Seafloor expression and shallow structure of a surfacing fold-and-thrust system: an example from Isfjorden, West Spitsbergen.

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Abstract

A detailed map of the structure of the West Spitsbergen Fold-and-Thrust Belt in the shallow part of the Isfjorden area, Spitsbergen, is presented. The map was constructed from a new dense grid of 2D multichannel reflection seismic and bathymetrical surveys. Interpretation of two different datasets gave a possibility to observe and compare tectonic structures detected along the uppermost part of the seismic sections and those reflected in morphological data at the seafloor. Correlation of the tectonic structures as expressed in the two datasets shows a good match and three major thrust faults were identified. The outcropping thrusts display a dominant NW-SE strike. The westernmost thrust fault (T1) is an out-of-sequence hinterland-directed thrust, whilst the central and easternmost thrust faults (T2 and T3) represent foreland-directed in-sequence thrusting. The thrusts divide Isfjorden into three subareas. Subarea 1 is bounded by thrust faults T1 and T2 and comprises Tertiary rocks surrounded by Jurassic-Cretaceous strata. The structural signature of Subarea 1 is that of a system of hinterland- and foreland-directed thrust faults, resulting in a seafloor relief characterized by parallel ridges and lows. Subarea 2 is limited by thrust faults T2 and T3. It includes an area of Jurassic-Cretaceous strata outcropping on the seafloor. Subarea 3 is situated east of the main thrust fault T3, and mainly incorporates outcrops of Triassic-Jurassic rocks. Together, Subareas 2 and 3 are dominated by foreland-directed thrusting with NW-SE and NNW-SSE strike directions, which are hardly detectable in bathymetric data.

Introduction

The archipelago of Svalbard is located at the north-western Barents Sea continental shelf. The Palaeogene West Spitsbergen Fold-and-Thrust Belt (WSFTB) at the west coast of the main island Spitsbergen was developed during the latest tectonic event in response to breakup and initial opening of the Norwegian-Greenland Sea (Talwani & Eldholm 1977; Srivastava 1985; Olesen et al. 2007; Engen et al. 2008; Gaina et al. 2009). The evolution of WSFTB has been explained as a result of a head-on convergence between the Greenland and the Eurasian plate by Lyberis and Manby (1993ab), Tessensohn & Piepjohn (2000), the CASE team (2001) and Saalman & Thiedig (2002). According to the alternative model the contractional component of a strain partitioning (Faleide et al. 1988; Maher & Craddock 1988) in a transpressional setting (Harland 1969; Lowell 1972) has induced the fold-and-thrust belt itself. The latter model has been supported by analogue modeling performed by Leever et al. 2011a,b. Hence, the main tectonic regime responsible for the development of the fold-and-thrust belt (Fig. 1) was related to evolution of a dextral transform fault system between Greenland and Svalbard (Harland 1969; Birkenmajer 1972; Srivastava 1978; Birkenmajer 1981; Faleide et al. 1993; Lundin & Dore 2002; Mosar et al. 2002; Faleide et al. 2008; Gaina et al. 2009).

A series of detailed field-based studies of the structure and evolution of the fold-and-thrust belt in the Isfjorden area have been performed (Maher et al. 1989; Andresen et al. 1992; Braathen et al. 1995; Braathen & Bergh 1995; Braathen et al. 1999; the CASE team 2001; Piepjohn & von Gosen 2001; Tessensohn 2001; von Gosen et al. 2001), leaving a very good database for correlation to offshore reflection seismic and bathymetric data. Interpretation of the fold-and-thrust belt structures based on the Isfjorden marine reflection seismic data were presented by Nøttvedt (1994) using several multichannel lines. Bergh et al. (1997) published a regional structural compilation map of central Spitsbergen based on field and offshore data. They also constructed an offshore geologic and tectonic map of the central part of Isfjorden by means of 12 multichannel seismic lines crossing the area. In the present work a dense grid of new multichannel seismic lines and widespread echo sounder survey coverage in Isfjorden were utilized, permitting the construction of a more detailed structural map of the Isfjorden area.

Isfjorden is the largest fjord of Spitsbergen extending about 100 km inland and its coastal part is widening to 20 km. It is located at the west coast of the central part of the island (Fig. 1). The glacial erosion in the Isfjorden area left a seafloor relief that reflects the varying mechanical strengths of the various lithologies of the fold-and-thrust units emergent at the seafloor, thus promoting identification and mapping of the tectonic units based on the seafloor relief itself. By combining these observations with the shallow parts of the reflection seismic sections a structural map of the upper part of the thrust system can be produced, opening for detailed correlation to structural features already identified by onshore structural mapping. Marine acoustic records in the fjord revealed that the bedrocks in the area are covered by ca. 5- 20 m thick (5-20 ms twt) layer of unconsolidated mud (Elverhøi et al. 1983; Germond 2005). Generally, this layer of post-erosion sediments repeats morphology of underlying bedrock, and thus do not prevent observation of its structures on seafloor relief.

The main goal of this study is to construct a detailed map and describe tectonic features in the shallow part of the fold-and-thrust belt in Isfjorden based on compilation of two different data sets, the multibeam echo sounder data and 2D multichannel seismic (MCS) data. Linking the observed uppermost structures to deeper ones is beyond the scope of this article and is described in a separate publication (Blinova et al. in preparation). The high resolution bathymetric chart derived from the echo sounder data allows for observation of tectonic features that are expressed at the seafloor. Furthermore, multichannel seismic data provide images of the subsurface tectonic structures. A compilation and integration of independent interpretations of these two data sets was performed to correlate seafloor relief with subsurface structures. Detailed mapping of tectonic features in the fjord might provide a better understanding of tectonic settings of WSFTB related to transpressional deformation along the western coast of Spitsbergen.

Geological setting

The geology of Spitsbergen comprises strata of Precambrian to Recent age displaying a complex deformation during various tectonic regimes since Palaeozoic times (Fig. 1) (Dallmann 2007). Accumulation of an almost unbroken upper Paleozoic to lower Tertiary sedimentary succession in Svalbard took place due to submergence of the area during most of its geological evolution (Hjelle 1993). Basement rocks of Spitsbergen comprise magmatic and metamorphic units of Precambrian – Silurian age that were intensely deformed during the Caledonian Orogeny (Harland 1959, 1985; Birkenmajer 1975; Ohta 1992; Fossen et al. 2008; Gee et al. 2008). Since the end of the Caledonian Orogeny, the Svalbard area underwent several periods of erosion, sedimentation and tectonism. Extensive erosion of the Caledonian mountain range in the Devonian period is reflected in accumulation of up to 8 km thick pile of Old Red Sandstones preserved in major down-faulted crustal blocks (Friend & Moody-Stuart 1972; Murashov & Mokin 1979). In the Late Devonian these sediments were folded and trusted in the Svalbardian event (Vogt 1928, 1929; Dallmann 1999; Bergh et al. 2011), whereas the period from the later Carboniferous to mid-Permian times was characterized by deposition of limestone and dolomite interbedded with evaporites (gypsum and anhydrite) (Worsley & Aga 1986; Dallmann 1999; Worsley 2008). During the Mesozoic a thick succession, mainly consisting of shales, siltstones and sandstones, was deposited in conditions influenced by pronounced sea level fluctuations. In the latest Jurassic - Early Cretaceous volcanic activity took place in Spitsbergen area leaving intrusions of dolerite dykes and sills within the sedimentary sequence (Worsley & Aga 1986; Hjelle 1993; Dallmann 1999).

During fold-and-thrust belt formation, strata along the west coast of Spitsbergen underwent uplift and erosion whereas a foreland basin (the Central Tertiary Basin) developed in the central part of the island, south of Isfjorden (Steel et al. 1985; Worsley & Aga 1986; Dallmann et al. 1993). Eastward propagation of the fold-and-thrust belt occurred above basal decollements localized in Permian gypsum and Middle Triassic and Upper Jurassic organic rich shales (Fig. 1; Braathen et al. 1995; Braathen & Bergh 1995; Bergh et al. 1997; Piepjohn & von Gosen 2001). A tensional tectonic configuration prevailed between Svalbard and Greenland since the Oligocene time (magnetic anomaly 13), following a plate tectonic reorganisation of North Atlantic (Talwani & Eldholm 1977; Tessensohn & Piepjohn 2000; Engen et al. 2008; Faleide et al. 2008). At that time WSFTB became inactive (Faleide et al. 1993).

Data

The geophysical data used in the present study (Fig. 2) encompass bathymetric recordings and 2D multichannel seismic profiles. The bathymetrical data were provided in an acoustic survey that was carried out by the University of Bergen (Norway) in 2004 by the use of a Multibeam Echo Sounder EM 1002. The equipment provides high resolution data of seafloor relief at water depths varying between 10-1000 m. The acquired acoustic data were exported as xyz grid format with 30 meters cell size for 2 and 3 dimensional visualizations by “ArcGis” and “Fledremaus” softwares (Germond 2005).

The 2D multichannel seismic lines were acquired by the University of Bergen during “Svalex” surveys in 2004, 2005, 2006 and 2007 (Mjelde 2004, 2008). The data were acquired with 50 meters shot-interval and a streamer of 3000 meter length. These surveys cover in total ca. 1850 km of seismic lines with 500 m distance in between. A data set of multichannel seismic acquired by Statoil in 1985 and 1988 was recorded with streamers lengths of 2400 and 3000 meters respectively, and a 25 meter distance between the shot-points. The data acquired in the Statoil surveys comprise approximately 1660 km of profiles.

Interpretation

The dense grid of multichannel seismic data and the multibeam echo sounder data have been used for correlation of seafloor morphological features and tectonic structures in the shallow part of the fold-and-thrust belt in Isfjorden. The resolution of the multichannel seismic data enables detailed interpretation of tectonic structures within the upper part (1 sec. twt) of the sections. The seafloor reflection along some seismic lines has been affected by muting during seismic data processing.

Correlation of seismic units with the stratigraphy as established from onshore studies of the Isfjorden area was based on Ohta et al. (1992), Nøttvedt (1994), Bergh et al. (1997) and Dallmann (1999). A typical representation of the seismic signatures and its stratigraphic correlation is shown in Fig. 3, displaying the lowermost angular unconformity separating chaotic, discontinuous reflections and strong continuous reflections that corresponds to the transition between Devonian(?) and Carboniferous-Permian units. Weak discontinuous reflections of Sassendalen Group shale are overlain by the Kapp Toscana sandstones of higher reflectivity comprising the typical seismic character of the Triassic-lowermost Jurassic strata. Furthermore, the low velocity shales of the Janusfjellet Subgroup and overlying high velocity sandstones of the Helvetiafjellet Formation produce a pronounced impedance contrast and a strong reflection. Finally, the base of the Tertiary sequence is defined as a thin transparent unit covered by a sequence of strong, continuous reflections. Principal decollements, which can be correlated over longer distances along multichannel seismic sections are shown in Fig. 3 as well.

Key transect

An example of the seismic image of the Isfjorden section of the WSFTB and our interpretation is shown in a transect compiled from the two seismic lines ST8815-222 and ST8515-121 in Fig. 4. The sections allow the identification of continuous reflectors that separate the Carboniferous-Permian, the Triassic - lowermost Jurassic, the Jurassic – Lower Cretaceous, and the Tertiary sequences. The sediments dip westward so that the rocks cropping out at the seafloor become older to the east.

Two main contractional tectonic structures are observed in the field and described by use of terms “decollement” and “thrust”. The term “decollement” stands for faults that are basal and layer-parallel, while the “thrust” corresponds to low-angle faults cutting the bedding.

Three major thrust levels with a characteristic top-to-the-east contraction are evident, but local (most likely out-of-sequence) back-thrusts are observed in the western part of the sections adjacent to the basement-involved fold-thrust complex (0-10 km along the transect; Fig. 4). The thrusting inflicted easterly rotation of the strata and the formation of a syncline that affects the shallower units encompassing the Central Tertiary Basin.

The three very pronounced decollements are clearly displayed in the transect (Fig. 4). The uppermost and intermediate decollements are located within the Upper Jurassic and Middle Triassic black shales respectively, whereas the lowermost is developed in the Permian evaporite. Two of the major thrusts (T2 and T3 in Fig. 4(b)) are foreland-directed and emerge to the seafloor. The thrusts are affiliated with the uppermost decollement level within the Upper Jurassic. Also thrust T1 breaks the seafloor. It is, however, hinterland-directed, belongs to the uppermost decollement (D1) and is probably an out-of-sequence structure. Thus, T2 defines the frontal part, whereas T1 defines the trailing edge of the nappe above the upper decollement (D1) that includes the Tertiary Basin. T1 is the most westerly major thrust fault that can be identified in the acquired seismic lines. The deepest decollement (D3) is identified along the full length of the section, but either terminates as a blind thrust fault within the Permo-Carboniferous sequence, or merges up-section with the intermediate decollement (D2) near the eastern end of the section (Fig. 4(b)). The T1, T2 and T3 separate regions of different tectonic/structural styles on the seafloor and therefore delineate three tectonic subareas (Fig. 4(b)). Subarea 1 is bounded by master faults T1 to the west and T2 to the east, both of which emerge from the decollement (D1) within the Janusfjellet Subgroup. Subarea 1 therefore contains Jurassic, Lower Cretaceous and Tertiary deposits. Subarea 2 is bounded to the east by master fault T3 that emerges from the decollement of the same stratigraphic layer as that of Subarea 1. However, this subarea is dominated by rocks of Janusfjellet Subgroup outcropping at the seafloor. Subarea 3 covers an area on the seafloor where mostly Triassic-Lower Jurassic strata crop out, surrounded by thin units of Jurassic-Cretaceous and Carboniferous-Permian sediments to the east and west of it, respectively. A correlation of the lithological boundaries and tectonical structures defined offshore with onshore geology is shown in Fig. 5. According to the map, thrust fault T2 can be directly correlated with the Fuglefjellet Thrust at Grumantbyen. This fault cuts the Central Tertiary Basin strata along the southern shore of Isfjorden (Dallmann et al. 1993).

Multichannel seismic data

An interpretation of a seafloor reflector along all available multichannel seismic lines was used to produce a seafloor relief map (Fig. 6). The seafloor bathymetry strikingly displays the most prominent morphological features associated with Subarea 1 and Subarea 2. Thus, the eastern boundaries of Subarea 1 and Subarea 2 are both well defined by long, continuous escarpments. Internally, Subarea 1 is characterized by an uneven and undulating bathymetry with the deepest part situated to the north close to the shore of Oscar II Land. Some of these features can directly be linked to contractional structures, which, taking the seafloor bathymetry into account, probably are discontinuous in the section represented by the seafloor. In contrast, Subarea 2 is to a larger degree affected by elongated and continuous escarpments, representing outcropping to seabottom faults with more continuous traces. Compared to Subareas 1 and 2 the seafloor relief in Subarea 3 is smoother, although several elongated minor escarpments can be identified, which also can be correlated to minor thrusts (Fig. 6). Based on these observations it seems evident that the image emerging from the cross-sections, with principal decollements separating thrust sheets, which are affected by internal secondary contractional faults and folds could also be expressed in map view.

Subarea 1

The major part of Subarea 1 contains Tertiary rocks surrounded by outcrops of Jurassic-Cretaceous strata (Fig. 7 (a)). This subarea is characterized by abundance of back-thrusts. Good examples of the structural style of Subarea 1 are shown for lines ST8815-222, SV04-4, -7, -19, -27 and SV05-38 in Fig. 7. Fig. 7(b) and (c) is typical for the structural style adjacent to the western boundary of Subarea 1. The major back-thrust (fault T1) cuts up-section to the west rising from the decollement D1 in Upper Jurassic strata. Fault T1 carries another back-thrust in its hangingwall, splaying out from the same decollement. The hinterland-directed system also encompasses uplifted snake-head structures in the hangingwalls of footwall ramps, fault propagation folds and pop-ups (Fig. 7 (c,d,e)). The general strike of observed morphological highs and minor thrust faults in the eastern part of the subarea is NW-SE.

The north-eastern boundary of Subarea 1 is defined by the surfacing of foreland-directed thrust fault T2. As seen in Fig. 7(f) and (g) this is a thrust system with the geometry of an imbricate fan, the leading edge of which breaches the sub-glacial erosion surface. This feature includes an anticline (6 in Fig. 7(g)) bounded by thrust fault T2 to the east, which is interpreted as a hangingwall fault propagation fold.

Subarea 2

The most significant tectonic features of Subarea 2 (Fig. 8(a)) are the boundary thrust faults T2 to the west and T3 to the east. Both thrust faults branch from decollement D1 evolved within the Upper Jurassic sequence. In the cross-section image we observe a discontinuity of decollement D1 along the regional transport direction (20-24 km along the line ST8815-217, Fig. 8(b)). The discontinuity might be caused by the influence of the deeper structures in this segment. Generally, Subarea 2 has a tectonic/structural style, which is very different from that of Subarea 1. Its south-western border consists of a duplex where the uppermost horse has been exposed and eroded. To the north-east of the duplex two back-thrust fault branches (1 and 4) ramp up from the principal decollement D1 forming a topographic high (2) in between the two faults. The westernmost part may be a collapsed horse belonging to the duplex already mentioned. The affiliation to the back-thrusts (1 and 4) hangingwall-structure implies that two reverse faults (3 and 5) producing local pop-up features. The back-thrust (4) is followed northeast by other thrust branches (6 and 7) emergent from the decollement and associated with moderate seafloor morphology. Fig. 8(c) illustrates an interpretation of the major thrust fault T3 that ramps steeply up from the decollement and produces a laterally extensive escarpment on the seabed. The north-eastern part of Subarea 2 has the geometry of a regular foreland-directed in-sequence thrust system.

Subarea 3

In spite of the relatively smooth relief characteristics of Subarea 3, the underlying thrust system indicates an intensive deformation in the area (Fig. 9). The faults are easily identified in the reflection seismic data and define a pattern of en echelon thrust branches and associated folds (Fig. 9(b,c,d)). The seafloor topography displays highs and lows which are sub-parallel to the master fault branches, and escarpments are most likely derived by erosion of the outcropping fault scarps. Thrusts emergent to the seafloor of this area appears mainly to have evolved above the decollement D2 within Middle Triassic strata (Fig. 9(b,c)). Branches of thrust faults arising from the basal decollement D3 in Permian gypsum are observed only along slivers of outcropping Carboniferous-Permian deposits in the easternmost area (Fig. 9(d)). It is noteworthy that the north-eastern termination of the structures coincides with a wide and steadily climbing frontal footwall ramp.

Multibeam data

Data derived from the multibeam echo sounder survey allows us to obtain a detailed view of the seafloor relief. This can be used to confirm and evaluate the interpretation of the main tectonic structures as reflected in submarine morphology further to MCS data interpretation in a 3-D framework.

The interpretation of tectonic structures based on analysis of the submarine relief in Isfjorden is shown in Fig. 10. In Subarea 1 we can observe two groups of major topographical highs: one is striking SE-NW (marked by axes 1, 2 and 3) and the other is striking in the NNW-SSE direction (marked as 4, 5, 6). Topographical highs that are bounded on one side by escarpments and by a gentle slope on the other side were interpreted as thrust faults emergent to the seafloor (groups 7 and 8). Subarea 3 is characterized by relatively weak relief and less pronounced features. Nevertheless, two groups of the thrust traces were distinguished at the seafloor. As in the case for the Subarea 1, these two groups also differ by NNW-SSE and SE-NW strikes of thrust traces (group 9, 10 and 11 respectively; Fig. 10). Areas of uneven topography and lack of along-strike continuity may reflect sheet-like geometry of some folds and thrust units and perhaps the existence of transport-parallel ramps.

Discussion and conclusions

The observations from the multichannel seismic and multibeam data sets have been plotted together with aim to compare the interpretation of the two data sets. A combined geologic and tectonic map was produced displaying features derived from the multibeam data (red colour) and multichannel seismic data (black colour), including also onshore structures based on published material (Fig. 11).

The general trend of the interpreted features from the seafloor relief repeats the interpretation of the tectonic structures observed within the upper sedimentary sequence. However according to the map, structures which breaches to the seafloor are not always reflected in the bathymetry. For example, the tectonic map in Subarea 1 shows a good match between the two data sets interpretation, whereas the area of Subarea 3 shows that most of the structures identified in the upper sedimentary section that are cropping out to the seafloor are not pronounced in the bathymetry. The differences in correlation of the subsurface structures and bathymetry for Subareas 1 and 3 could be related to varying lithology of outcropping rocks. Thus, the Tertiary and the Lower Cretaceous (Helvetiafjellet Formation) sandstones may have been more resistant to erosion than the Triassic-Jurassic shaly sequences. The data coverage by the multibeam echo sounder data in Subarea 2 was not large enough to yield a reliable interpretation of the tectonic structures. Some of the structures that are well detected in multibeam data represent minor structures in reflection seismic and were not identified along cross-sections. For example, thrust fault (Fig. 7(f), 10km) was not interpreted along the seismic section but it left a pronounced imprint in bathymetric data (Fig.10). Thus, complementary interpretation of geological structures detected in multichannel seismic and multibeam data shows an advantage of different data sets integration.

Compilation of the study results with geological observations onshore demonstrates a direct correlation between lithological boundaries and tectonical structures of Isfjorden seafloor with structures on land (Fig. 11). The Fuglefjellet Thrust at Grumantbyen is well correlated with major thrust fault T2 outcropping at seafloor of Isfjorden. Detailed mapping of the shallow structures shows that most of the structures in Isfjorden are dominated by foreland-directed in-sequence thrusts and folds with NW-SE and NNW-SSE strike. Furthermore, the general picture demonstrates a significant effect of hinterland-directed out-of-sequence thrusting in some zones and particularly in the southern part of Subarea 1, which is in accordance with onshore observations along the western Nordenskiöld Land (Ohta et al. 1992).

Comparing the constructed geologic and tectonic map with observations published by Bergh et al. (1997), the new data introduce a correction and refinement in the interpretation of geological boundaries and of tectonic features offshore Isfjorden. According to our observations, the Central Tertiary Basin covers less area in Isfjorden than previously anticipated. We also suggest that the architecture of Isfjorden part of the WSFTB is similar to that seen onshore and that some major thrust planes can be directly correlated across it.

The detailed mapping of the shallow structures in Isfjorden area may also help to interpret the origin of the WSFTB. Geometry of the structures observed in Isfjorden area is in accordance with result of the analogue tectonic modelling supporting the hypothesis that formation of the WSFTB can be related to the low-angle transpression (Leever et al 2011a,b).

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Figures:

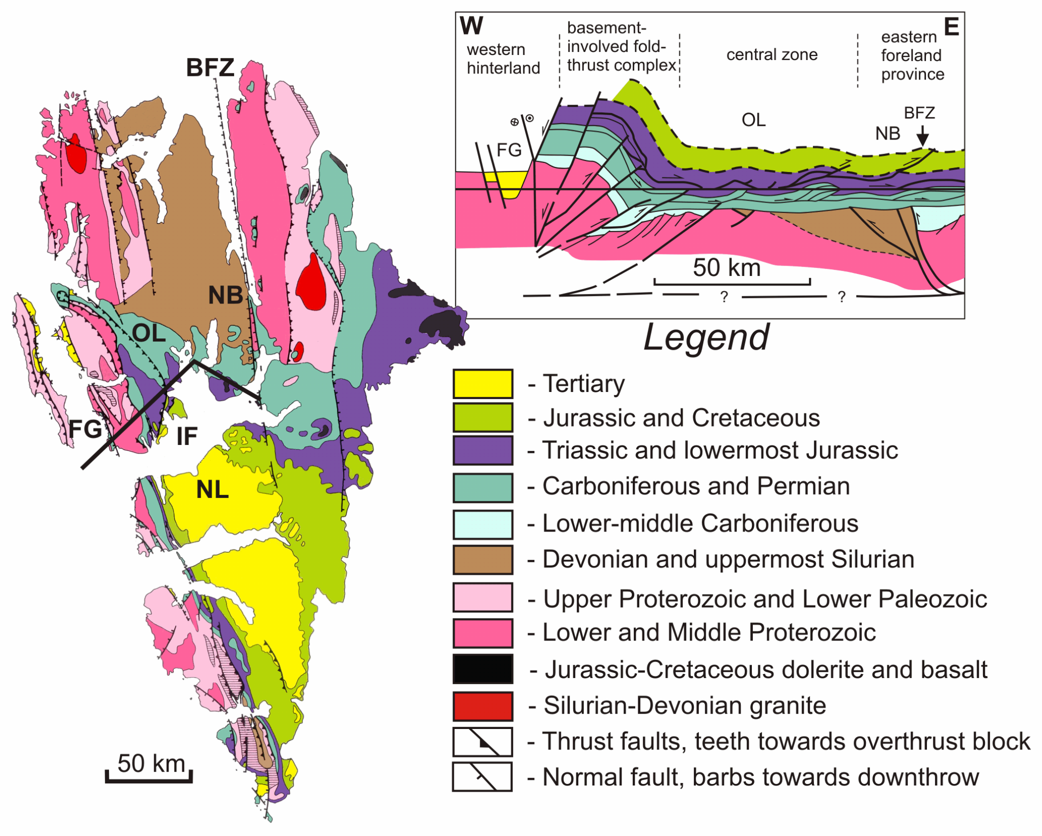

Figure 1. Geological map of Svalbard (Hjelle 1993) and generalized cross-section of the Isfjorden transect. Abbreviations: BFZ – Billefjorden Fault Zone, FG – Forlandsundet Graben; OL – Oscar II Land, IF – Isfjorden, NB – Nordfjorden block, NL - Nordenskiöld Land. The cross section shows a division of the fold-and thrust belt from the west to the east into: western hinterland, basement involved fold-thrust complex, central zone of folding and thrusting and eastern foreland province (Dallmann et al. 1993; Braathen et al. 1999; Bergh et al. 2000).

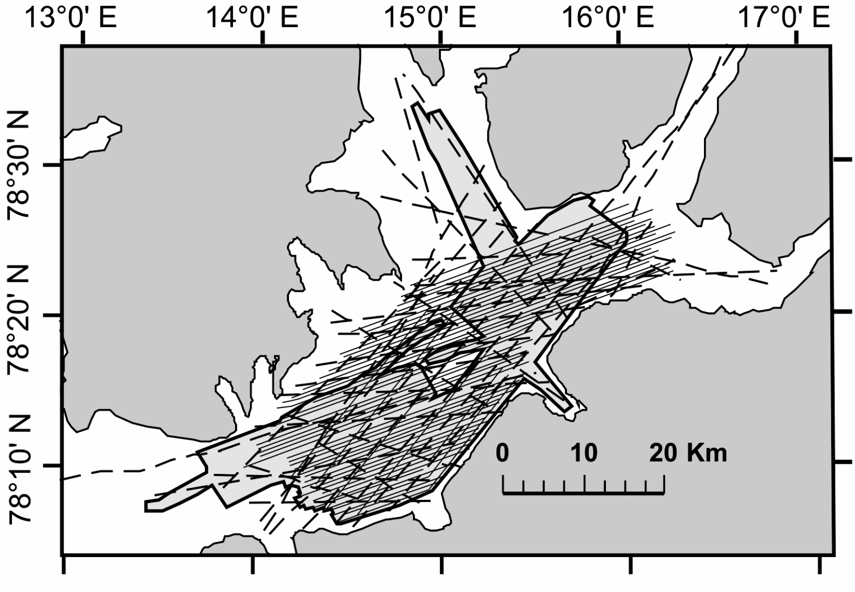

Figure 2. Survey map, Isfjorden. Solid lines – surveys Svalex 2004, 2005, 2006 and 2007, Dashed lines – surveys ST8815 and ST8515, grey polygon – boundary of multibeam echo sounder data coverage.

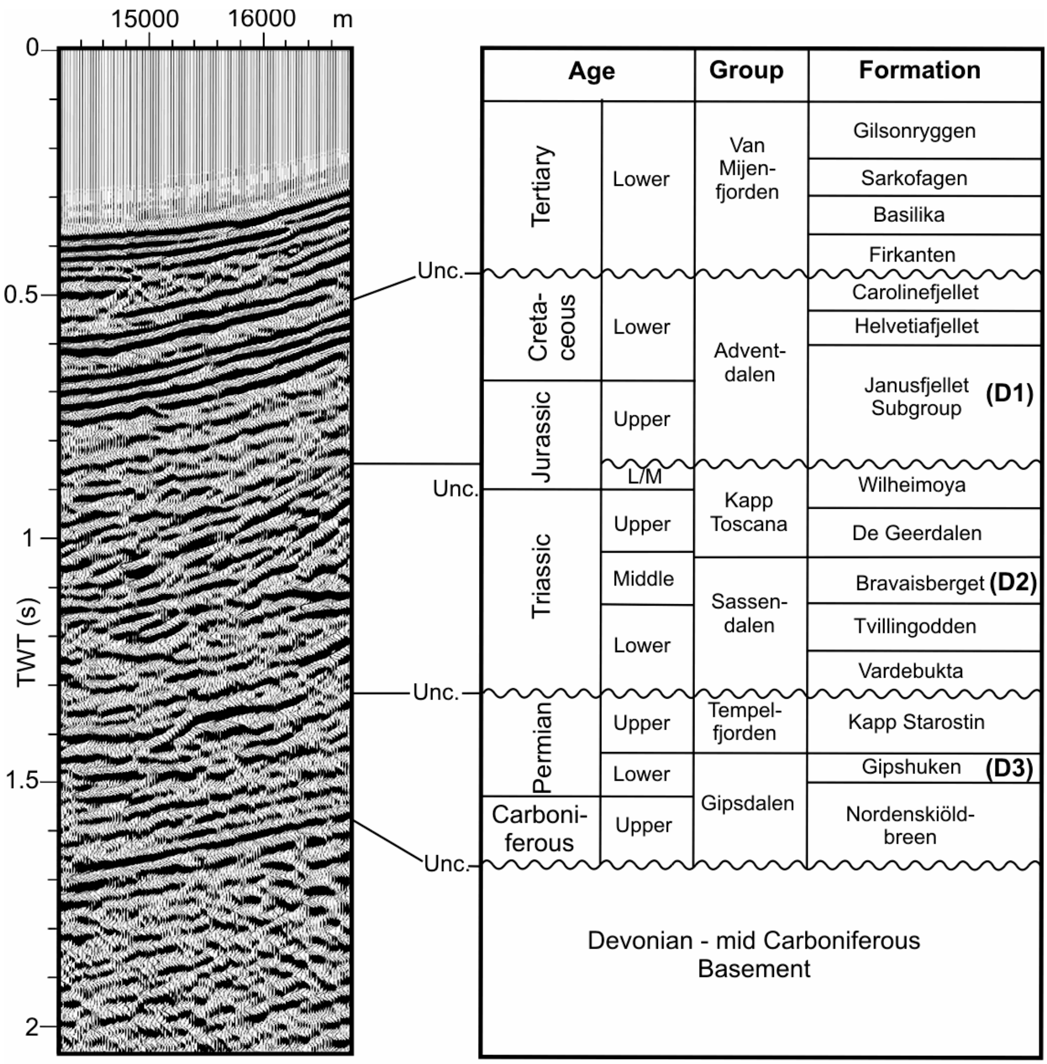

Figure 3. Correlation diagram of stratigraphic and seismic units. Example of seismic – line ST8815-227. Unc. – Unconformity; D1 and D2 – decollements in organic rich (black) shales of Janusfjellet Subgroup and Sassendalen Group (Bravaisbeget Fm), D3 – decollement in gypsum of Gipshuken Formation. Correlation is based on stratigraphical tables published by Ohta et al. 1992, Nøttvedt 1994 and Bergh et al. 1997.

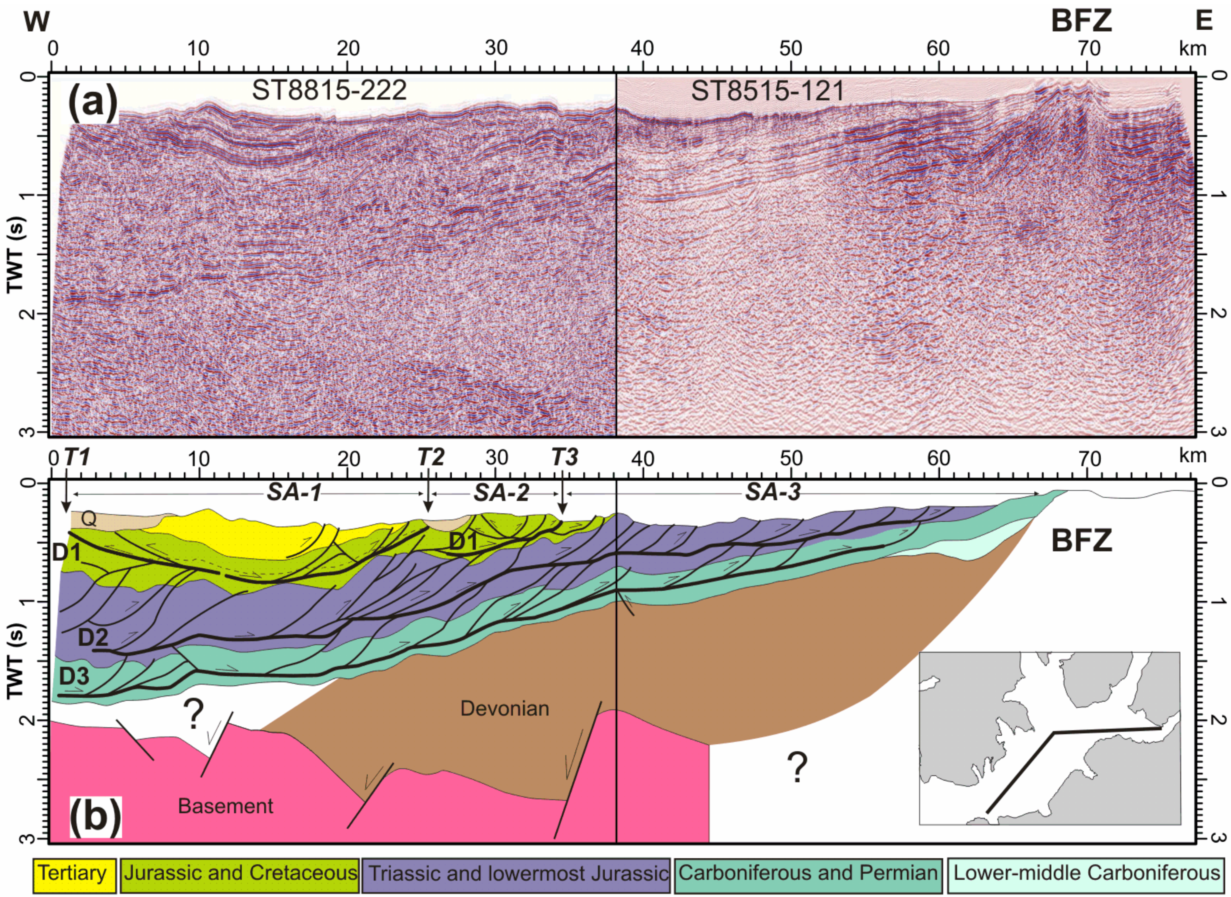

Figure 4. Seismic section along transect (joined lines ST8815-222 and ST8515-121 (a)), and its interpretation (b). Abbreviations: BFZ – Billefjorden Fault Zone, Q – Quaternary. T1, T2, T3 – major thrust faults. The defined three subareas are marked by: SA-1, SA-2 and SA-3. Thick lines – decollements (D1, D2, D3), thin lines – thrust faults; dashed line within interpreted Jurassic - Cretaceous strata corresponds to the base of Helvetiafjellet Formation.

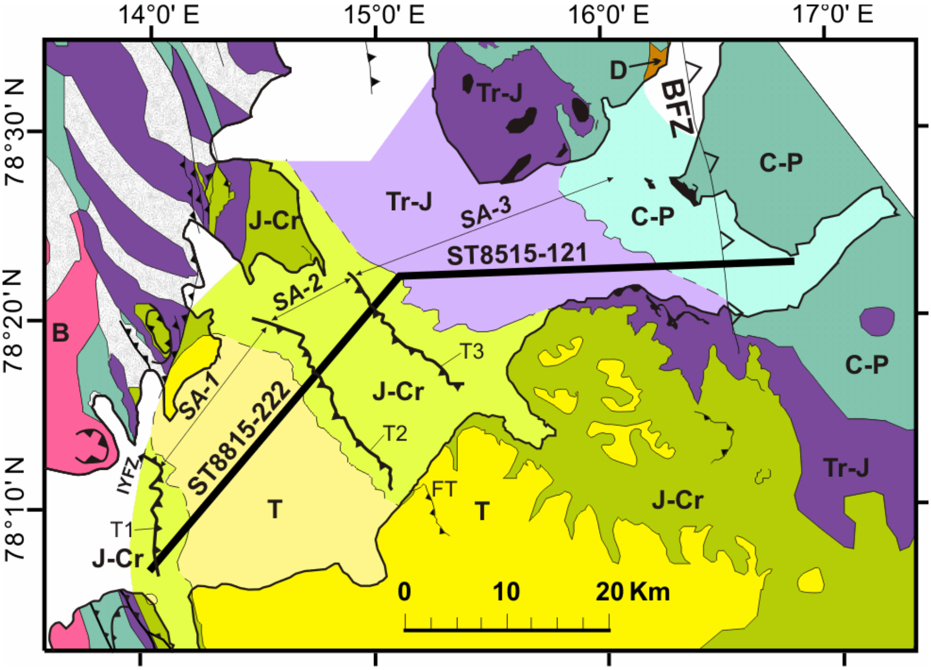

Figure 5. Geological map, Isfjorden area. Offshore geological boundaries derived from interpretation of multichannel seismic data within Isfjorden (see Fig. 3). Interpretation of transect along lines ST8815-222 and ST8515-121 is shown in Fig. 4. Grey areas on the map view represent glacial cover onshore and absence of data offshore. Abbreviations: BFZ – Billefjorden Fault Zone, IYFZ - Isfjorden-Ymerbukta Fault Zone, T – Tertiary, J-Cr – Jurassic and Cretaceous, Tr-J – Triassic and lowermost Jurassic, C-P – Carboniferous and Permian, B – Basement. T1, T2, T3 - major thrust faults. SA-1, SA-2, SA-3 – defined subareas. FT – Fuglefjellet Thrust at Grumantbyen. The onshore geological map in the figure is compiled from several maps published by Norwegian Polar Institute (Major & Nagy 1972, Lauritzen et al. 1989, Ohta et al. 1992, Dallmann et al. 1993, Major et al. 2000, Bergh et al. 2003, Dallmann et al. 2009).

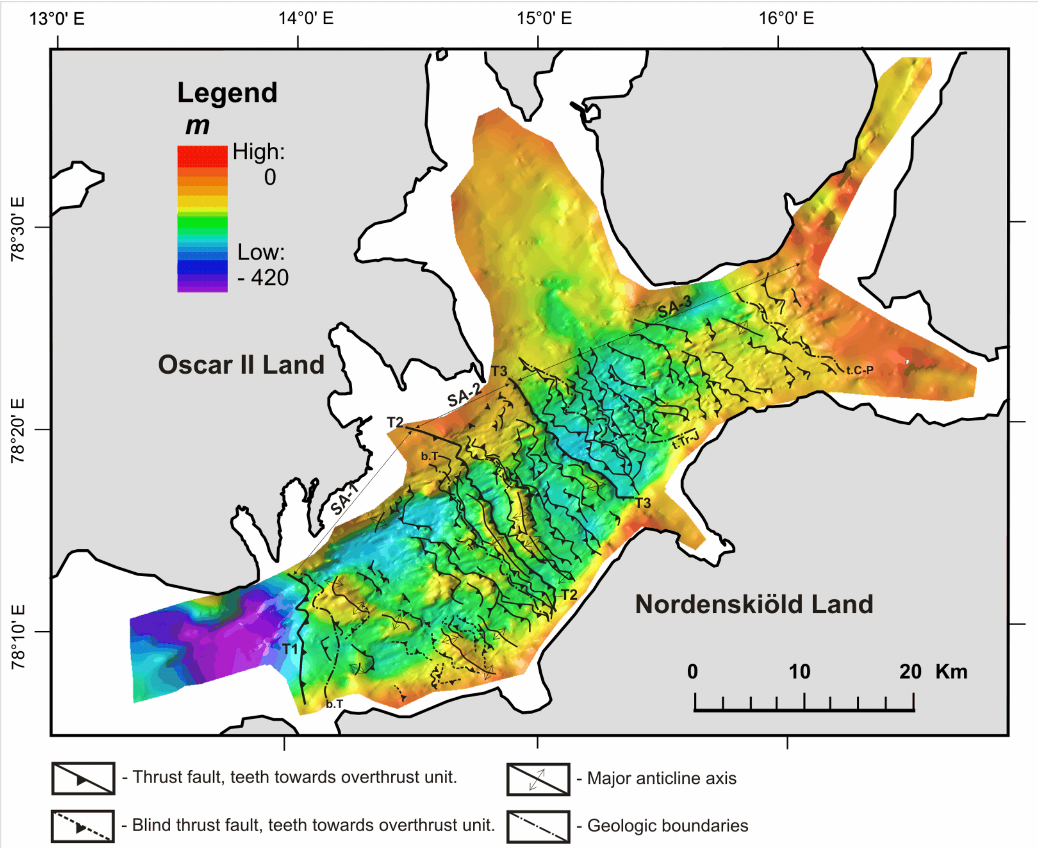

Figure 6. Seafloor morphology derived from interpretation of MCS data. Interpretation of the shallow tectonic structures in Isfjorden projected to the seafloor morphology map, derived from the MCS data. T1, T2, T3 – major thrust faults; b.T – base Tertiary horizon, t. Tr-J – top of Triassic and lowermost Jurassic strata, t.C-P – top of Carboniferous-Permian strata; SA-1, SA-2, SA-3 – defined subareas. The major thrust faults (T1, T2 and T3) are marked on the map by thick lines and represent boundaries between the subareas. The minor thrust faults are shown on the map as thin lines of two types – solid lines correspond to faults emergent to the sea-surface, whereas dashed lines refer to blind thrusts.

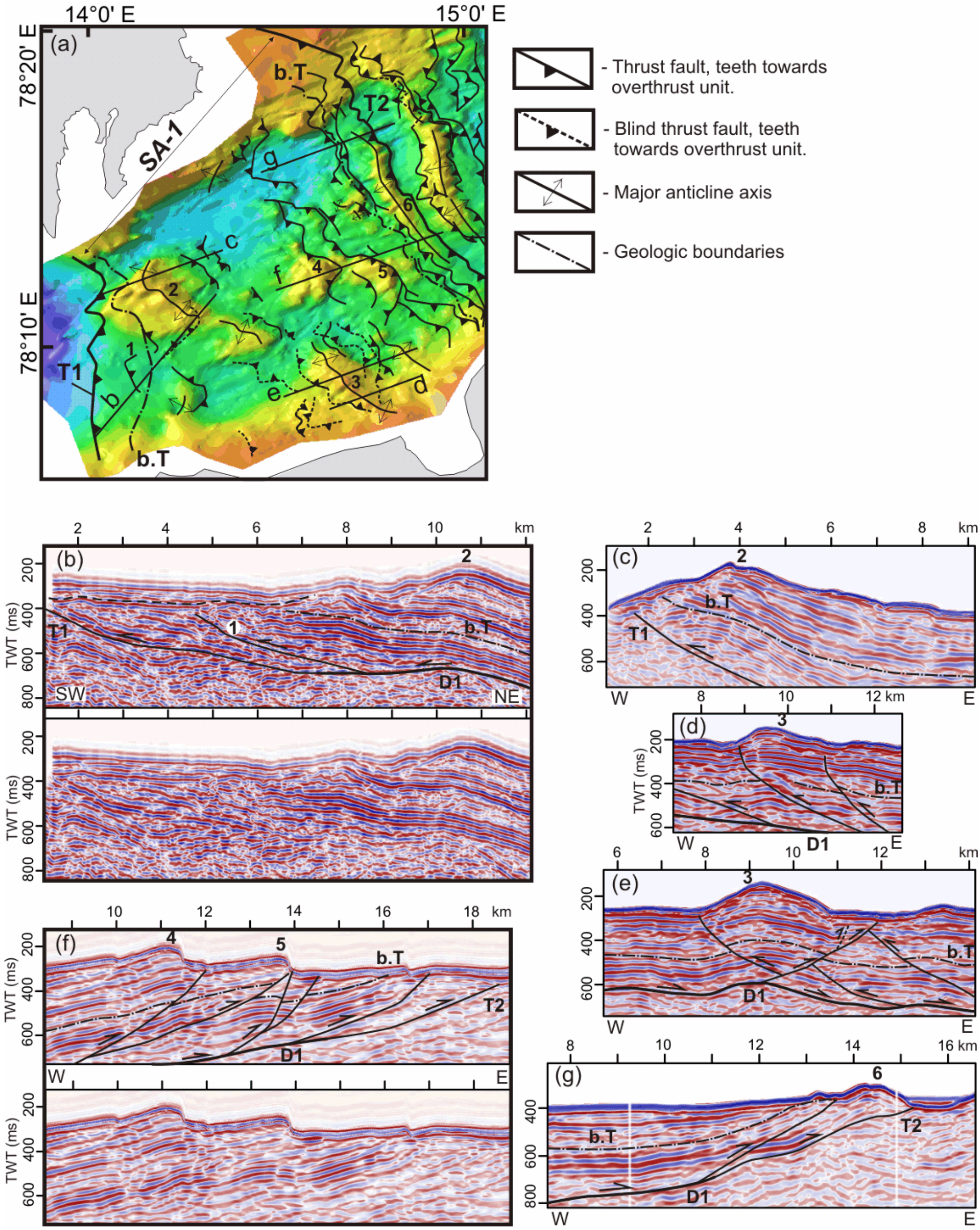

Figure 7. A - close-up view of the tectonic interpretation in Subarea 1 (SA-1) with locations of example seismic sections and numbers of identified tectonic structures. Examples of interpreted seismic sections: b – ST8815-222, c - SV04-27, d – SV04-4, e - SV04-7, f – SV04-19, g – SV05-38. T1 and T2 – major thrust faults; D1 – decollement; b.T – base Tertiary horizon.

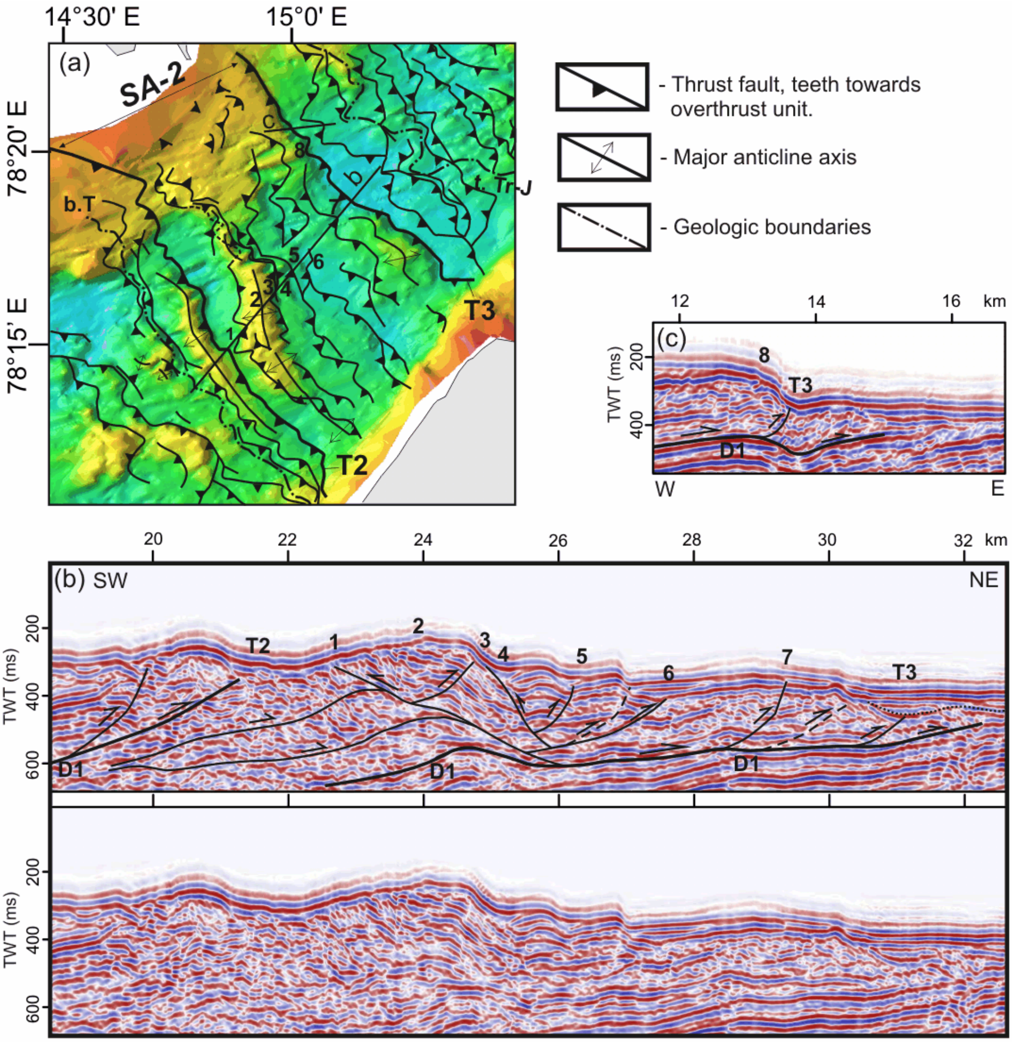

Figure 8. A - close-up view of the tectonic interpretation in Subarea 2 (SA-2) with locations of example seismic sections and numbers of identified tectonic structures. Examples of interpreted seismic sections: b – ST8815-217, c – ST8815-125. T2 and T3 – major thrust faults; D1 – decollement; b.T – base Tertiary succession, t. Tr-J – top of Triassic and lowermost Jurassic strata. Thrust faults marked on the section b with dashed lines are not shown in the map view.

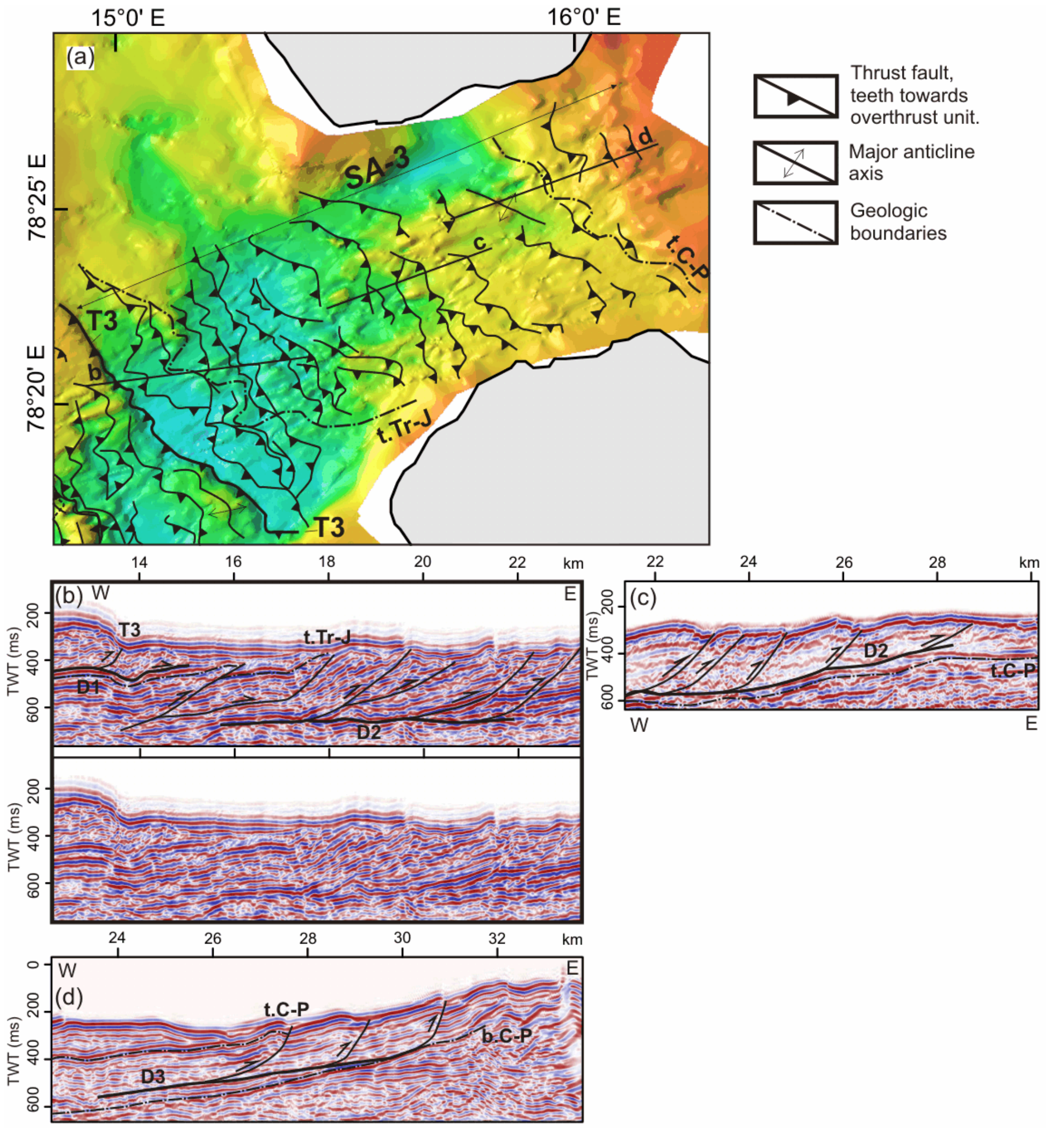

Figure 9. A - close-up view of the tectonic interpretation in Subarea 3 (SA-3) with locations of example seismic sections. Examples of interpreted seismic sections: b – ST8815-125, c - SV06-47, d – SV06-51. T3 – major thrust fault; D1, D2, D3 – decollements; t. Tr-J – top of Triassic and lowermost Jurassic strata, t.C-P – top of Carboniferous-Permian strata, b.C-P – base of Carboniferous-Permian strata.

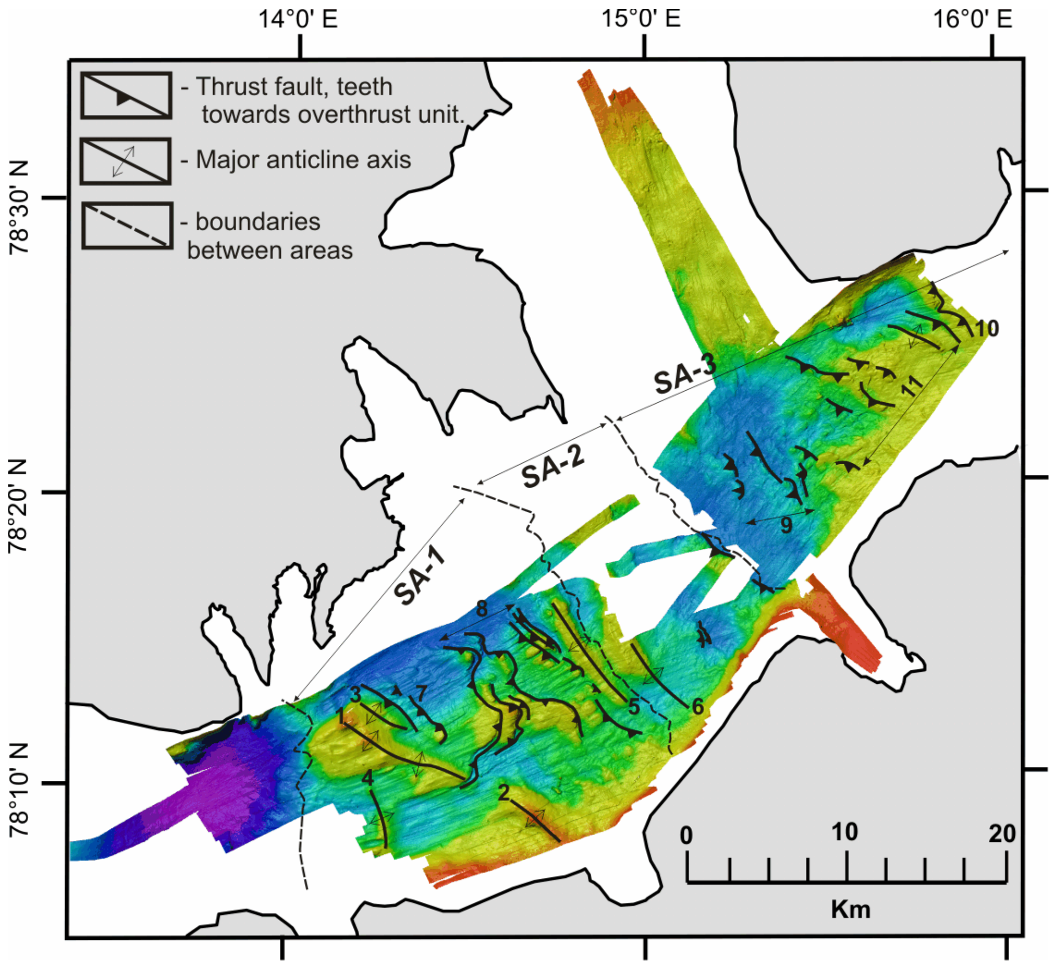

Figure 10. Interpretation of the seafloor morphology of Isfjorden based on the multibeam echo sounder data. SA-1, SA-2 and SA-3 - Subareas 1, 2 and 3 correspondingly.

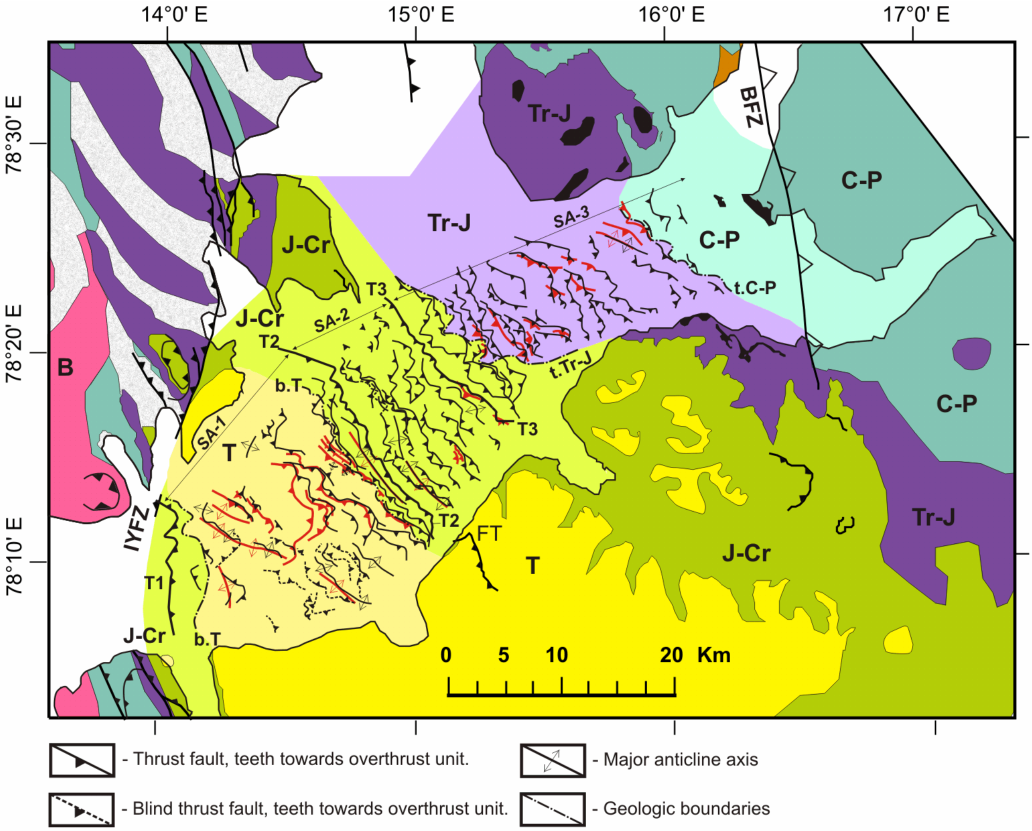

Figure 11. Combined geologic and tectonic map of Isfjorden. Map of the offshore tectonic features is derived from interpretation of MCS data and multibeam echo sounder data (see Fig. 2). Red colour on the offshore tectonic map represents interpretation based on seafloor morphological features (multibeam echo sounder), black colour represents interpretation based on MCS data. Grey areas on the map view represent glacial cover onshore and absence of data offshore. Abbreviations: T – Tertiary, J-Cr – Jurassic and Cretaceous, Tr-J – Triassic and lowermost Jurassic, C-P – Carboniferous and Permian, B – Basement, BFZ – Billefjorden Fault Zone, IYFZ - Isfjorden-Ymerbukta Fault Zone, FT – Fuglefjellet Thrust at Grumantbyen. T1, T2, T3 – major thrust faults. SA-1, SA-2 and SA-3 - Subareas 1, 2 and 3 correspondingly.