorden Trough terminating towards deep-seated faults. It is well documented that the basin formed towards Carboniferous extensional faults (Bælum & Braathen 2012; Harland et al. 1974; Manby et al. 1994).

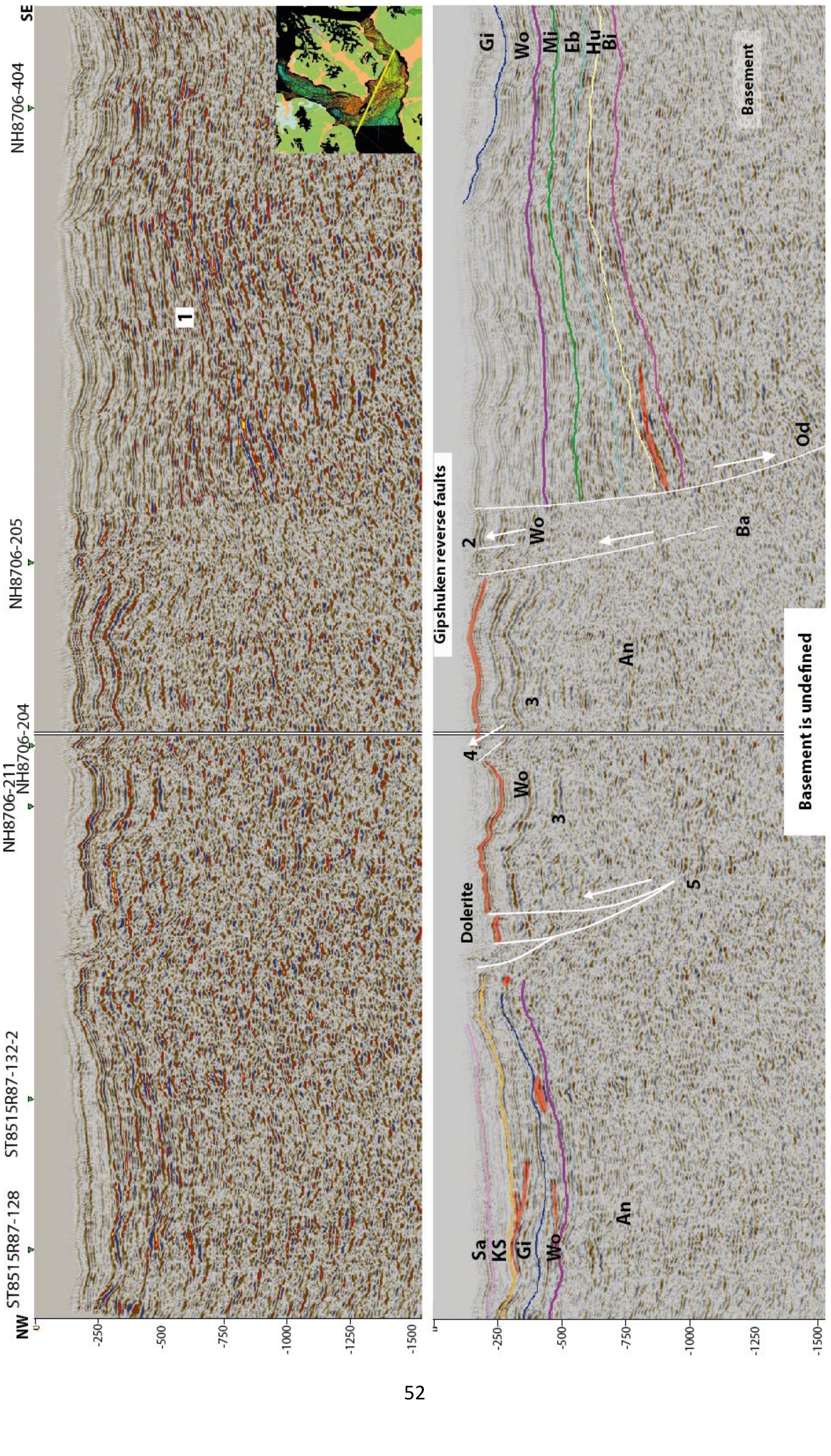

NW
SE
ST8515R87-128
ST8515R87-132-2
NH8706-211
NH8706-204
NH8706-205
NH8706-404
1
0
-250
-500
-750
-1000
-1250
-1500
Sa
KS
Gi
Wo
An
Dolerite
5
3
Wo
4
3
An
Gipshuken reverse faults
2
Wo
Ba
Od
Gi
Wo
Mi
Eb
Hu
Bi
Basement
Basement is undefined

Fig. 3.5 Seismic line NH8706-203 with profile along Templet and Gipshuken. SE basin terminates towards normal fault (Od?). Further NW is a reverse fault (Ba?) towards An with overlying dolerite (red areas). 1- multiples interacting with reflectors, 2-4 faults. The NW segment shows Sassendalen and older units ending towards a reverse fault (5). For abbreviations, see Fig. 3.2.

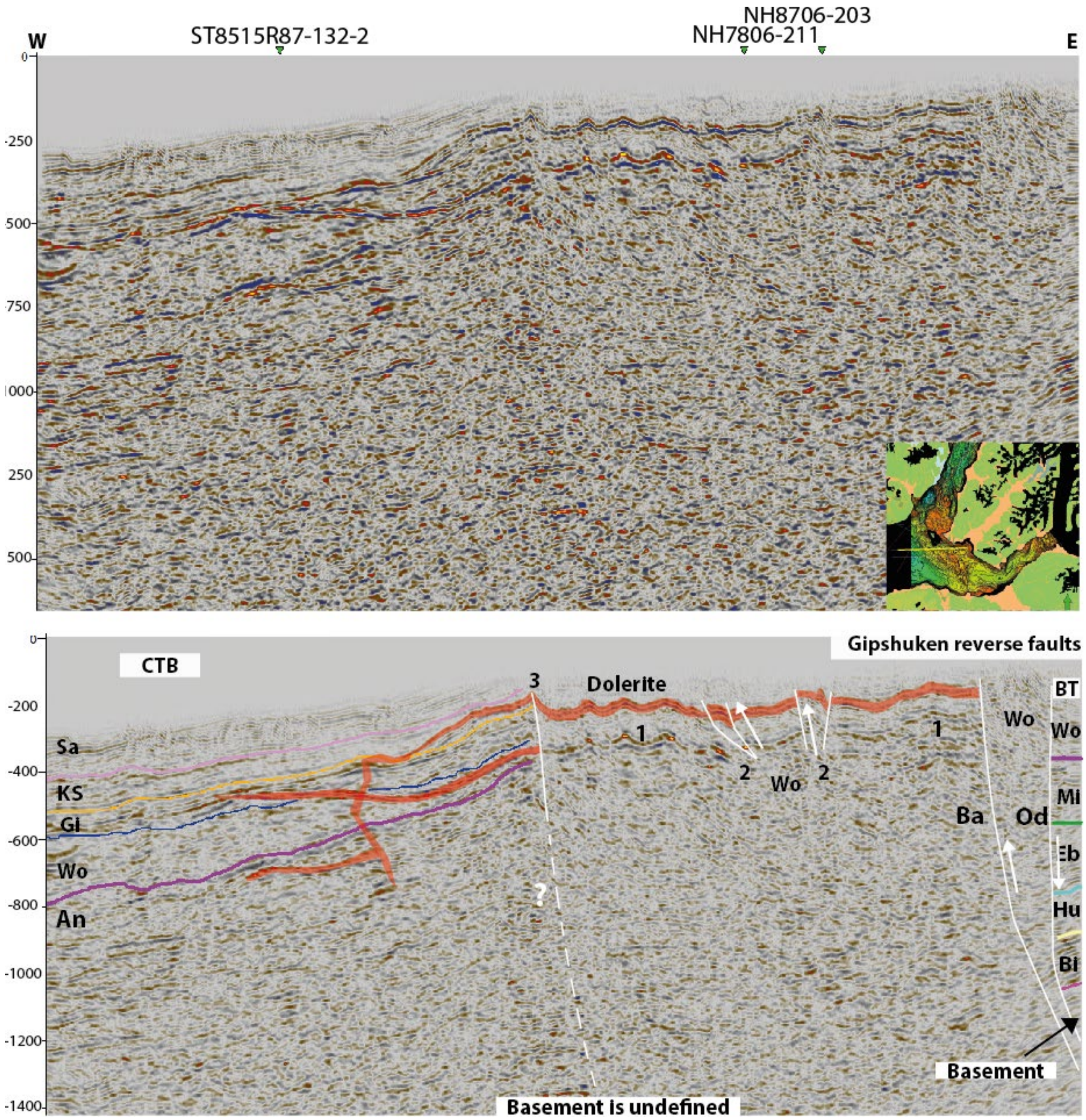


Fig. 3.6 Line NH8706-204. For abbreviations, see Fig. 3.2. From east to west: basin stratigraphy against normal fault (Od?) then reverse fault (Ba?), basement high with overlying dolerite intrusion, stratigraphy under dolerite is undefined. 1- multiples, 2- faults. Ridge (3) is a possible fault. Dolerite intrusions are reflected in stratigraphy to west.

Suggesting that the easternmost fault in the image (Od, Fig. 3.6) formed as a normal fault towards BT and therefore is likely the Odellfjellet Fault. Adjacent to the normal fault is another fault (Ba, Fig. 3.6). It appears as a vertical change in contrast in the section. Based on the same criteria as described in line NH8706-203 it is interpreted to be the Balliolbreen Fault. The two faults closest to the BT are offshore to the Gipshuken reverse faults and are interpreted to be the offshore continuation of this fault array.

Dolerite intrusions cut the stratigraphic profile up to the Kapp Starostin Formation. In this section, the intrusions appear as both dikes, sills and diagonal ramps across the stratigraphy. Extrapolation from maps suggest that Wordiekammen Formation is at the top of this section, but its lower boundary is not reflected in the seismic image. The dolerite at the top centre of the profile is masking underlying reflectors and therefore the interpretation is undefined. Multiple reflections of the intrusions (1, Fig. 3.6) appear at about 300 ms TWT. The dolerite is interpreted as an offshore continuation of the dolerite belonging to the Diabasodden Suite exposed at Gipshuken. The strong undulations are probably pull-up and push down. There are no tight folds of this type anywhere in the area, neither in the sedimentary rocks nor in the dolerite. So, it is unlikely they suddenly appear locally and especially in more competent rock than for example the soft schists and carbonates of the sedimentary basins.
In addition, it is apparent that the seismic data do have a lot of artefacts in the images. This specific artefact appears in other sections as well.

Shallow thrust faults (2, Fig. 3.6) dipping E-NE cut the dolerite and the Wordiekammen Formation. These faults are associated with Palaeogene contraction. It is possible that the faults continue deeper than interpreted, as the dolerite will not only shadow stratigraphic boundaries but also structures like faults. A larger fault (3, Fig. 3.6) reflects at the centre of the image. This structure appears in the other seismic lines from Sassenfjorden (Fig. 3.7, 3.8.) as well and it coincides with a topographic ridge in the bathymetry, suggesting the presence of a NW-SE trending fault. However, the kinematics of the lineament are uncertain. The western extent of the image reflects stratigraphy from Sassendalen to Andrée Land Group. The top of the basement is unknown and lies most probably deeper than the resolution of the seismic can reach. This section of the image shows a part of the CTB.

1.3.1.4. NH8706-205

Line NH8706-205 runs parallel, just south of line NH87106-204. It has a total of 16.9 km along the vertical and resolution to about -1400 ms TWT (Fig. 3.7). To the east, the image reflects Billefjorden Trough bordering a normal and then reverse fault (Ba and Od Fig. 3.7). The interpretation is based on the same criteria as described for line NH8706-204. At the top of the section (1, Fig. 3.7) there are reflections of deformed stratigraphy towards the faults. Noise conceal this area in line NH8706-204. The geometry of the fold bears similarities to the onshore Gipshuken reverse faults. Unfortunately, towards the eastern corner the image loses resolution and it´s difficult to pinpoint whether the folding is restricted to west of the normal fault or if it overprints some of the normal movement. If so, this would indicate reverse overprint on a normal fault.

Some multiples (2, Fig. 3.7) appear in this image. Dolerite intrusions overlying Wordiekammen Formation at the top centre of the profile hide underlying reflectors. Lower boundaries are therefore left undefined. Further to the west, the seismic profile depicts basin stratigraphy disrupted by dolerite. This is a part of the CTB. The dolerite ramp diagonally through the stratigraphy and spreads into sills. Very much alike the dolerite intrusions in NH8706-204. A narrow vertical line (3, Fig. 3.7) crosses the entire reflected profile, this is an artefact called jitter.

An E-NE dipping thrust fault (4, Fig. 3.7) cut form the seafloor down to Andrée Land Group. It is possible it continues further than what can be seen in the image due to loss of resolution. The fault follows the same trend as the trust faults of NH876-203 and 204. Another similarity between the Sassenfjorden seismic lines is the fault structure (4, Fig. 3.7) which separates basin stratigraphy to the west from Andrée Land Group to the east. Once more, the relative movement of the fault is difficult to determine.

1.3.1.5. NH8706-211

Seismic line NH8706-211+211A is a 21.6 km profile (Fig. 3.8). To the south, it reveals Lower Triassic to Carboniferous stratigraphic units overlying Andrée Land Group in Sassenfjorden. The uppermost unit Sassendalen Group is mapped along the coast west of Sassendalen. The coastal stratigraphy hosts intrusive sills, which locally cut the stratigraphy by ramps. Further north, the seismic line crosses between Gipshuken and Gåsøyane where dolerite intrusions are present at the top of the section. The dolerite appears as a strong anomaly at the top of the sea floor. These strong reflectors are frequently occurring around Gåsøyane. The subsurface dolerite is assumed to be part of the same intrusive event as the Gåsøyane and Gipshuken dolerite. Below the dolerite, there are no primary reflectors only a multiple (1, Fig. 3.8) from the dolerite. The intrusion is masking underlying stratigraphic boundaries. The dashed lines show the expected depth of underlying units (3, Fig. 3.8). A jumper section leaves a gap between 211 and 211A (due to inaccessibility for the vessel). Steep reverse (?) faults (2, Fig. 3.8) cut the basin stratigraphy down to Andrée Land Group. North of Gåsøyane the line reflects uplifted Devonian Andrée Land Group at Billefjorden. The black dashed lines indicate internal deformation within the group which is characteristic for the unit. Due to the jumper gap, it is not possible to see the transition from the southern basin stratigraphy and the underlying Devonian but with no other indications, it is assumed that Kapp Starostin Formation eventually thins out to the surface and that Andrée Land Group north and south of the jumper is a continuous unit.

The white dashed line (c, Fig. 3.8) delineates a possible reverse fault. To the north, the footwall seems to fold onto a flexure towards the fault while the hanging wall bends upwards. Either side of the fault has different internal deformation. The idea of a fault is supported by the presence of onshore faults in the Devonian which are cut by the Carboniferous unconformity. However, the reflectors are vague and therefore the interpretation of a fault has uncertainty and is up for debate. Together with lines NH8706-203, 204 and 205, the four profiles show many similarities that are summarised and interpreted in the Discussion.

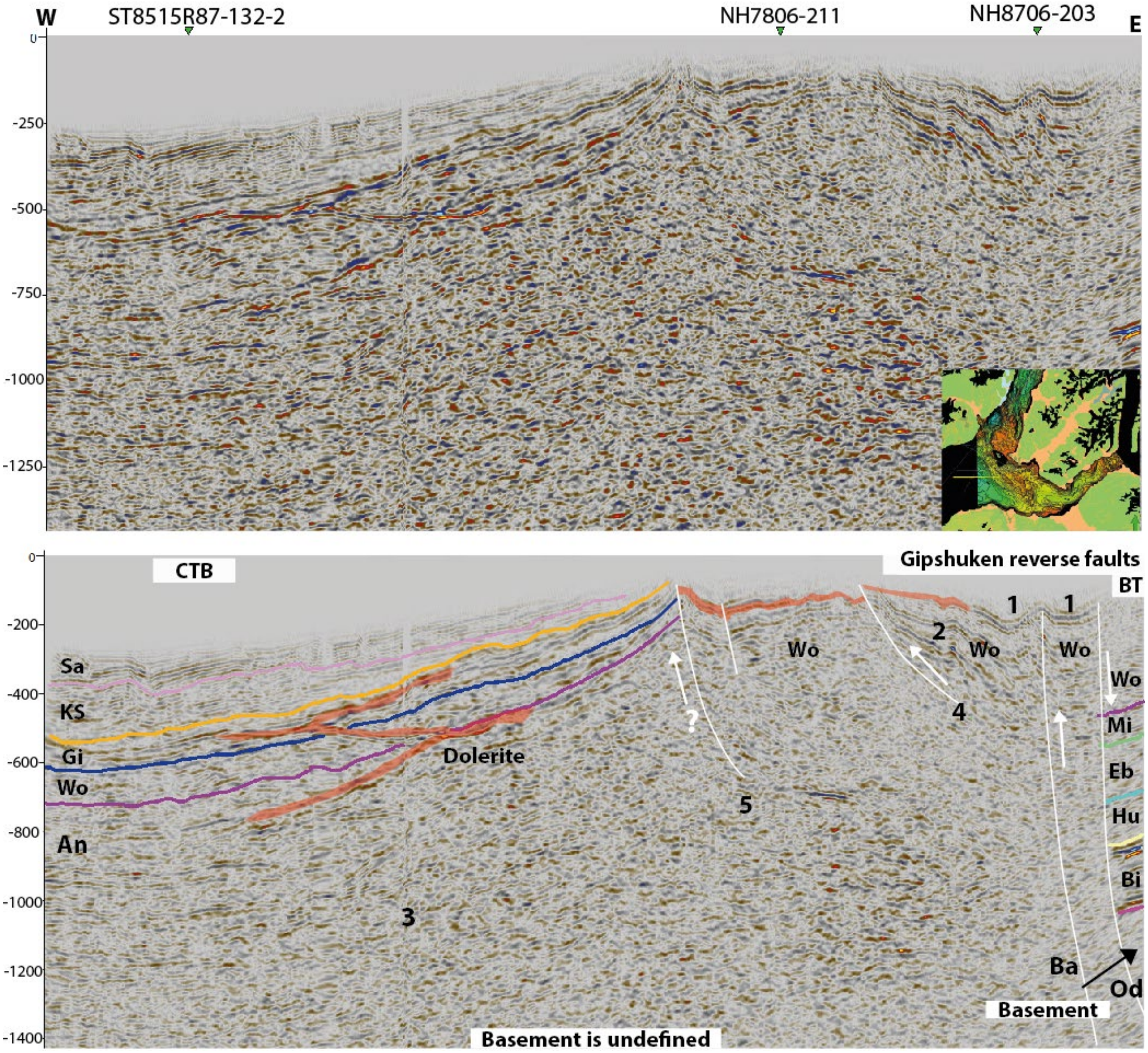


Fig. 3.7 Seismic line NH8706-205. For abbreviations, see Fig. 3.2. Similar profile as line 204: basin stratigraphy against normal fault (Od?) in east. Then reverse fault (Ba?), basement high with overlying dolerite intrusion, stratigraphy under dolerite is undefined. A number of north-east dipping reverse faults cut dolerite and downwards. Dolerite intrusions cut stratigraphy to west. 1- deformation structure, 2- multiples, 3- jitter, 4 and 5- faults?

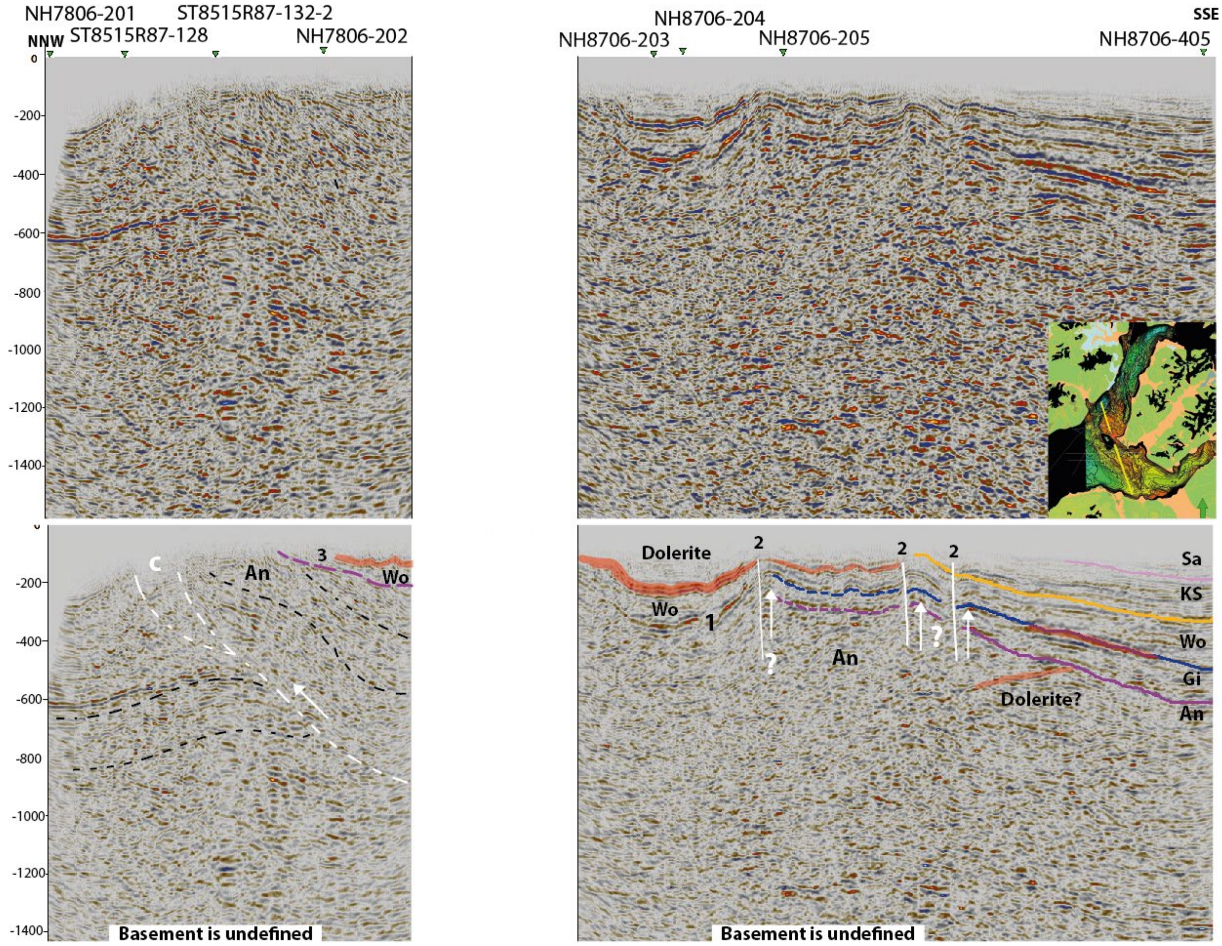


Fig. 3.8 Seismic line NH8706-211. For abbreviations, see Fig. 3.2. Profile across Sassenfjorden and Billefjorden showing Carboniferous to Triassic sedimentary units overlying Andrée Land Group. The top of the basement is undefined. Steep faults (2) cut across down to Andrée Land Group. Dolerite intrusions lie at the seafloor outside Gåsøyane. To the NNW Andrée Land Group seems folded and faulted (c).1-multiple, 2-faults, 3-suggested boundary, c-possible fault.

3.3.2. Billefjorden

Seismic line NH8706-402 was considered for interpretation. The line runs parallel in inner Billefjorden. However, due to poor quality is omitted from the study.

3.3.2.1. NH8706-202

Line NH8706-202 is of very poor quality. It runs 11.2 km across the mouth if Billefjorden (Fig. 3.9). Most of the line is chaotic and it´s questionable if there are any readable reflectors from stratigraphic

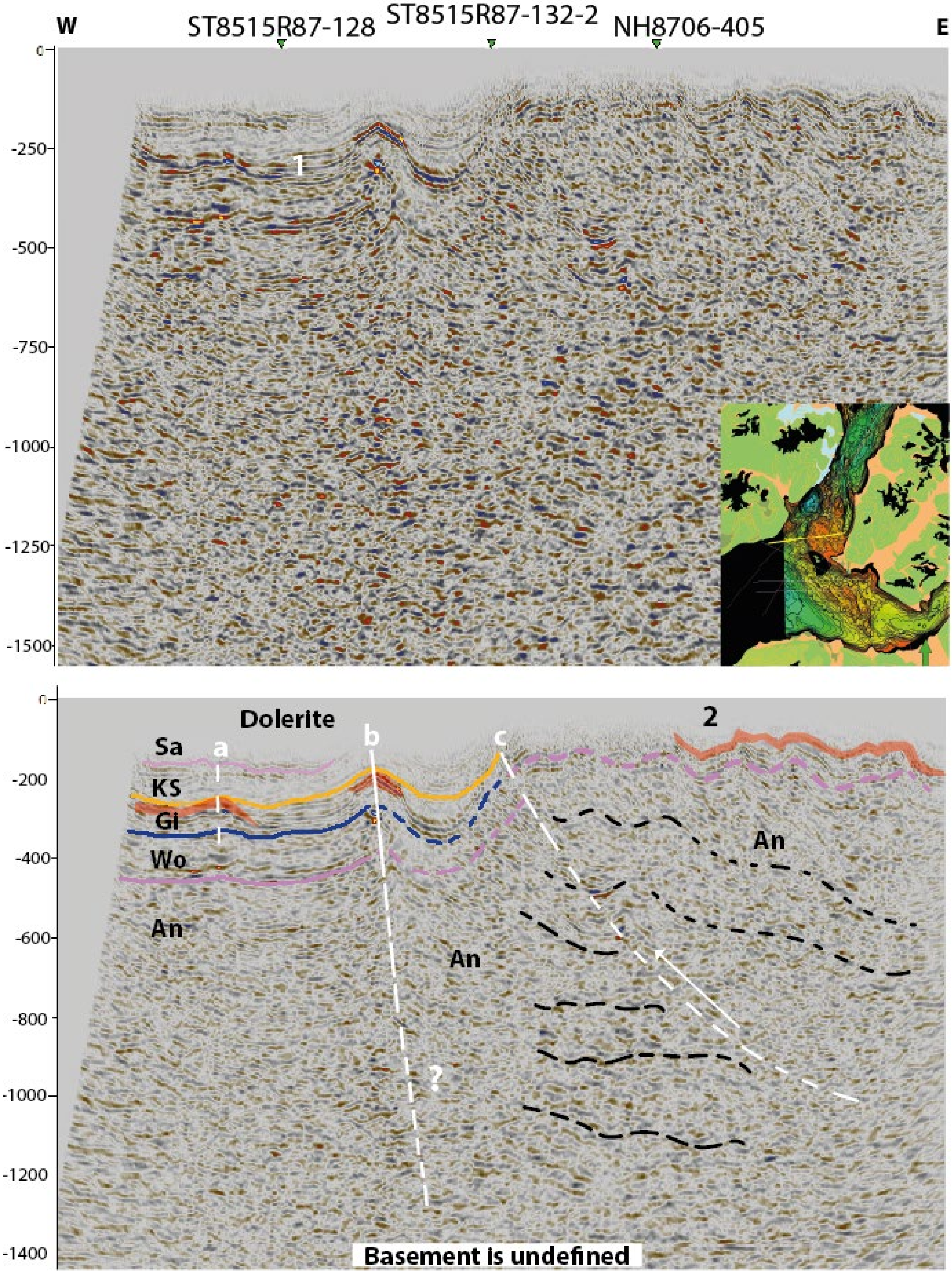


Fig. 3.9 Seismic line NH8706-202. For abbreviations, see Fig. 3.2. An with suggested fold (a) and faults (b and c) overlain by Carboniferous stratigraphy. 2- undulations due to pull-up and push-down.

boundaries. From the middle of the image and westwards there are some strong reflectors (1, Fig. 3.9) that may be multiples from dolerite or seafloor rather than primary reflectors from stratigraphic boundaries. They do not show likeness to the seismic reflections of the stratigraphic units as they appear in other better quality profiles. Furthermore, the arrival times and spacing are indications that they might be multiple reflections of the seafloor. The strong anomaly of the reflectors suggests they may be intrusive sills. This idea is supported by the presence of dolerite intrusions in younger units onshore north to north-west of the seismic profile.

The stratigraphic division and horizons are placed based entirely on extrapolation from the coast (using thickness and velocity calculations) and by tying the stratigraphy from crossing lines ST8515R87-128 and 132-2. The miss-tie between the surveys makes this method highly inaccurate. There is a gentle fold (a, Fig. 3.9) at the sea floor that appears along the strike of the lineament described across Sassenfjorden suggesting is continues to the NW (Fig. 3.10). The horizons are traced as dashed lines east of the westernmost fault due to uncertainty. Any reflections in this segment are too distorted by pull-up to determine if the stratigraphy is moving up or down. Therefore, it is very unclear to determine the relative movement along fault (b, Fig. 3.9). It´s even questionable if it is a fault that is reflected or if the amplitudes are distortions. The contrast between geological structures in this seismic image is very low. If this is a fault, based on a topographic slope evident in the bathymetry, it has a NW-SE strike. The suggested fault is not confirmed on maps. However, it can be traced to a topographic ridge that extends from Billefjorden across Sassenfjorden.

The top of the seafloor is strongly undulating as a result of pull-up. The top of Andrée Land Group (2, Fig. 3.9) appears tightly folded and could easily be interpreted as deformation connected to the reverse fault (c, Fig. 3.9) which is suggested in the interpreted profile (similar to fault c in NH8706-211). However, this is unlikely as no such tight folds are found anywhere in the area. The internal deformations in Andrée Land Group are typically larger, more open structures (black dashed line). The undulations (2, Fig. 3.9) closely match the seafloor topography as seen in the bathymetry.

3.3.2.2. NH8706-201

Line NH8706-201 is another example of poor data quality where the interpretation is based on seafloor bathymetry and onshore geology rather than reflections in the seismic image. The image shows a 10.8 km profile diagonal to Billefjorden and the BFZ (Fig. 3.11). The only clear reflector (1, Fig. 3.11) shows a strong anomaly that has the same trend as the seafloor topography. Locally the anomaly seems to show multiple reflections.

The dramatic peaks and down warping is caused by pull-up and push-down from the topography. From map observations, it seems that the block between fault Gr and Ba (Fig. 1.7) should either begin with a thin layer of Billefjorden Group or Andrée Land Group. The close up in Fig. 1.7 B shows that Billefjorden Group is present at the coast between Gipshuken reverse faults, at the south end of the seismic line. Meanwhile the same maps show Devonian Andrée Land Group at the coast north of the line.

Thus, somewhere along the line the top of the seafloor transitions from Billefjorden Group to underlying Andrée Land Group. The strong reflectors can be explained as a strong contrasting reflection between loose sediment and a thin layer of Billefjorden Group to Andrée Land Group and the apparent thickness above the reflector to be distorted by push-down. It could also be reflection of a high contrast layer within in Andrée Land Group, a dolerite intrusion or even the top of a basement horst. Unfortunately, the poor image quality, lack of a nearby borehole and accurate velocity survey it's difficult to narrow the interpretation. There are no good criteria to make a decisive interpretation. However, all four seismic profiles that cross this area show a strong reflection with similar appearance. This is a good indication that there really is a strong contracting surface, which generates a strong anomaly and not an artefact. This is especially apparent in line ST8515R87-128 and 132-2. The anomaly is discontinuous (2, Fig. 3.11) which is interpreted as short, local thrust faults. The stratigraphic horizons at the NE corner of the image are drawn based on the geology at Tyrrellfjellet and isopach

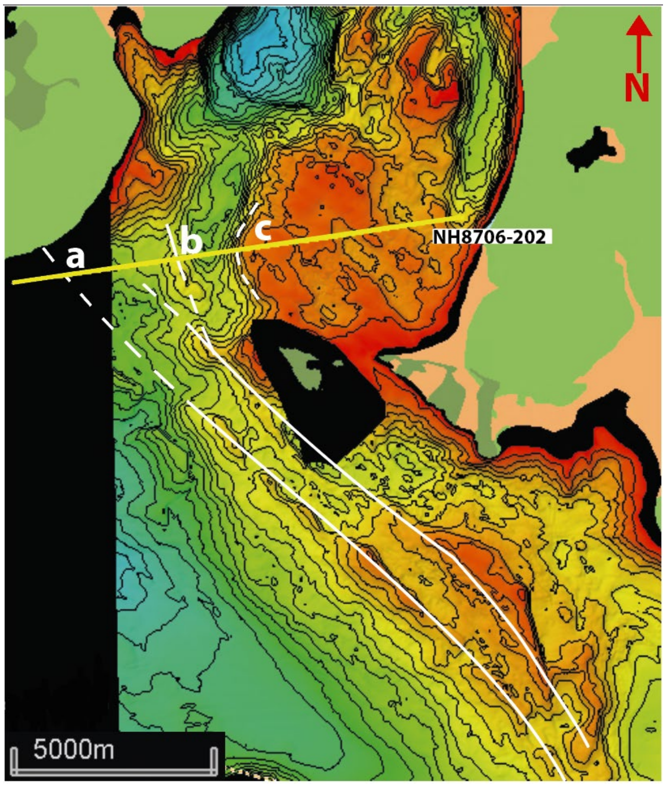


Fig. 3.10 part of Bathymetric map with seismic line NH8706-202. Suggested connection to lineaments in bathymetry and seismic line (a, b and c). (For bathymetry colour legend see fig. 3.15)

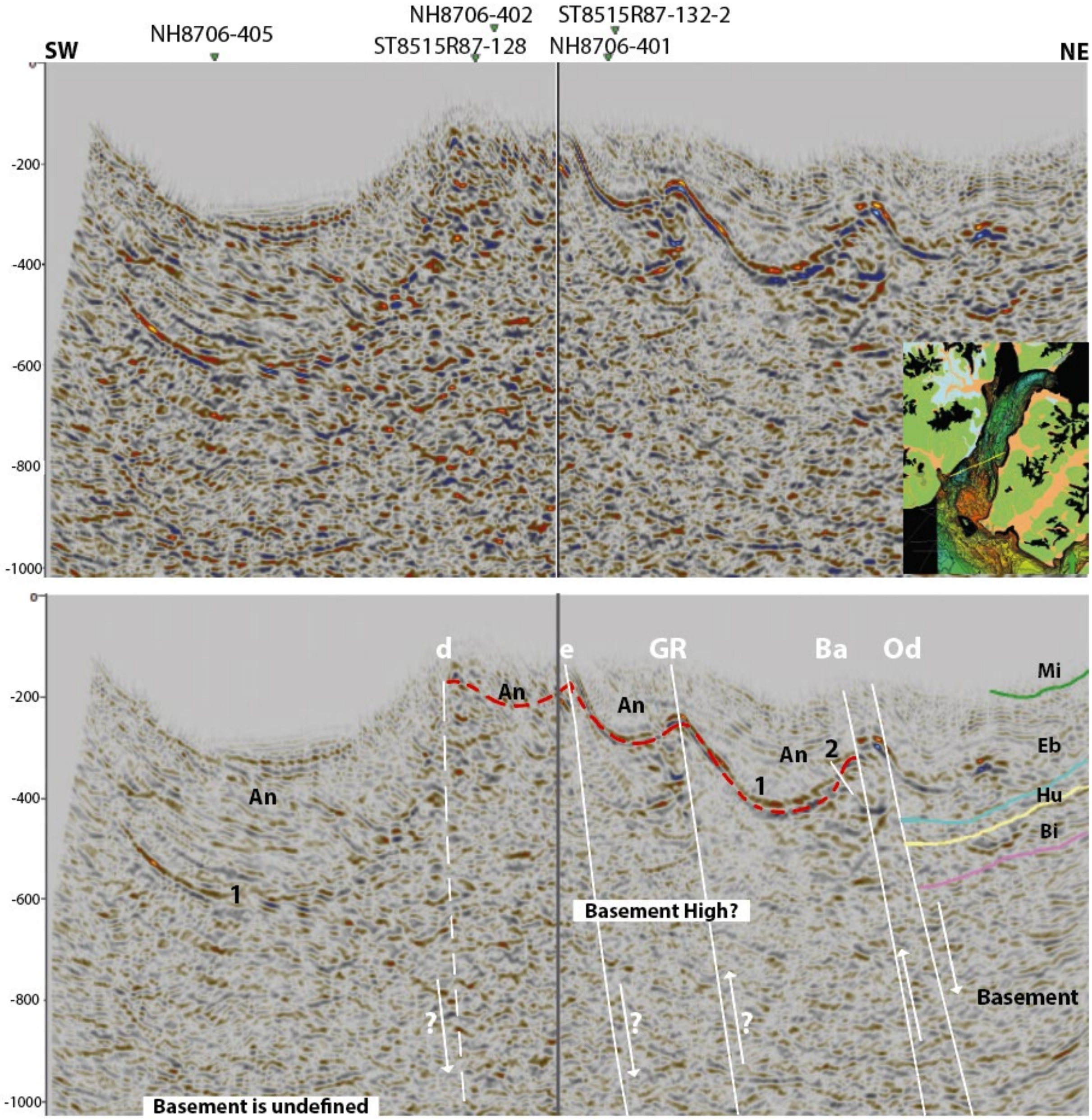


Fig. 3.11 Seismic line NH8706-201. For abbreviations, see Fig. 3.2. Across the centre of Billefjorden, the line shows basement blocks and Ba and Od towards the Billefjorden Trough to the north-east. 1- anomaly and possible base of An, 2-small faults.

maps as well as accounting for water depth (Dallmann 2016; Dallmann et sl. 2004b). They indicate a basin stratigraphy dipping towards a steep east-dipping fault (Od, Fig. 3.11). The basin is part of the Billefjorden Trough. In the BT Ebbadalen Formation is a syn-rift unit and therefore it is traced thickening towards the fault. Underlying early-rift Hultberget Formation is drawn slightly thickening towards the fault while pre-rift Billefjorden Group has uniform thickness. The problems with this type of interpretation method are discussed in section 4.

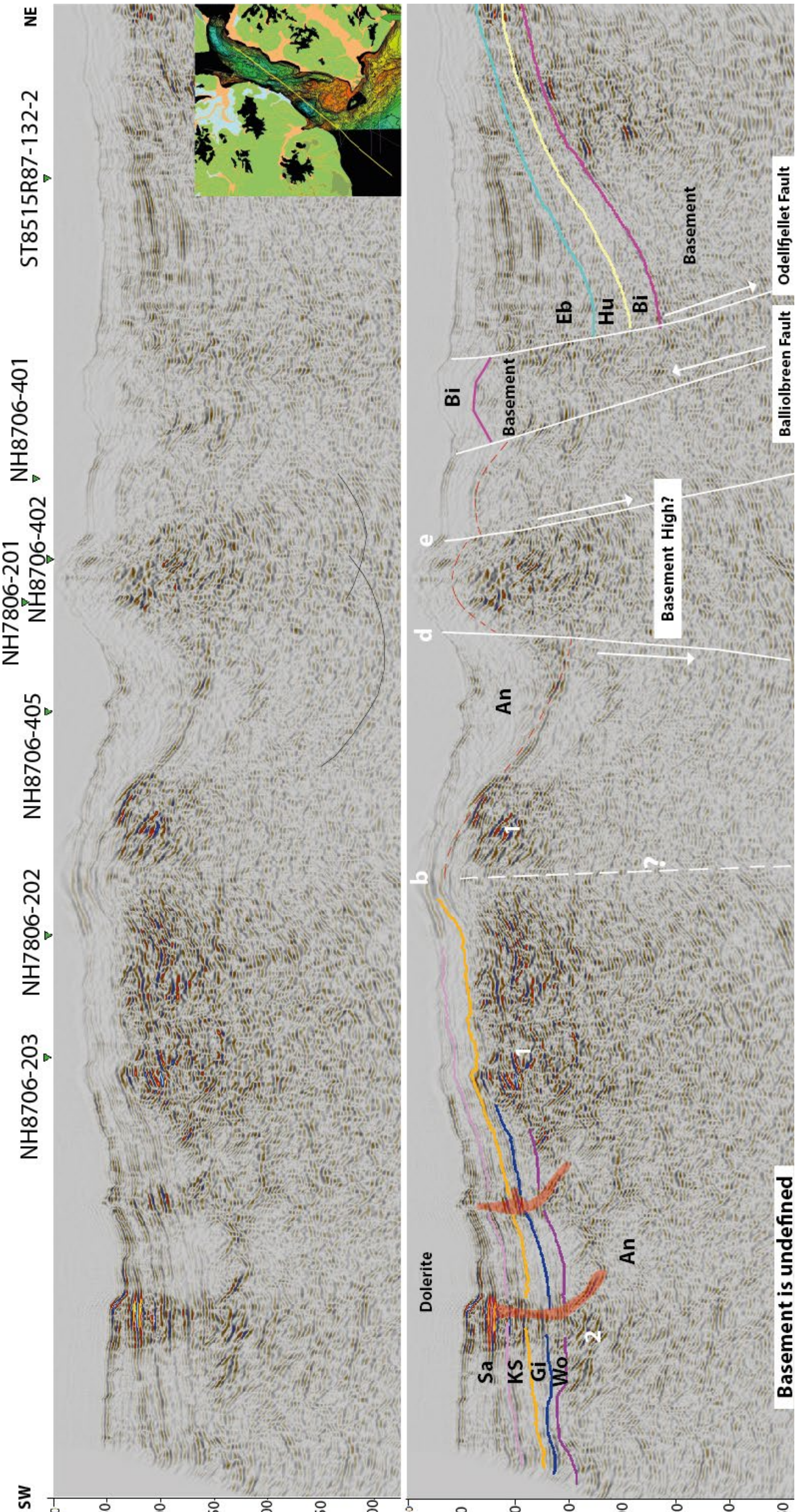
South-west of the basin the geology is dominated by Andrée Land Group, which is cut by a number of faults. The five seismic lines and bathymetry are combined into a regional interpretation of lineaments across Billefjorden (section 3.4) At the base of Feyling-Hanssenfjellet (Fig. 1.7) Devonian rocks outcrop at the coast which mean that from the seafloor and down there is Andrée Land Group overlying basement rock (at unknown depth). A big topographic depression just of the coast of Skansen might be a graben towards a fault (d, Fig. 3.11). If so, the block between faults d and e could be a basement horst. These faults and basement high would precede the deposition of Carboniferous stratigraphic units since they do not cut Gipsdalen Group at Skansen. However, Balliolbreen Fault extends onshore in Devonian rock and displaces Wordiekammen and Ebbadalen formations against Andrée Land Group at Yggdrasilkampen.

3.3.2.3. ST8515R87-128 & 132-2

ST8515R87-128 (Fig. 3.12) and ST8515R87-132-2 (Fig. 3.13) are two out of three lines, which run with the length of Billefjorden. From the north-east to the south-west they cross and reflect profiles from Billefjorden Trough, fault bound basement highs and Early Triassic to Carboniferous basin stratigraphy overlying Devonian rocks. With 35,4 km in length, line NH8706-128 is the longest marine profile of the survey. Line ST8515R87-132-2 is 33,7 km long.

The seismic lines have weak primary reflectors, which are partially overprinted by artefacts but also distorted by poor migration and seafloor pull-up and push-down. At 1000 ms TWT and downwards the reflectors are distorted by a parabolic curvature (black lines) across the profile. This is attributed to poor migration and loss of resolution. The lower boundaries of Billefjorden Group, Hultberget and Ebbadalen formations east of Odellfjellet Fault, are calculated from thickness maps and geological boundaries. In addition, thickening towards the fault is based on the same criteria as described for line NH8706-201.

South-west of Odellfjellet Fault is the reverse Balliolbreen Fault and a number of fault-bound basement highs. The relative movement of faults is difficult to establish from the seismic image alone. The movement directions that are implied in the interpretation are based on the type of faults extending onshore, topography, strong reflectors in the seismic image and comparison to crossing lines. For example, fault “e” (Fig. 3.12 and 3.13) lies offshore to a fault with unknown kinematics at Narveneset. All three lines NH8706-401, ST8515R87-128 and 132-2 show a displacement down to the NE that coincides with a bathymetric ridge. South of fault e (Fig. 3.12 and 3.13) a similar relation to an onshore fault and topographic high is seen. In the seismics, this fault (d, Fig. 3.12 and 3.13) seems to indicate a down to the SW. By combining all of the observations it is understood that (d) and (e) may be the two



SW
NE
NH8706-203
NH7806-202
NH8706-405
NH7806-201
NH8706-402
NH8706-401
ST8515R87-132-2
Basement is undefined
Dolerite
Sa
KS
Gi
Wo
An
Basement High?
Bi
Basement
Eb
Hu
Balliolbreen Fault
Odellfjellet Fault

Fig. 3.12 Seismic line ST8515R87-128. For abbreviations, see Fig. 3.2. Section along Billefjorden. CTB stratigraphy to the south-west. Faulted (b, d and e) basement blocks lie in the centre of the fjord and the BT to the north-east. 1- strong anomaly possibly indicating basement rock, 2- dolerite intrusion.

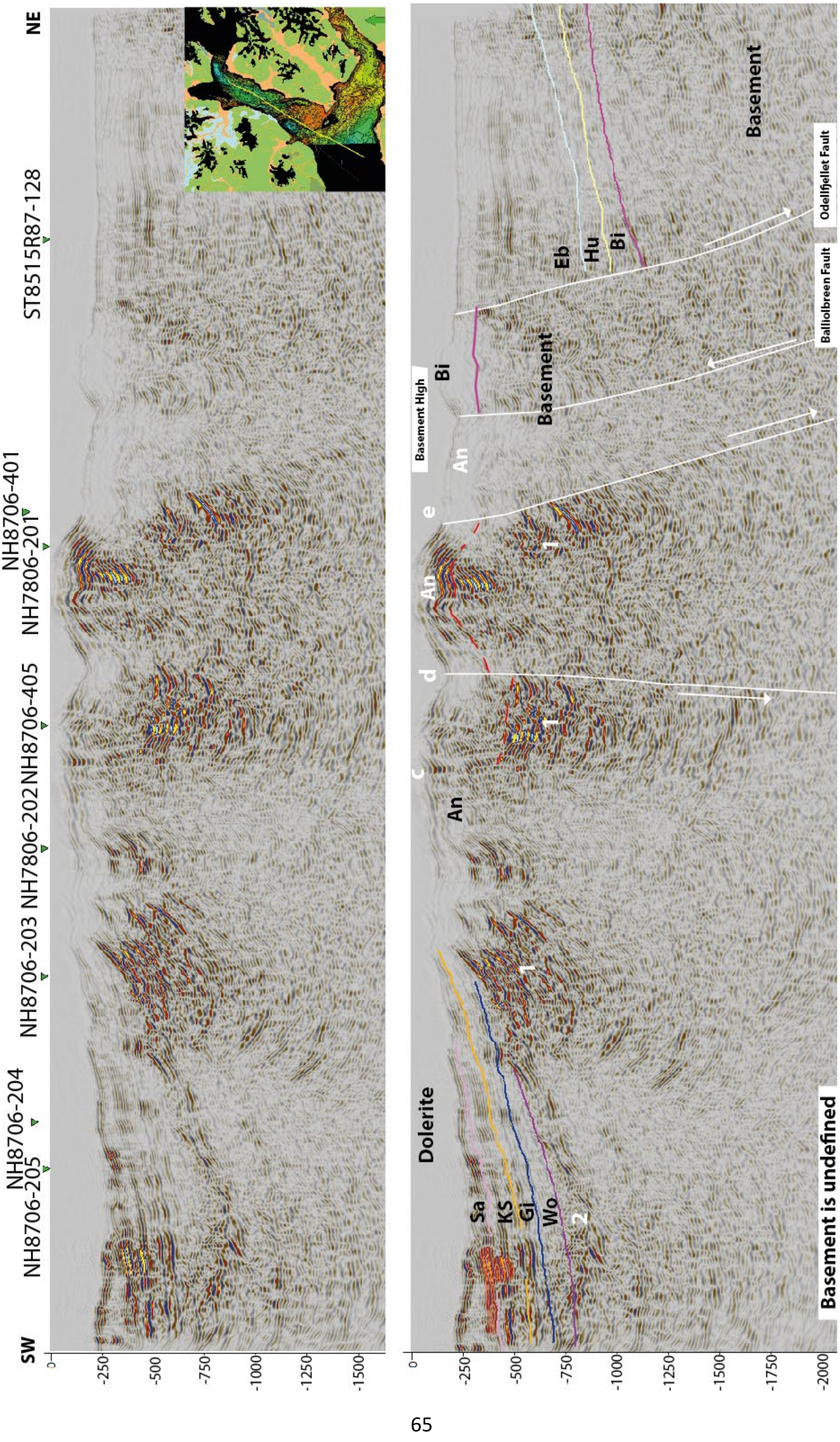
faults of a basement horst. A ridge (b, Fig. 3.12 and 3.13) lies on a topographic ridge that appears in the bathymetry. It is unclear whether this is the reflection of a fault or a fold. Strong anomalies (1, Fig. 3.12 and 3.13) may be basement highs that appear due to the contrast in acoustic velocities to overlying rock. The thickness of Andrée Land Group is unknown, which makes it difficult to determine whether the depth of the basement here is reasonable.

Hyperbolic or diagonal reflectors (2, Fig. 3.12 and 3.13) appear along the base of Wordiekammen in the south-west. This may be either dolerite intrusions (ramps) or the top of Andrée Land Group. In the case of the latter, artefacts likely, affect the boundary. The overlying stratigraphic basin is crosscut by strong anomalies which appear to be dikes and sills. Dolerite intrusions only reach a few tens of meters in the region, thus the width of the dikes and sills in the seismic image is likely exaggerated.

3.3.2.4. NH8706-401

Line NH8709-401 shows a 20.3 km profile of inner Billefjorden (Fig. 3.14). It reflects the Billefjorden Trough to the north. Odellfjellet and Balliolbreen faults reflect poorly, but their location is pinpointed by comparing to the topography and position on land. From this interpretation, the base of the basin lies at -1500 ms TWT. In lines ST8515R87-128 and132-2 the base is at about -1200 ms TWT. This suggests that between the seismic lines the basin tilts to the north. This is in agreement with isopach maps, which indicate that the depocentre lies towards inner Petuniabukta. This strengthens the likelihood that stratigraphic horizons are placed reasonably well.

At the top of the basin a small local fault thrusts Wordiekammen and Mumien formations over Ebbadalen Formation. This fault can be traced onshore. The interesting feature in this line is a possible reactivation of the Balliolbreen Fault that is not seen south of this line. South of Pyramiden the Balliolbreen Fault bends westward to Yggdrasilkampen. North of Pyramiden it clearly has a revere nature displacing the basement over Devonian rock. However, at Yggdrasilkampen Carboniferous stratigraphy is deposited east of a fault towards older Devonian rock. Carboniferous stratigraphy can be extended offshore where the seismic line crosses and reflects at the top of the line. Everything put together it appears that Balliolbreen Fault has a deep seated reverse movement along Billefjorden and



SW
NE
NH8706-205
NH8706-204
NH8706-203
NH7806-202
NH8706-202
NH8706-405
NH7806-201
NH8706-401
ST8515R87-128
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
Dolerite
Sa
KS
Gi
Wo
2
1
An
c
d
e
Basement High
Bi
Basement
Eb
Hu
Balliolbreen Fault
Odellfjellet Fault
Basement is undefined

Fig. 3.13 Seismic line ST8515R87-132-2. For abbreviations, see Fig. 3.2 Section along Billefjorden. CTB stratigraphy to the south-west. Faulted (between d, e, Balliolbreen and Odellfjellet faults) basement blocks lie in the centre of the fjord and the BT to the north-east. 1- strong anomaly possibly indicating basement rock, 2- possible dolerite intrusion.

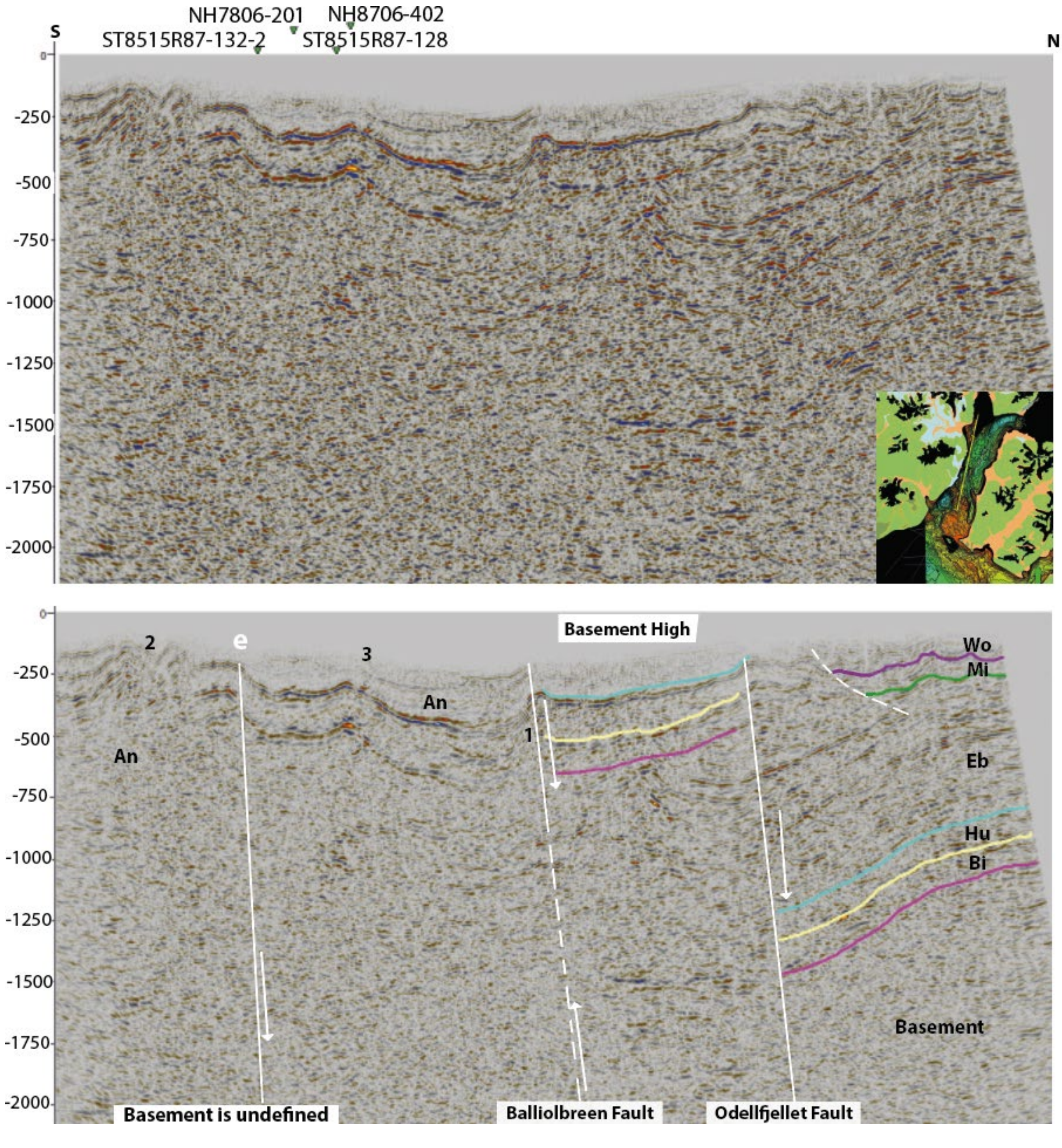


Fig. 3.14 Seismic line NH8706-401. For abbreviations, see Fig. 3.2. Basement blocks in the south lie towards BT separated by the Ba and Od. 1- reflectors indicating displacement, 2- distortion, 3- strong reflector in An.

Sassenfjorden, but local normal reactivation, which is seen as Carboniferous strata on the hanging wall towards Andrée Land Group (1, Fig. 3.14). As described previously fault e (Fig. 3.14) is interpreted as a steep normal fault trough Andrée Land Group. The top of reflections (2, Fig. 3.14) in the south are distortions. The line passes an area with topographic variations, which are likely caused by glacial erosion (see section 3.4). Two strong reflectors (3, Fig. 3.14) lie at the top of the section between fault e and Balliolbreen Fault. The location of the anomaly crosses lines ST8515R87 128 and 132-2. The two lines also have strong anomalies in this area. The lower reflector is probably a multiple reflection while the upper is either Andrée Land Group overlying the basement or a strong reflecting seafloor.

3.4. Description and interpretation of fjord bathymetry data

Average depth in Sassenfjorden and Billefjorden is about 150 m, while Tempelfjorden is shallower at 125 m below sea level (Fig. 3.15). The seafloor in Tempelfjorden is flat along the centre of the fjord but with steep slopes offshore from headlands cutting into the fjord. The slanting seafloor lies along the seismic line NH8706-404. The entire coastline up to Billefjorden is characterised by steep slopes and locally a nearly vertical drop.

The dashed lines (Fig. 3.15) highlight north-east to south-west oriented channels cutting a north-west to south-east lying high (1, Fig. 3.15). These are most likely caused by glacial erosion. The solid lines are expected to be moraines deposited by receding glaciers. A narrow, north-south oriented ridge (2, Fig. 3.15) cuts across Billefjorden. It lies along the BFZ in between the Balliolbreen Fault and the Odellfjellet Fault. The two ridges (1 and 2, Fig. 3.15) are parallel and a possible explanation is that they are fault bound basement horsts.

Another large topographic high (3, Fig. 3.15) lies north of Gåsøyane and Anservika. It is not apparently delineated by faults. Therefore, this structure might show the offshore extent of the dolerite suite which lies at Gåsøyane and Anservika. In contrast, a steep depression (4, Fig. 3.15), over 200 m deep lies north of the high. The competent dolerite may have protected the underlying rock from glacial erosion, forming a bottleneck. Instead, erosion focused on the north lying area, carving out a dramatic depression. Neither maps nor bathymetry show whether the high is fault bound to the north. Thus, it cannot be excluded that the area is a fault bound basement high.

Two narrow north-west to south-east oriented ridges in Sassenfjorden (5, Fig. 3.15) lie at an angle to the BFZ. Their southern extent lies towards a small north-south oriented high which lies along the Gipshuken reverse faults (6, Fig. 3.15). The two ridges (5, Fig. 3.15) have a steep drop on the north-east end and a shallower longer slope to the south-west. Furthermore, while the western ridge is narrow and straight, the eastern is wider and curved.

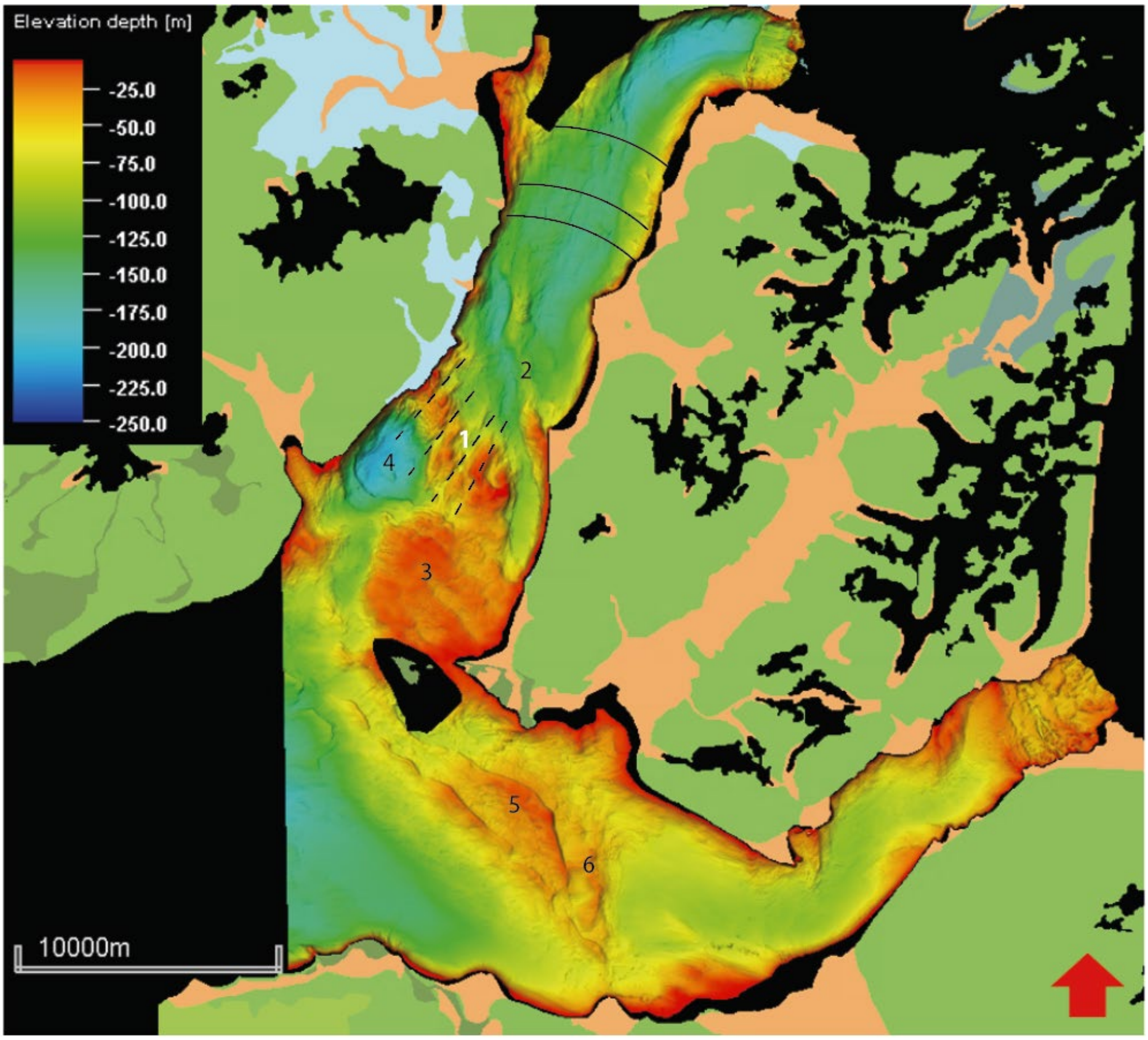


Fig. 3.15 Bathymetry survey from Billefjorden, Sassenfjorden and Tempelfjorden. The area is characterised by steep slopes and deep seafloor. A number of topographic ridges appear (1,2,5,6) as well as a large plateau (3). The deepest point is a depression (4) at the mouth of Billefjorden.

4. Discussion

4.1. Tectonic development

To start, it is important to keep in mind that all interpretations presented here from the seismic data and bathymetry ought to be read with a critical eye. With the well-tie far from the study area, poor reflectors and high noise-to-sound ratio in the seismic data, all interpretations have a high error margin. Due to the limits of the data quality, only large-scale structures are considered. This said, the following interpretation presents a possible explanation of the tectonic development of the study area in Billefjorden and Sassenfjorden (Fig. 4.1-4.3). The purpose of this section is to explain all the structures, which are described in chapter 3 within a regional tectonic context. The focus is on the major tectonic events from Late Devonian to Cenozoic presented in chronological order. This chapter describes the relation between offshore structures and adjacent coastal geology, larger structures of Spitsbergen and the tectonic event that forced the deformation as is understood from this study.

The oldest recorded event in Billefjorden and Sassenfjorden postdating the Caledonian Orogeny begin with the deposition of Devonian Andrée Land Group (Fig. 4.1 A) (Myhre 2009). The Old Red Sandstone deposited over a faulted Pre-Caledonian Basement (Ohta 1992). Accumulating thick sequences of coarse deposits over a basement graben west of Pyramiden. Andrée Land Group has been mapped out in the seismic profiles from the tie-line at Sassenfjorden (Fig. 3.2C) to Narveneset in Billefjorden (Fig. 3.5-3.14). The Devonian sedimentation is recorded along the north-west coast of Billefjorden at Narveneset where Wordiekammen Formation overlies it by an angular unconformity (Stensiö 1918). It is also present north of Yggdrasilkampen and Pyramiden where is if faulted against a basement high to the east by Balliolbreen Fault (Fig. 1.7 map).

Two faults cut the Devonian rock at Narveneset. These faults appear to continue offshore labelled as d and e in Fig. 3.11-3.13., where they delineate a horst. This horst appears in the bathymetry as an elevated ridge (1, Fig. 3.15). This structure indicates an extensional event dated after the deposition of Andrée Land Group but before the deposition of the overlying unfaulted Wordiekammen Formation. However, the kinematics of the Narveneset faults are undetermined and the relative movement of faults is questionable in the seismic images. There are no definitive stratigraphic boundaries to go from, thus the suggested normal movement is highly speculative. The decision to mark these structures in the seismic image as a horst bound by normal faults comes in large part from the suggested post-orogenic relaxation and extension (Haakonian Event and Monacobreen Event) after the Caledonian Orogeny (Fig. 4.1 B). It is recorded that the Devonian rocks were locally faulted and sheared as the crust adjusted after the mountain building event when the mountains eroded and the load on the curst shifted (Gee 1972; McCann 2000).

Normally one can argue that a horst bound by two faults dipping away from the high ought to be regarded as normal faults and extension. However, some restrictions have to be taken into account regarding these “straight forward” interpretations due to the long history of the area with reactivation of lineaments and overprinting deformation (Andresen et al. 1992; Bergh et al. 1988; Haremo et al. 1993; Manby et al. 1994; McCann & Dallmann 1996). Meaning, that in Spitsbergen it is frequently recorded that faults which initiated as for example, a normal or strike-slip fault may at a later stage, have the original displacement overprinted by reverse reactivation (McCann & Dallmann 1996). Therefore, it is possible that fault e and d (Fig. 4.4) are reverse faults formed later during the Svalbardian Event (Ellesmerian Orogeny).

The Svalbardian Event (Famennian-Tournaisian boundary) was a period of crustal shortening (Fig. 4.1 C) (Piepjohn 2000). During this event Devonian stratigraphy was locally folded (Piepjohn 2000). The best seismic profile reflecting the folded Andrée Land Group is NH8706-211 (Fig. 3.8). The profile shows folding in the north to north-west end of the profile. A possible fault (c, Fig. 3.8) is suggested as a thrust fault within the unit. The fault is very poorly reflected. It appears as an abrupt change in the orientation of reflectors. It is possible that the fault formed during this compressional event.

Interpreting the Andrée Land Group in the seismic sections is problematic, because the boundary to the basement is undefined. The two units have high acoustic velocities and thus the contrast between the two is low and reflects poorly. Furthermore, both units are heterogeneous and folded. The unknown depth of the Andrée Land Group makes it difficult to predict where the boundary to the basement is. It is therefore a risk to erroneously interpret structures of a basement high as internal Devonian structures. This would place deformational events in the wrong geological timespan. The most likely interpretation is that the oldest deformational event observed in the seismic images are post-Caledonian extension followed by the Svalbardian Event resulting in a faulted horst across Billefjorden and possibly an elevated plateau (3, Fig. 3.15) north of Gåsøyane.

The folded reflectors west of the Balliolbreen Fault and east of the tilted CTB are likely Andrée Land Group, folded during the Svalbardian Event that followed the extension. During this phase of contraction, the Balliolbreen Fault (Fig. 4.1 C) formed on a pre-existing shear zone where the rock had been weakened along a north-south oriented zone (Bergh et al. 2011; Steel & Worsley 1984). The shear zone formed during the Caledonian Orogeny. In the seismic data, the Balliolbreen Fault appears in line

ST8515R15-128 and 132-2 (3.12 and 3.13). The seismic reflectors are poor, but the fault lies offshore to where the Balliolbreen Fault terminates towards the fjord. North of Pyramiden the BFZ has two main fault-strands; the Balliolbreen Fault to the west with basement thrusted over Devonian units and the Odellfjellet Fault with the Billefjorden Trough to the east (Dallmann et al. 2004b). This coordination of structures seems to be reflected in the seismic data all the way from Billefjorden (Fig. 3.12-3.14) to southern Sassenfjorden (Fig. 3.2 C and 3.5-3.7). From the seismic profiles, it appears the fault block between the Balliolbreen and Odellfjellet faults narrows southwards.

The Odellfjellet Fault reflects relatively well since the termination of basin stratigraphy towards the basement creates a clear contrast, this is especially clear in line NH8706-203 (Fig. 3.5) and lines ST8515R15-128 and 132-2 (Fig. 3.12 and 3.13). The characteristic appearance of the Odellfjellet Fault gave higher confidence for the interpretation of the linear structure southwards. The Odellfjellet Fault was therefore used to guide the interpretation of the Balliolbreen Fault, which often does not reflect in the seismics apart from a topographic relief above the structure. Therefore, south of Gipshuken the interpretation of the Balliolbreen Fault is very uncertain.

Harland et al. (1974), Bergh et al. (2011) and other studies describe the Balliolbreen Fault as a main fault along which basement was thrusted above the Andrée Land Group during late Devonian-early Carboniferous contraction. There are no signs in the seismic data used in this study that would contradict this concept. However, neither is the evidence to support the exact timing and movements of the fault as is described in other studies. Essentially, there is not much that can be said about the development of the fault from the seismic images alone. It is only possible to say that based on the seismic reflectors and bathymetry, the Balliolbreen Fault continues offshore south of Yggdrasilkampen and towards Gipshuken. There are indications in the seismic images that the Balliolbreen Fault continues all the way across Sassenfjorden (Fig. 3.2C and 3.5-3.7).

A depositional hiatus separates the Andrée Land Group from the overlying Carboniferous Billefjorden Group. The Billefjorden Group was deposited in local depressions (Fig. 4.1 D) after the Svalbardian Event (Ellesmerian Orogeny) that caused the folding of the Andrée Land Group and thrusting of the basement over Devonian rocks along the Billefjorden Fault. The unit was deposited during a tectonically stable phase (Cutbill & Challinor 1965). This stage however is not reflected in the seismic images. The interpretation is taken entirely from other studies and isopach maps.

Drill holes north of Petuniabukta (Verba 2013) show that the unit is present at the base of the Billefjorden Trough, but the poor seismic reflectors don’t allow an accurate placement of the unit. Without the ability to pinpoint the unit with confidence, nothing can be said about the timing

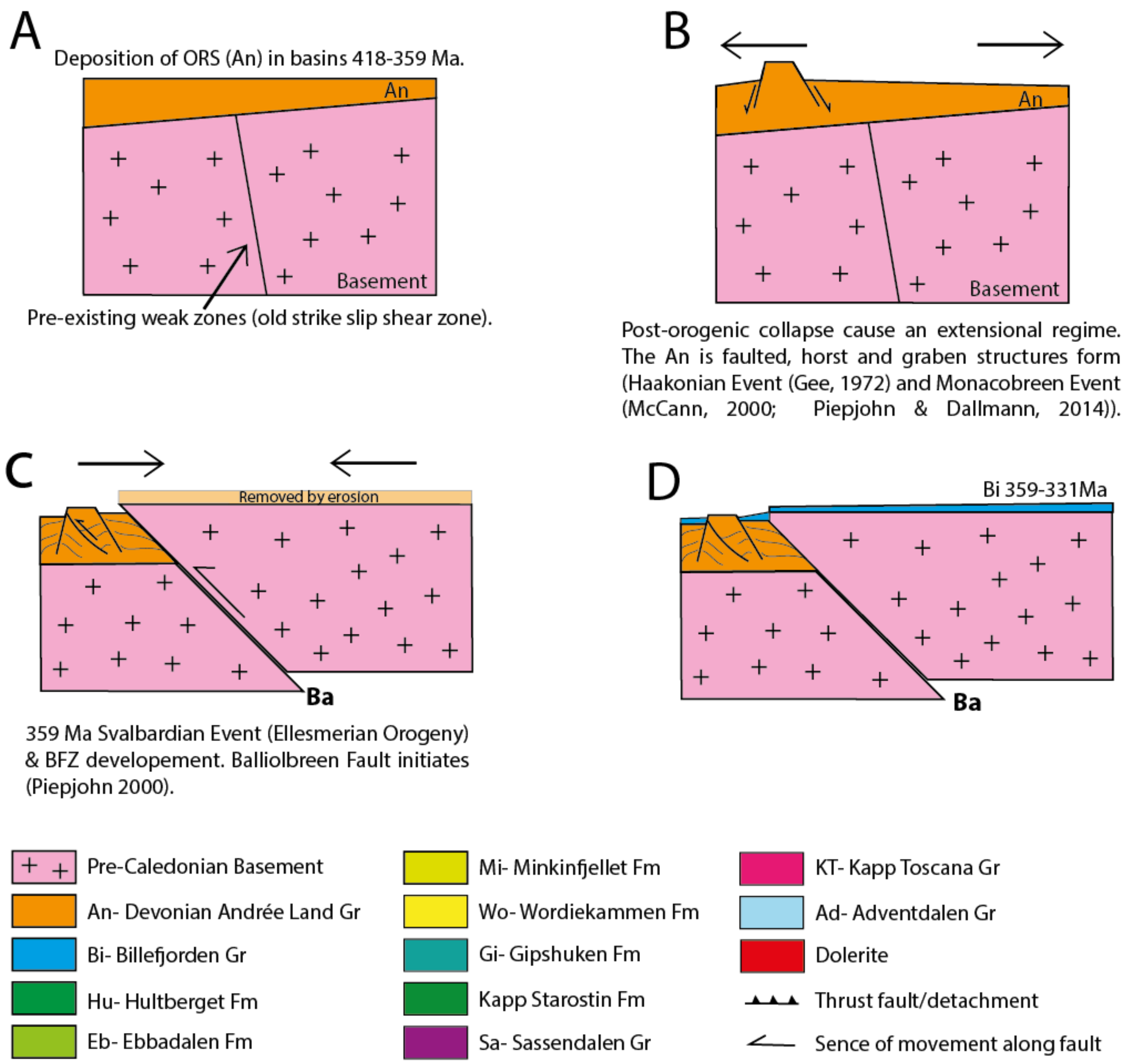


Fig. 4.1 The illustration does not represent a specific transect, it is a conceptual illustration of the development of the Billefjorden-Sassenfjorden area on a W-E line across the BFZ. Fig A-D illustrate Devonian development. Ba-Balliolbreen Fault; Od- Odellfjellet Fault

of deposition in regard to fault activity from the seismic images alone. What is apparent form maps and studies is that the unit is present across the Billefjorden Trough and the BFZ west of the Balliolbreen Fault. Further west the extent is not certain.

The basin stratigraphy of the BT and the normal fault that defines the western limit of the basin are structures that formed during the next big event that affected the area. Carboniferous rifting reactivated the BFZ and the BT developed along the Odellfjellet Fault (Fig. 4.2 E-F) (Haremo & Andresen 1992; Haremo et al. 1993; Johannessen & Steel 1992; Manby et al. 1994). The seismic images from the tie-line (Fig. 3.2C), Sassenfjorden (3.5-3.7) and Billefjorden (Fig. 3.11-3.14) show a fault that continues along the strike of the Odellfjellet Fault at Pyramiden. This indicates that the Odellfjellet Fault continues all the way across Billefjorden and Sassenfjorden. In the seismic data, a basin appears to the east of the fault.

The reflectors in the seismic data show that the sedimentary units thicken towards the fault. This can be an indication about the timing of faulting. The expectation is that pre- and post-rift sediment would have the same thickness along the basin, while syn-rift strata is expected to thicken towards an active normal fault since the sediment accumulation is focused toward the growing depocentre (Roberts et al. 1993). This is of course an oversimplification and a very general guideline, more so it demands accurate knowledge of stratigraphic boundaries and their age. Since, it is difficult to pinpoint the units in the seismic data with good confidence, the sedimentation and fault movement relation is difficult to assess. In addition, spaced 2D seismic lines will never reveal the exact geometry of a 3D world. A sedimentary basin can be a very dynamic geological structure and a lot of information is missing when only two-three parallel seismic profiles exist.

Nonetheless, it is apparent that the structures described from the seismic images are a rift-basin, the Billefjorden Trough that formed towards an extensional fault, Odellfjellet Fault (Gjelberg & Steel 1981; Johannessen & Steel 1992). Early works of Harland et al. (1974), Johannessen & Steel (1992) and others conclude that Carboniferous extension is characterised by reactivation of old faults of the BFZ and the development of a new major fault strand, the Odellfjellet Fault.

There is evidence that indicates a reactivation of the Balliolbreen Fault (Fig. 4.2 G-H). North of Pyramiden it has a reverse character with the basement to the east thrusted over Devonian rock on the west side of the fault. Southwards however, at Yggdrasilkampen the stratigraphy on either side of the fault shows extensional displacement. Andrée Land Group with overlying Wordiekammen Formation form the footwall in the west. In the hanging wall in the east, younger Ebbadalen and Wordiekammen formations are displaced upwards relative to the footwall. These field observations indicate inversion in the upper units of the Balliolbreen Fault. The extensional reactivation of the Balliolbreen Fault is suggested in the seismic interpretation in lines ST8515R87-128 and 132-2 (fig 3.12 and 3.13) and NH8706-401 (Fig. 3.14).

On the BBH that is located between Balliolbreen and Odellfjellet faults, Billefjorden Group, Hultberget and Ebbadalen formations (the two latter in line NH8706-401) are suggested to overlie the basement. The upper units are displaced downwards relative to the footwall. It has to be stressed that this interpretation is not based on direct measurements by a well and a velocity survey. It is an

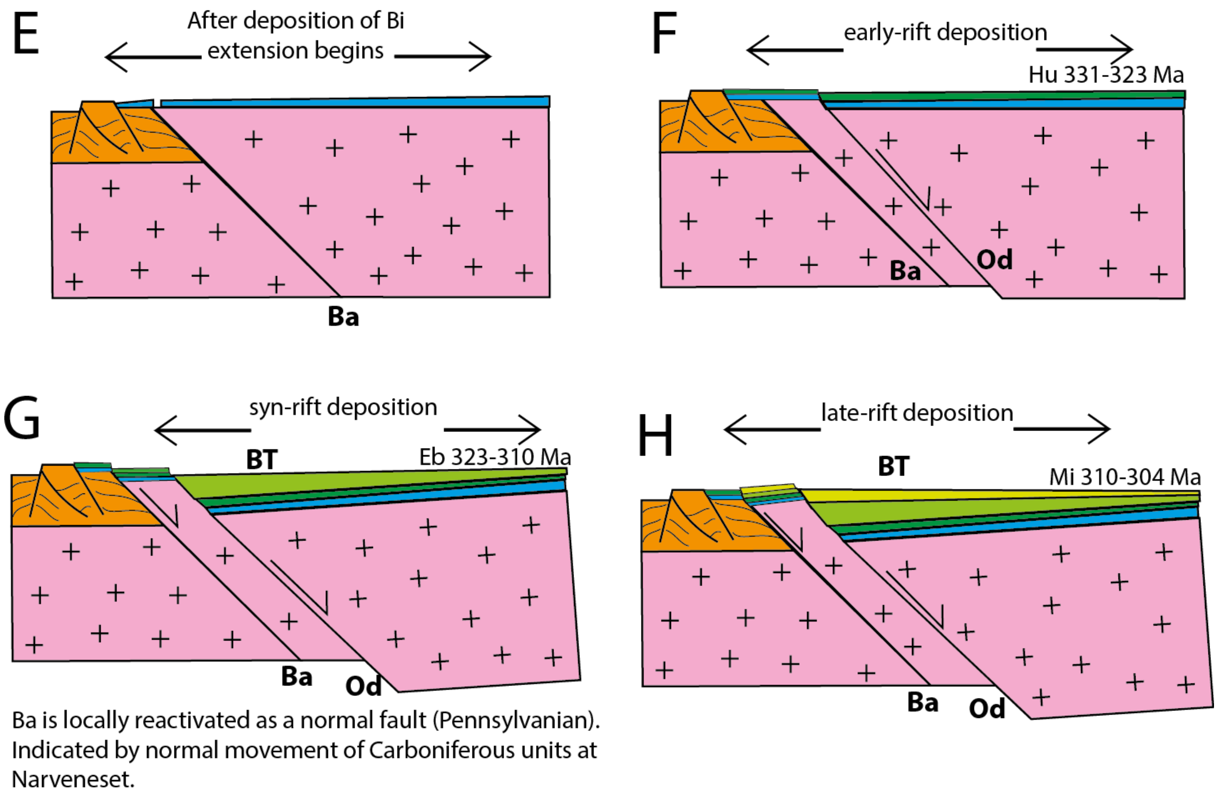


Fig. 4.2 Conceptual illustration of Carboniferous extension. For abbreviations and colour legend, see Fig. 4.1

interpretation based on previous work and extrapolating the geology from maps. Thus, it is highly speculative and in no way can this be considered an evidence for inversion. It should rather be considered a suggestion for what the seismic profile might be reflecting.

The Wordiekammen Formation was deposited after the main extensional movement along the Odellfjellet Fault (Fig. 4.3 I). In the BT, the Wordiekammen Formation has a post-rift depositional style. It does not thicken towards the fault. It has been regarded as a post-rift unit in several publications. However later studies show that some extension and subsidence continued (Johannessen & Steel 1992; Maher & Braathen 2011). As mentioned above, the Wordiekammen Formation is faulted along the Balliolbreen Fault at Yggdrasilkampen (Fig. 4.4). Some extension in Late Carboniferous to Early Permian must have occurred after the main fault movement (Bashkirian-Moscovian) along the Odellfjellet Fault. The faulted Wordiekammen Formation at Yggdrasilkampen is an indication of extensional reactivation along the Balliolbreen Fault. Apart from some late movement and subsidence, the Wordiekammen Formation was deposited under stable tectonic conditions, which prevailed until the Early Cretaceous (Gee et al. 1952). This appears in the seismic data from the observation that the Wordiekammen Formation is deposited continuously over large areas without dramatic thickness variations. Deformations of the unit seem to be post-depositional. The unit is exposed along the coast of Billefjorden. It is the most continuous unit in the area.

The Permian to Early Cretaceous periods saw stable conditions and the deposition of Tempelfjorden, Sassendalen, Kapp Toscana and Adventdalen groups (Fig. 4.3 J) (Worsley 2008). In the study area, post-Carboniferous units only appear west of Billefjorden due to a regional south to south-west tilt of the

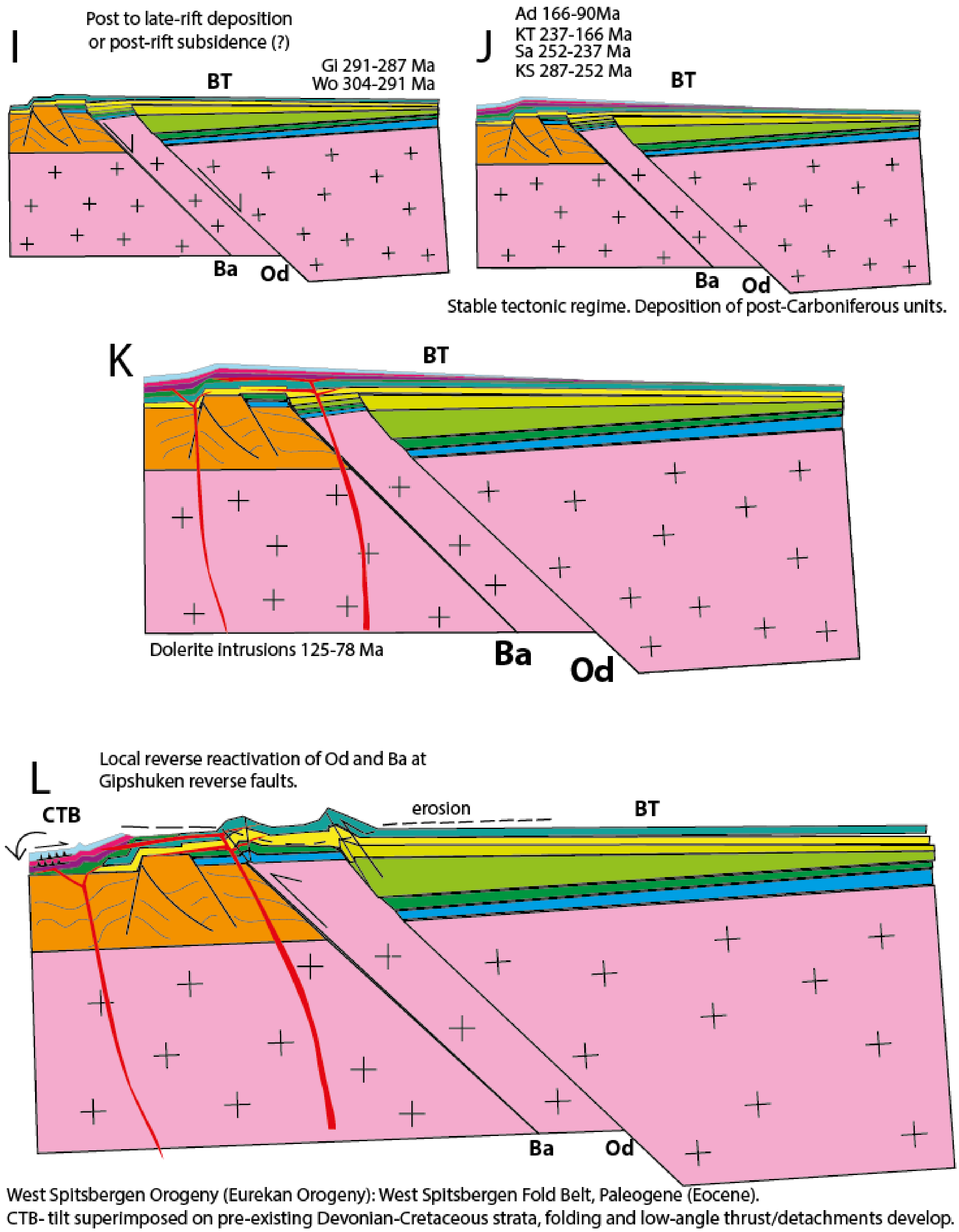


Fig. 4.3 Conceptual illustration of post-Carboniferous development. Abbreviations and colour legend Fig. 4.1

stratigraphy. Around Billefjorden, post-Carboniferous units have been eroded.

Strong seismic anomalies offshore of Gåsøyane have been identified as dolerite intrusions (Fig. 3.5-3.9 and 3.12-3.13). The islands of Gåsøyane consist of a thick horizontal sill that is likely to be a continuation of the Gipshukodden sill. Intrusions have been mapped at Diabasodden and southern Dickson Land. The whole area of intrusions including the one interpreted in the seismic profiles likely belong to the same intrusive event. The Diabasodden suite including Gåsøyane is dated from 125.5±3.6 to 78.3±2.6 Ma (Fig. 4.3 K) (Nejbert et al. 2011). The Cretaceous intrusions are believed to have formed by multiple pulses, representing the peripheral expression of the High Arctic Large Igneous Province (HALIP) (Maher 2001). The extensive magmatism may have been triggered by the extensional regime in the Early Cretaceous during the opening of the Amerasian Basin and northern Atlantic.

Folds and thrust faults that overprint earlier structures show evidence of Palaeogene contraction. Seismic profiles from Sassenfjorden show ridges and faults that follow long north-west to south-east ridges across Sassenfjorden (a and b Fig. 3.10). It is not conclusively clear from the seismic images whether the lineaments are folds or faults. However, it is apparent that they are later structures as they affect stratigraphy from Devonian to Early Triassic as well as Middle Cretaceous dolerite intrusions. A more interesting feature are the Gipshuken reverse faults and their relation to the Balliolbreen and Odellfjellet faults. Analysis of the seismic data suggests that the Balliolbreen and Odellfjellet faults continue across Gipshuken and across Sassenfjorden (Fig. 4.4 and 4.5). This suggests that Gipshuken reverse faults directly overlie the two main fault strands of the BFZ. The Gipshuken reverse faults have a more north-west to south-east strike than the Balliolbreen and Odellfjellet Faults.

The combined observations point to another possible reactivation of the Balliolbreen and Odellfjellet faults, this time under compressive forces. It is suggested that the Gipshuken reverse faults might connect to the Odellfjellet and Balliolbreen faults (Fig. 4.3 L). Their angle to the original lineaments might be explained as an accommodation to the new tectonic forces. The newly developed shortening directions across Sassenfjorden are oriented south-east to north-west (compared to east-west shortening and later extension of Devonian and Carboniferous deformation). These structures might have formed during the development of the WSFB (West Spitsbergen Orogeny/Eurekan Orogeny). Several studies, including Haremo & Andresen (1992), McCann & Dallmann (1996) and Manby et al. (1994) propose that in Palaeocene-Oligocene the BFZ was reactivated by the West Spitsbergen Orogeny (Eurekan Orogeny). Haremo et al. (1990, 1993) and Johannessen & Steel (1992) interpret the steep reverse faults in Gipshuken in terms of a Palaeogene inversion of the BFZ.

Low angle thrust faults (Fig. 4.3 L) in the Early Triassic Sassendalen units and Early Jurassic Adventdalen units near Adventdalen are explained as thin-skinned Palaeogene deformation (Bergh et al. 1997). Furthermore, Bergh et al. (1997) identify ridges similar (and parallel) as those identified in this study in Sassenfjorden, but further west in Isfjorden. They suggest the ridges are folds formed due to Palaeogene compression during the West Spitsbergen Orogeny/Eurekan Orogeny. It is suggested here that the ridges in Sassenfjorden are related to the ones described by Bergh et al. (1997) and formed during Palaeogene shortening.

On a larger scale, the central parts of Spitsbergen host the Central Tertiary Basin, which formed during the Palaeocene-Eocene contraction (Bergh et al. 1997; Braathen et al. 1999a, 1999b; Helland-Hansen 2010). The basin formed as a flexure response to the developing mountain belt in the west, it imposed a tilt to older stratigraphic units (Fig. 4.3 L) (Bælum & Braathen 2012). The tilted strata appear in the seismic profiles west of Billefjorden (Fig. 3.12 and 3.13). Due to the tilt, younger units are deposited at an angular unconformity over pre-Cretaceous stratigraphy (Bælum & Braathen 2012).

The Palaeocene contraction was part of a large-scale defamation event. Rearrangement of the tectonic plates in the Cenozoic triggered the rifting in the Labrador Sea in the Palaeocene and the development of the Eurekan Fold Belt across Canada, Greenland and Ellesmere Islands. On Svalbard, this tectonic event forced the development of a new fold belt. The WSFB developed due to compression and/or transpression as Greenland moved past Svalbard along long and complex shear zones, located across Barents shelf (Lowell 1972; Lyberis et al. 1993; Tessensohn et al. 2000,). Post-Caledonian to Palaeocene tectonic events have slowly shaped Spitsbergen into a complex landscape with basement highs, basins, folds and faults (Fig. 4.3 L) which record the long history of the Arctic archipelago.

4.2. BFZ along-strike changes (comparison to other studies)

South of Austfjorden the BFZ appears to widen (Bergh 2011; Dallmann et al. 2000; Harland et al. 1974,). Across north-eastern Dickson Land, the reverse Balliolbreen Fault is accompanied by the normal Odellfjellet Fault. The two faults delineate a basement high (the BBH) (Fig. 1.2). The seismic profiles suggest that the BBH continues offshore into Billefjorden with the Balliolbreen Fault to the west and the Odellfjellet Fault to the east. Across Billefjorden, seismic interpretation indicates that the BBH attenuates. Across Sassenfjorden, the same fault array as is described across Dickson Land and Billefjorden persists, but the basement block has thinned from its maximum width of 2.5 km to 1.1 km.

At Reindalen, the seismic image reflects a different fault array than in the north. The normal fault with basin stratigraphy to the east is no longer detectable. Unfortunately, the seismic data quality is too poor to reflect the faults below Gipsdalen Group for an accurate interpretation. Little more can be said than that the BFZ (possibly with the Balliolbreen Fault) is present under a compression structure and the transect seems to display dominantly reverse movement. The deep-seated faults are very steep, even near vertical. The vertical angle of faults (6, Fig. 3.2A) could suggest strike-slip movement. Although, this idea is highly speculative. Younger low-angle thrust faults that cut the Adventdalen Group (1 Fig. 3.2A) are interpreted to be detachments formed during the development of the WSFB. The same interpretation is concluded by Haremo (1992, 1990), who suggested that the well is drilled through a Triassic detachment. Skilbrei's et al. (1992) study of the magnetic basement implies that the BFZ continues southwards into Storfjorden.

This study suggests that the Balliolbreen Fault may continue across Sassenfjorden as the main reverse fault strand of the BFZ. Bælum & Braathen (2012) describe a different understanding of the fault array. Their interpretation of a west-east seismic line across Sassenfjorden suggest that a lineament they refer to as Drønbreen Fault lies west of the Balliolbreen Fault, which they present as an extensional fault. The dramatic change in fault array that they suggest from Billefjorden to Sassenfjorden seems questionable. First, seeking trough literature, there is no structure formally defined as "Drønbreen Fault". As structures are named after the location where they are first described or have their type section, the assumption is that they are referring to faults at Drønbreen. The only fault at Drønbreen, north of Reindalen is a low-angle thrust fault or detachment, likely of Palaeogene age (Fig. 1.2). It is unlikely that one single fault can be a low-angle detachment, parallel to Jurassic-Cretaceous stratigraphy, and 30 km to the north, a deep-seated basement fault (Fig. 4.6).

Secondly, their model of the fault array of the BFZ suggests a number of relay ramps between the faults. From north to south, they present the Balliolbreen Fault as a mainly reverse fault and the normal Odellfjellet Fault. Southwards, they imply that across relay ramps, the Balliolbreen Fault takes over the extensional movement, while the Odellfjellet Fault dies out, replaced by the "Drønbreen Fault" south of Gåsøyane. They base their idea of relay ramps based on lateral and thickness changes of sediment. The idea that sediment supply reflects changes along fault movement is established, but their conclusions seems to go too far. Nevertheless, there are no doubt variations in displacement along the faults, which in turn may affect sedimentation, but their study is not convincing with respect to the relay ramps, large normal displacement of the Balliolbreen Fault south of Sassenfjorden and the suggested Drønbreen Fault. Instead, another model of the fault array is proposed in Fig. 4.4 and 4.5.

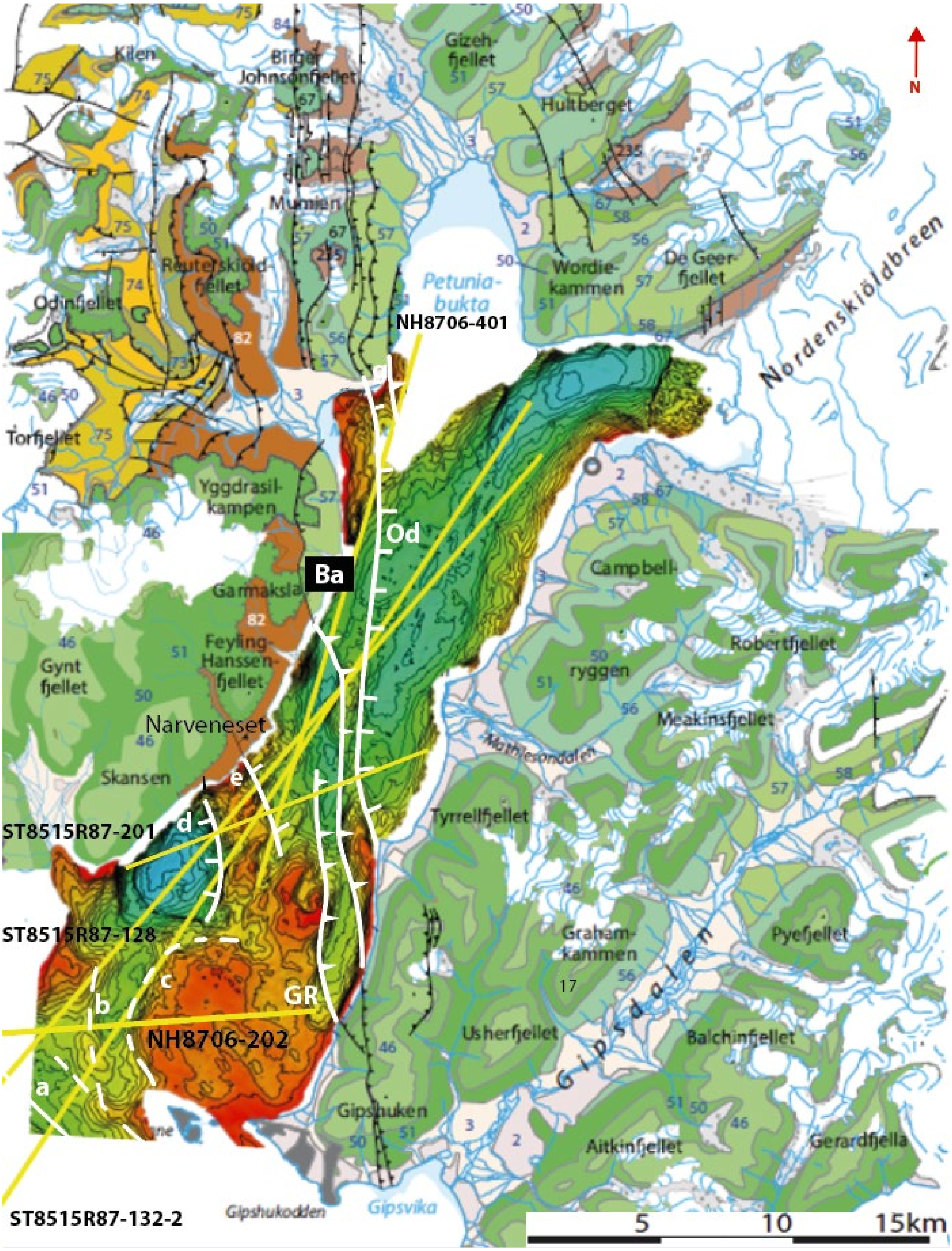


Fig. 4.4 Bathymetry with geological map (Dallmann et al. 2009) over Billefjorden. Suggested lineaments a-e, GR, Ba and Od are indicated with white lines, solid lines show higher certainty while dashed lines show possible but uncertain structure continuation. Lineament legend see Fig. 4.5. (Colour legend for geological map see Fig. 1.7 C, for bathymetry legend see fig. 3.15)

The interpretation of the seismic lines and bathymetry are compiled into a regional map of lineaments and structures (Fig. 4.4 and 4.5). South of Pyramiden a steep east dipping normal fault with basin stratigraphy on its hanging wall can be traced in the seismic lines (Fig. 4.4, Od). The sediments show from pre-, syn- and post-rift geometry. A north-south trending lineament is evident in the bathymetry. The structure coincides with the location of the faults in the seismics but also as a continuation of the Odellfjellet Fault on land.

The Balliolbreen Fault passes Pyramiden and across Yggdrasilkampen on land. A continuation of the fault is traced in the seismic images and seafloor topography (Fig. 4.4, Ba). In the seismics, it appears as a steep east dipping reverse fault, which together with the Odellfjellet Fault cut the basement into a narrow horst. It is interpreted that the Odellfjellet and Balliolbreen faults continue offshore south of Pyramiden, past Gipshuken and across Sassenfjorden (Fig. 4.5). The configuration of the faults seems to persist across Sassenfjorden. However, at the well in Reindalen the fault zone seems to show a different fault array.

Although, the faults reflect poorly at the well, there is no sign of a normal fault similar to the Odellfjellet Fault. The map indicates that the Gipshuken reverse faults lie above the Balliolbreen and Odellfjellet faults. If so, then the Odellfjellet Fault may display normal movement in the subsurface and reverse movement and folding at the surface. Late reverse reactivation of what was initially a normal fault is implied.

Another fault bound basement block is suggested south of Narveneset. The faults d and e (Fig. 4.4) appear as short segments on land and in the seismics. On land they cut Devonian rocks and have undetermined relative movement. The topographic high runs between the suggested faults. It is likely that the faults extend further than can be mapped at the surface and in the seismics. Since the structure does not affect Gipsdalen Group, it is pre-Carboniferous.

The Gipshuken reverse faults show a northward continuation of shore (Fig. 4.4, Gr) west of the Balliolbreen Fault. It is parallel to the BFZ but disappears midway across Billefjorden. It does not reflect well in the seismics but based on land geology it is assessed to be a steep east-dipping fault.

In Sassenfjorden, dolerite intrusions reflect in the seismic profiles. They appear as sills, dikes and ramps that cut the stratigraphy. A topographic plateau north of Gåsøyane is suspected to be either a basement high against an old fault (c) or a sill intrusion, which protected the underlying rock form erosion. The area across Billefjorden north of Gåsøyane is an interplay of faulting, intrusions and erosion.

Across Sassenfjorden, two north-west to south-east trending ridges (a and b) are mapped out (Fig. 4.4 and 4.5). It is unclear whether the western lineament (a) is a fault or a fold ridge. The eastern ridge (b) is curved, wider and seismic profiles indicate reverse kinematics. The faults appear in seismic lines line

NH8706-203 (5, Fig 3.5) as well as NH8706-204, -205, -202 and -211. As described in section 1.3.1.2. and 1.3.1.4., the faults cut both Permian Kapp Starostin Formation and Cretaceous dolerite. Therefore, they must have formed after the intrusive event, likely during Paleogene convergence. These faults are not known from surface mapping and are new finding from the seismic survey. They are also illustrated in section 4.3 (cross section fig 4.7).

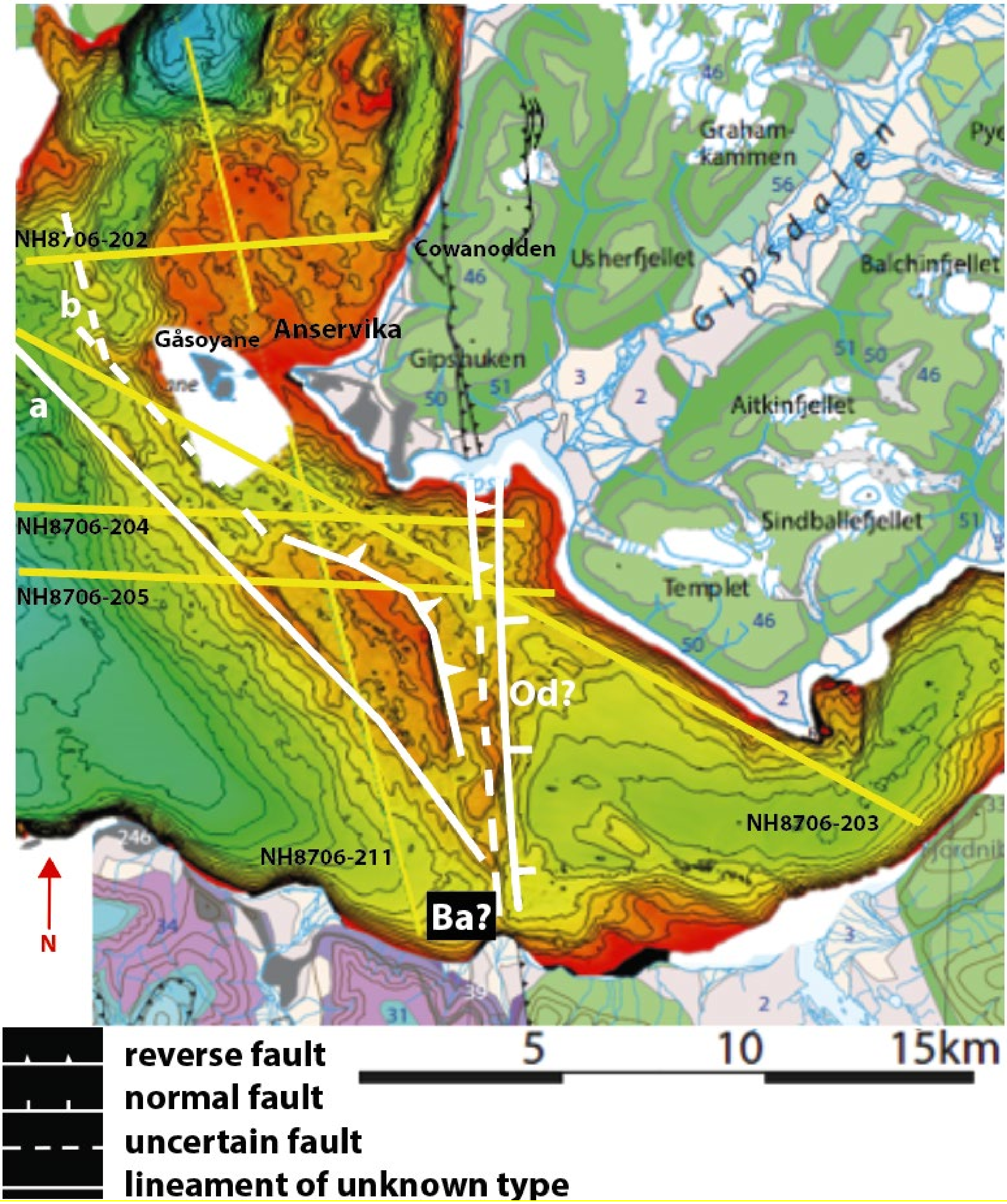


Fig. 4.5 Bathymetry with geological map (Dallmann et al. 2009) over Sassenfjorden. Suggested lineaments a, b, Ba and Od are indicated with white lines, solid lines show higher certainty while dashed lines show possible but uncertain structure continuation. The seismic data indicate that the Ba and Od continue south of the fjord. (Colour legend for geological map see Fig. 1.7 C, for bathymetry legend see fig. 3.15)

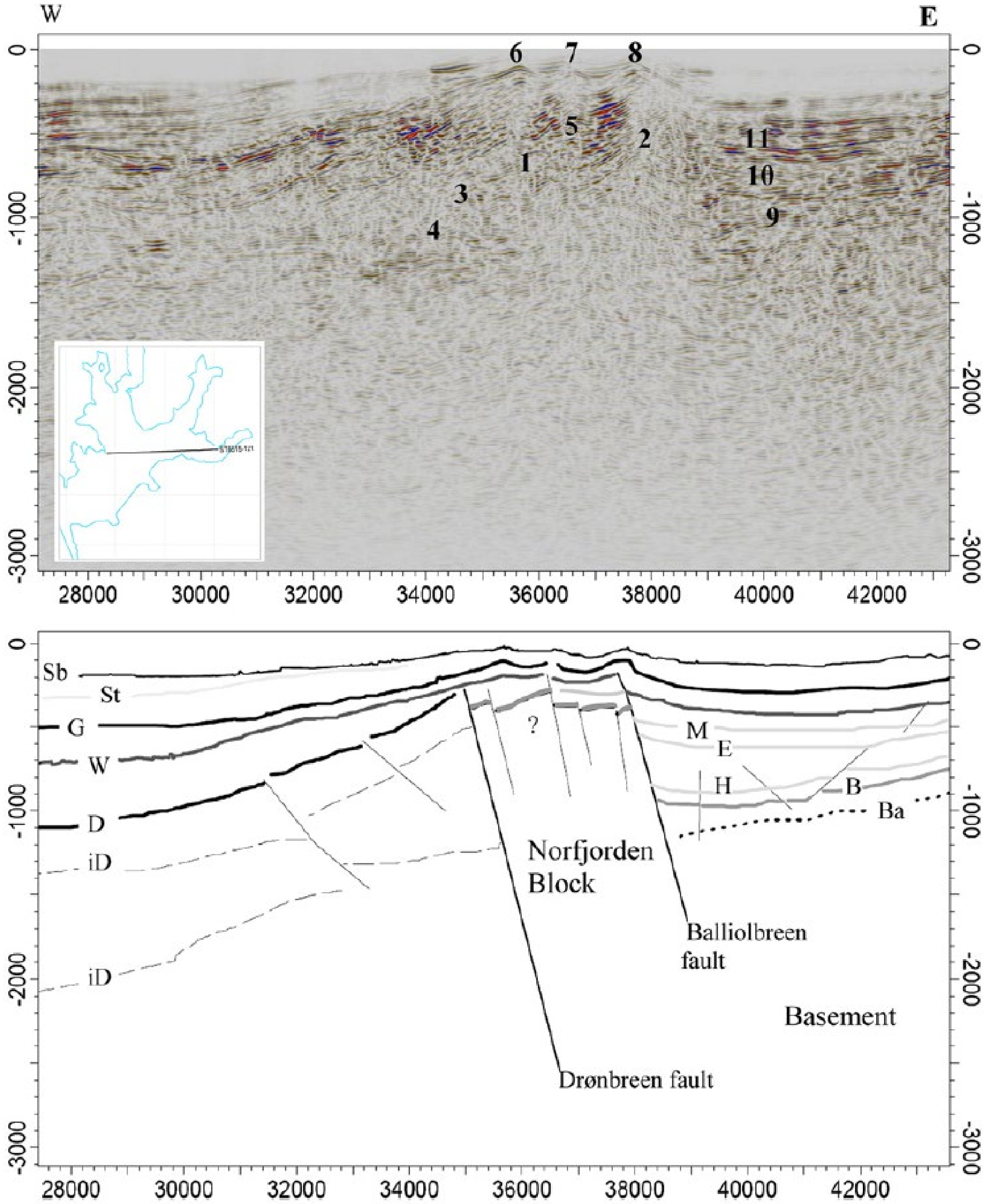


Fig. 4.6 figure from Bælum & Braathen (2012) showing their interpretation of line ST8515-121 Sb-seabed, St-top Kapp Starostin Fm., W-Wordiekammen Fn., D-top Devonian, iD-intra Devonian M-top Minkinfjellet Fm., E-top Ebbadalen Fm., H-top Hultberget Fm., B-top Billefjorden Gr., Ba- top basement.

4.3. Basin geometry

Braathen et al. (2011) present cross sections of the basin based on Lidar scans, outcrops and well data. The profile they suggest shows Billefjorden Group reaching a maximum thickness at around 300 meters. The authors add that at depth in Petuniabukta, the geometry of the BT is unknown, and their work is an extrapolation of surface geology. Smyrak-Sikora et al. (2018) present another cross section (Fig. 1.8) based on Braathen et al. (2011), here Billefjorden Group is drawn 350 m thick. Both authors assume that the Petuniabukta syncline continues in the subsurface affecting units down to Billefjorden Group and the units tilt up towards the fault. The exact geometry of the unit as is presented in the two papers cannot be observed in the seismic data. The reflectors in Fig. 3.12-3.14 seem to indicate that the basin stratigraphy deepen towards the fault but there is no indication in the seismic images of the stratigraphy tilting away from the Odellfjellet Fault as presented by Braathen et al. (2011) and Smyrak-Sikora et al. (2018). Although, an eastward dip towards the basin can be observed and is mapped west and north of Petuniabukta. This may show that there are geometrical differences along the basin. Fig. 4.7 shows a cross section based on seismic line ST8515R87-128 along Billefjorden. It is not converted to a metric depth domain. Therefore, it is expected to vary from Smyrak-Sikora et al. (2018) but it illustrates the differences of the basin geometry seen in the seismics and other suggested geometries.

As mentioned before, the seismic data are prone to artefacts and primary reflectors are weak. The true geometry of the basin is hidden. Multiple reflectors from the seafloor can make is appear as if underlying boundaries has a different trace, in the case of inner Billefjorden the seafloor lies relatively flat. The effect might be that at shallow depth the basin appears more horizontal than it really is. In contrast, as the seismic image loses resolution and migration is not as efficient, many reflectors take a synform shape. This could have the effect of making reflectors from the basin stratigraphy appear tilted and disrupted.

Another thing to consider is the directions of the cross section presented by Smyrak-Sikora et al. (2018) and the seismic lines. While the cross sections are across the basin, the seismic line is at an angle to the BT. The likely effect is that along-strike changes will reflect in the seismic image. Doing so, the efficient reflection is a combination of the basin structure along and across its axis.

An additional idea for this project was to compare structures across the BT eastwards toward the Lomfjorden Faults with the basin development model presented by Smyrak-Sikora et al. (2018). Smyrak-Sikora et al. (2018) suggests that the basin first developed as a symmetrical basin bound between the Odellfjellet Fault and the Lomfjorden Fault. The half graben asymmetry developed later as the main extensional movement was taken over by the Odellfjellet Fault. Unfortunately, this comparison was not possible since the eastward line NH8706-402 which might show the Lomfjorden Fault was of too poor quality to use in the study. Fig. 4.7 shows two cross sections along Billefjorden (upper) and across Sassenfjorden (lower). The cross sections are based on the seismic lines ST8515R87-128 and NH8706-203. They illustrate how the geology may appear if pull-up and push-down from the

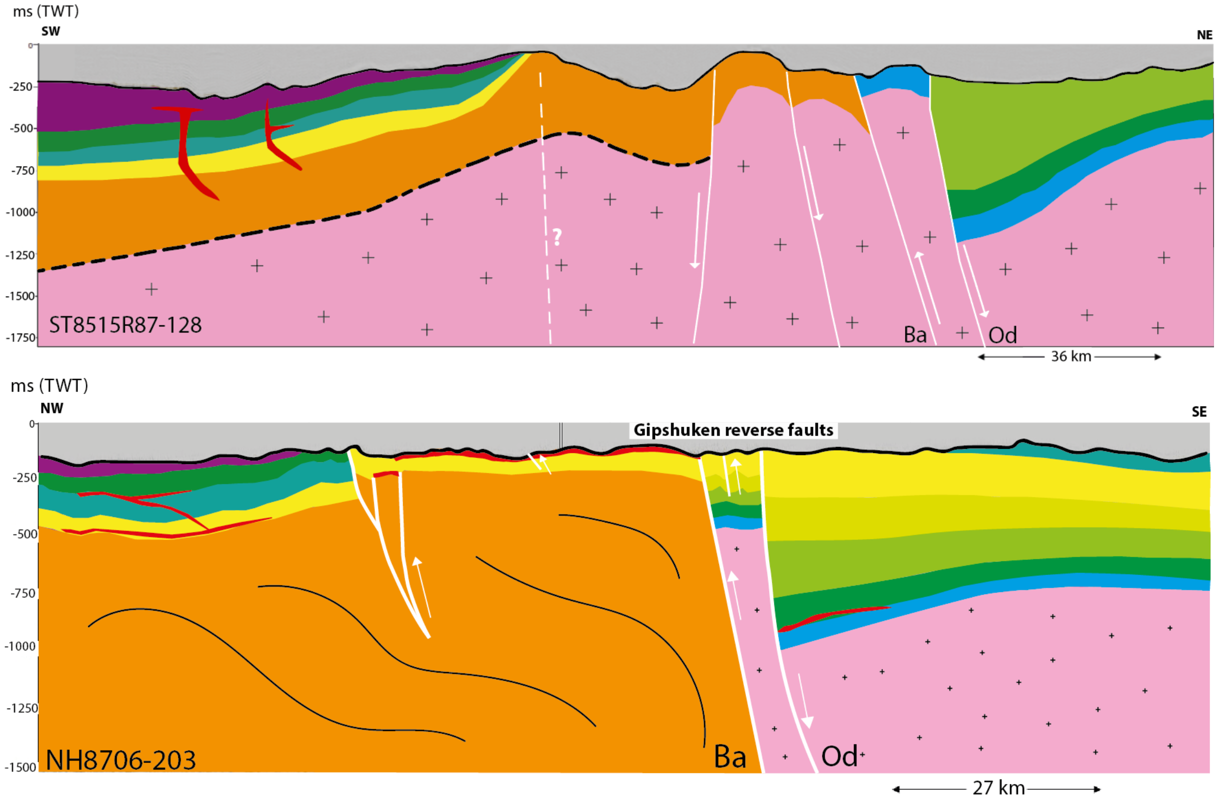


Fig. 4.7 Cross sections constructed based on seismic lines ST8515R87-128 and NH8706-203. The top profile is a suggestion for the geology along Billefjorden while the bottom one is for across Sassenfjorden. For colour legend, see Fig. 4.1.

seafloor is removed.

4.4. Problems with data quality and methods

The cause behind the poor data quality can be brought down to two main factors. The first is geological factors and the second processing and migration. The water depth in the fjords poses an issue for the data quality. In deep water, it becomes inaccurate to assume a constant p-wave velocity due to temperature changes, currents and swell. It is difficult to correct for these irregular variations during migration. If not corrected, it can manifest as jitter, multiples, loss of amplitude and other (Hall 2003).

Another posing issue is the highly varied seafloor topography and steep coastal slopes, which is evident from the bathymetry. This can blur and distort reflectors and create hyperbolas (Han et al. 2019). The glacial deposits in the fjords form a hard cemented seafloor, which have the tendency to generate seafloor multiples. It appears form the seismic data that these three issues have generated noise in the form of multiples, weakened amplitudes, jitter and distortions of primary reflectors. This was unsuccessfully removed during processing. As a result, it is difficult to assess what the reflected geological structures really look like. A clear example of this is the persistent pull-up and push-down of reflectors caused by a combination of strong topography and cemented seafloor. It appears in several of the seismic lines, but the most prominent examples are the undulations in the basin stratigraphy in line NH8706-404.

Additional sorts of artefacts are observed in the data set. The dolerite intrusions have a very high acoustic velocity. By absorbing the p-wave energy, they mask underlying reflectors creating a processing shadow. Furthermore, high p-wave velocity units can generate peg leg multiples which are difficult to identify and remove during migration. Peg leg multiples are short path multiples which may add to the primary reflector (Sheriff et al. 1995). Additional types of processing shadows that are found in the seismic data are fault shadows. They form when the reflection from the fault masks the structures of the footwall. In the tie-line, snow cover hampers the underlying geology to reflect.

Lateral changes in p-wave velocity across a unit can create artefacts. If the time anomaly is not corrected for during migration, parabolas can manifest in the image. This seems to be the case in several of the seismic lines. The parabolas cover the seismic image, which can become unreadable. On top of this, crossing parabola limb interfere resulting in a chaotic appearance of the seismic image.

The seismic datasets used in this study have been presented and published in several previous articles. However, this study finds that some of the interpretations are questionable and based on very poor evidence – especially, concerning the Devonian stratigraphy and basement. Bælum & Braathen (2012) published an interpreted seismic cross section from Sassenfjorden and Isfjorden (Fig. 4.8, top). They delineate the boundary between Devonian rock and the basement based on chaotic variations in reflector intensity and citing Bergh et al. (1997). A closer look at the seismics could easily trace the boundary in various ways. They describe both the Devonian and basement boundaries as "diffuse" and seismic velocities as >6km/s, factors that would make it extremely difficult to differentiate between the two units in a seismic survey. Especially, since both units show internal heterogeneity and folding that instead of assisting the separation of the units in seismic data, make it more diffuse.

A closer look at Bergh's et al. (1997) interpretation of seismic line ST8815-227 (Fig. 4.8 lower) does in fact not show any better resolution and confidence regarding the seismic reflection of the top of the basement despite them being quoted by Bælum & Braathen (2012) as presenting the basement with high confidence. They even declare the basement high as a "fact" (Bælum & Braathen (2012, page 44). This is a quite bold statement to make based on "diffuse" seismic data and no well data from those units to support the claim.

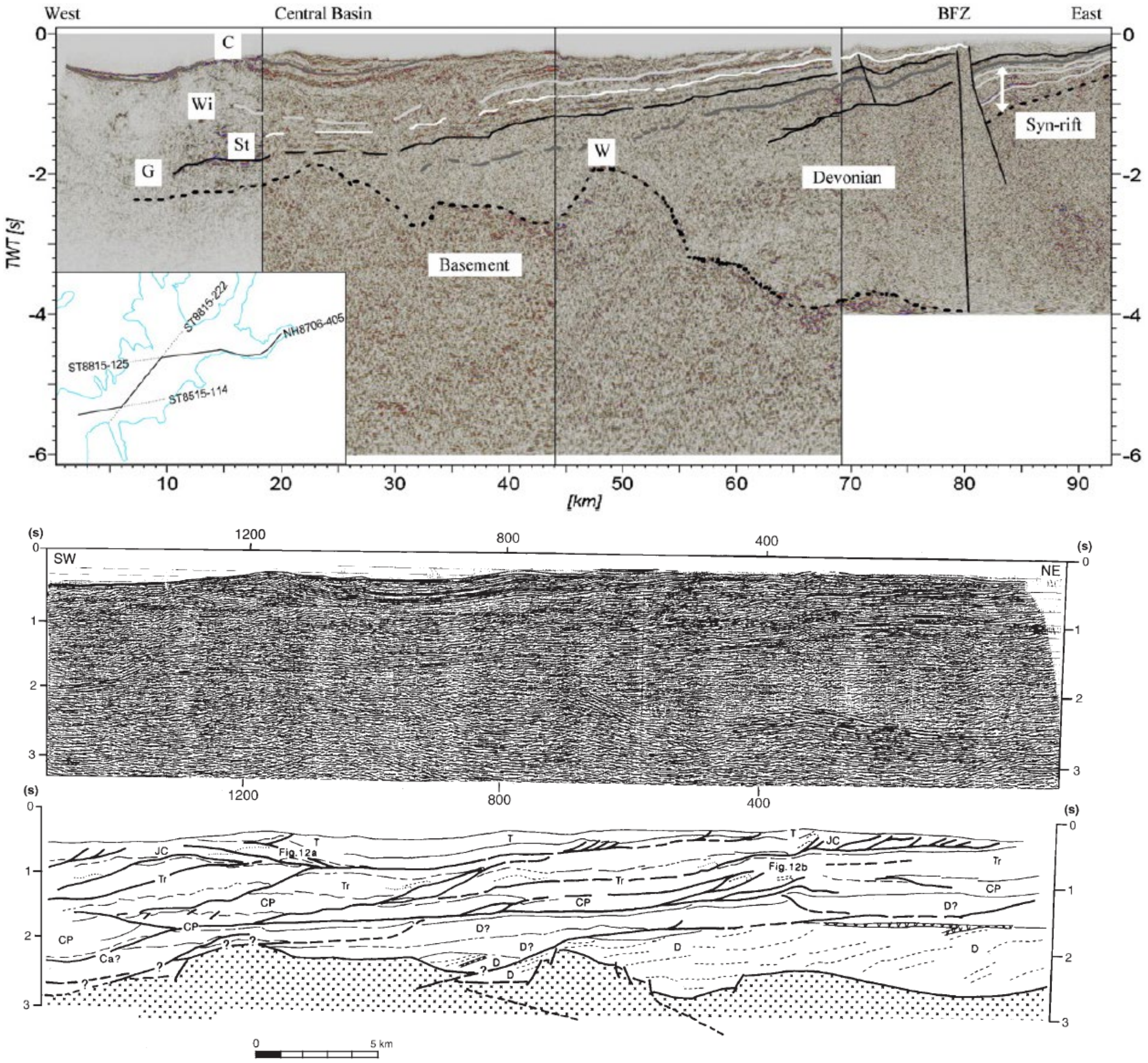


Fig. 4.8 Seismic interpretation of line across Sassenfjorden and Isfjorden. Above: Bælum and Braathen (2012) C-Top Gipsdalen Gr., Wi-Top Wilhelmøya Fm., St-Top Kapp Starostin Fm., G-Gipsdalen Gr., W-Wordiekammen Fm. Below: Bergh et al. (1997). D- Devonian, Ca- Lower Carboniferous, CP- Middle-Upper Carboniferous, P- Permian, Tr- Triassic, JC- Jurassic-Cretaceous, T- Tertiary. The two studies interpret the top of the basement on very vague reflectors.

Going further back, the initial idea of a basement high comes from gravity and aeromagnetic data (Skilbrei 1991). The data show a strong anomaly covering all of Isfjorden, Sassenfjorden, Billefjorden and southern Dickson Land. The anomaly is interpreted as a basement high. This is likely accurate to a large extent, but the problem is that not all of the basement is magnetic, thus the data are not representative for the entire Pre-Caledonian Basement. Furthermore, younger magnetic intrusions may be included in what is interpreted as basement. Finally, the geometry of the aeromagnetic survey does not resemble the lateral changes that are presented by Bælum & Braathen (2012).

The ideal method of seismic interpretation would be seismic data that have undergone good processing and migration, which has dealt with noise to minimise seismic artefacts. A well would be available directly in the study area, crossing a seismic line. Check shots and a borehole log data would be used to make a velocity survey. Now it would be possible to identify and pinpoint the depth of stratigraphic boundaries in TWT in the seismic survey. When the geological units are identified, it would be standard procedure to describe the seismic signature of each unit as they appear at the well. With all this information available, it would be the next step to trace each geological formation with a “horizon” laterally across the seismic survey. If the stratigraphy is cut by a fault or if any other uncertainty hinders continuous tracing of a horizon, the interpretation can be assisted by using seismic signature and expected thickness and velocity of geological units. After delineating and identifying stratigraphic units, structural analysis can be done. However, seismic interpretation is never this ideal.

Several deviations from the described method had to be done in this project. For one, the closest available well with a tie to both the stratigraphy and velocity survey is located very far from the actual study area. The well is drilled over fault and compression structures; this made seismic signatures not applicable for the basin analysis further north. A line segment along the tie-line was a raw line. This means that it was not subjected to some of the migration procedures as the rest of the data. Tracing reflectors across the section may cause vertical errors in placing stratigraphic boundaries. One could argue that is it possible to get seismic signatures from further north along the tie-line, the problem however is, that there already is uncertainty about the placement of reflectors due to the fault zone and raw seismic line. More so, the seismic reflectors in the seismic data are too weak and affected by noise to identify any characteristic appearance of the geological units.

Tracing reflectors continuously across faults and between seismic lines was problematic. No common date was determined during the processing of the datasets, this produces a miss-tie between surveys and the same reflector may end up at different TWT on crossing lines. The faults that cross Sassenfjorden cut the stratigraphy making it impossible to continuously trace the stratigraphy from the tie-line west of the BFZ and to Billefjorden. Furthermore, the velocity survey is likely deviating from the p-wave velocities in the basin further north, since the stratigraphic units will have different composition in the basin from the compression structure.

Changing depth is also a factor since p-wave velocities increase with pressure and depth (Shearer 2019). The same unit will have different acoustic velocities at different depths. To overcome these issues, the seismic images were interpreted to a great deal based on the land geology nearby. Extrapolating faults and basin stratigraphy offshore.

A general problem with this method is that the interpretation is backwards. The data, in this case seismic image, should give information about the geology. Instead, it seems that in many cases it is knowledge of the geology that has led to interpretations of the seismic image. For example, syn-rift sequences are identified by the increased thickness towards faults. In several cases these intervals in the seismic image are assigned geological units based on expectations, e.g. the behaviour of exposed geological units on land. However, this leads to giving the image meaning based on nearby geology instead of understanding the geology based on proof and measurements form the image. The risk is that errors extrapolate to larger areas and any geological knowledge taken from previous publications may be flawed.

4.5. Future studies

One of the main issues concerning the seismic data used in this project is migration and processing. The data were collected decades ago and the shortcomings of older technology are evident. Seismic processing has made great advances the past years. New algorithms, which greatly improve the quality of the seismic image, have been developed. If the data presented here are to be used in any other future study, reprocessing is necessary. This could improve the noise-to-sound ratio, eliminating many artefacts. Furthermore, correcting for water depth and a common date would minimize the miss-tie between surveys. Better-applied migration would improve reflectors and potential time anomalies. Reprocessing with a common date would allow creating amplitude maps, which are useful for basin and fault analysis.

The seismic datasets available for this survey can only be used for a very general regional interpretation of large-scale structures, e.g. the location and extent of basins, highs and lows and to some extent very general information about the location of large faults. The study is limited to 2D seismic lines and therefore I cannot say anything about lateral movement nor the exact dip or orientation of faults, if and where faults are connecting. The seismic data used in this survey are of no further use until it is properly reprocessed and migrated. In addition, wells with velocity surveys in outer Petuniabukta and/or offshore Narveneset would greatly increase the use of the seismic data.

Potential future studies could focus on the relation between the Balliolbreen and Odellfjellet faults with the Gipshuken reverse faults. It would be interesting to have a better understanding of the fault array crossing over from south-east Billefjorden to Gipshuken and Gipsvika. In addition, an analysis of the offshore dolerite intrusions around Gåsøyane could shed light on the seafloor plateau north of Anservika.

5. Conclusions

The discussion can be summarised with the following conclusions:

1. The geology in the study area records tectonic development from Caledonian mountain building to Palaeogene contraction.

2. The Andrée Land Group is deposited over a Pre-Caledonian Basement. A period of post-orogenic relaxation (Haakonian and Monacobreen events after the Caledonian Orogeny) faulted the Devonian Andrée Land Group. Later, contraction during the Svalbardian Event/Ellesmerian Orogeny initiated the BFZ on pre-existing weakness in the basement along an old shear zone. The Balliolbreen Fault formed as a reverse fault.

   After a short period of tectonic stability and the deposition of Billefjorden Group, the early Cretaceous is characterised by extension. During this time, the Odellfjellet Fault developed as a normal fault with the subsiding Billefjorden Trough to the east. Extensional reactivation along the Balliolbreen Fault is suggested by faulted Carboniferous stratigraphy.

   Another period of tectonic stability is suggested by Permian to Cretaceous deposits. Strong anomalies in the seismic profiles suggest Cretaceous dolerite intrusions lie offshore Gåsøyane and towards Rundodden. They are associated with large igneous provinces and rift development in the Arctic.

   The last recorded event is Palaeogene contraction. During this stage, the West Spitsbergen Fold Belt (West Spitsbergen Orogeny) developed in the west. The rocks in the study area show deformation structures that indicate crustal shortening. Fold ridges and low angle thrust faults are found across Sassenfjorden. Furthermore, the Gipshuken reverse faults overprint/reactivate the Balliolbreen and Odellfjellet faults, suggesting a second reactivation of the BFZ caused by the West Spitsbergen Orogeny. This time however, the reactivation had a reverse character. Lastly, a flexure-response to the West Spitsbergen Orogeny/Eurekan Orogeny caused the stratigraphy to tilt, forming the Central Tertiary Basin.

3. A different model for along strike changes of the BFZ is presented than what has been suggested by previous work. Bælum & Braathen (2012) proposed model with relay ramps, large extensional displacement along the Balliolbreen Fault and the existence of the steep deep-seated Drønbreen Fault is questioned. Instead, this study suggests that the Balliolbreen and Odellfjellet faults maintain a constant fault array across Pyramiden, Gipshuken and Sassenfjorden.

4. Previously unmapped faults are suggested across Sassenfjorden. They have a NW-SE strike and associated with the Palaeogene WSFB (West Spitsbergen Orogeny/Eurekan Orogeny). However, some uncertainty whether the lineaments are faults or folds remain due to the poor seismic data quality.

5. The seismic data available for this study are insufficient for an accurate interpretation of the Billefjorden and Sassenfjorden areas. Primary reflectors are very few and weak. Many faults do not reflect at all, instead, their location is based on map data form nearby land areas. Furthermore, the high noise-to-sound ratio and artefacts were unsuccessfully removed during processing and migration. The resulting seismic data are unreliable and do not always present a realistic image of the subsurface geology.

6. The seismic data are to a great extent interpreted based on the nearby geology and published work. It has become evident that some of the published articles also base their geological models on vague data. Thus, there is a risk that some poor interpretations are used during background study and misconceptions or errors are transferred into new studies. This is the problem when one is interpreting the data based on the geology and not vice versa. It becomes easy to misinterpret the data based on what one expects to find.

7. If used in future studies, the seismic data need to be reprocessed. Better migration has to be done in order to correct for water depth, steep topography and the cemented seafloor. Furthermore, wells from Billefjorden with stratigraphic logs and check shot surveys would greatly improve the reliability of any interpretation of the seismic data.

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