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Analysis of structural trends of sub-sea-floor strata in the Isfjorden area of the West Spitsbergen Fold-and-Thrust Belt based on multichannel seismic data

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Abstract: A dense grid of 2D multichannel seismic data was used for the interpretation of sub-sea-floor structures in the area of Isfjorden in western Spitsbergen. West Spitsbergen underwent Eocene transpressional deformation that resulted in formation of the West Spitsbergen Fold-and-Thrust Belt. Three horizons were defined for the seismic interpretation as well-expressed and continuous reflections: (1) the top of the metamorphic basement; (2) the base of the upper Carboniferous Nordenskiöldbreen Formation; (3) the base of the Lower Cretaceous Helvetiafjellet Formation. Time–structure maps and analysis of the sub-bottom structural trends were generated for each horizon. The top of the metamorphic basement displays north–south-trending graben structures, apparently representing continuation of the Devonian grabens from northern Spitsbergen. The tectonostratigraphic unit bounded by the base of the upper Carboniferous Nordenskiöldbreen Formation and base of the Helvetiafjellet Formation encloses the fold-and-thrust belt and is affiliated with WSW–ENE shortening involving three décollement levels. Within this unit the strata between the middle (Triassic shales) and upper (Upper Jurassic shales) décollements have undergone the most intense strain, whereas sediments situated between the basal (lower Permian evaporites) and middle décollements underwent a relatively mild deformation. The strata above the base of the Helvetiafjellet Formation are characterized by minor Tertiary deformation only.

The West Spitsbergen Fold-and-Thrust Belt of western Spitsbergen is an important piece of the puzzle for the understanding of the relation between plate tectonics and the structural geological history of the NE Atlantic. The formation of the fold-and-thrust belt corresponds to the Eocene transpressional deformation induced by shear along the Greenland and Eurasian plates during the North Atlantic opening (Talwani & Eldholm 1977; Srivastava 1985; Olesen *et al.* 2007; Engen *et al.* 2008; Faleide *et al.* 2008; Gaina *et al.* 2009). The core of the West Spitsbergen Fold-and-Thrust Belt is exposed along a 300 km long segment in western Spitsbergen, stretching from Brøggerhalvøya in the north to Sørkapp in the south. The exposed width for the belt's most intensively folded part is *c.* 30 km in Oscar II Land and decreases to 10–15 km southward (Fig. 1; Dallmann *et al.* 1993).

Many researchers have described the tectonic structures and geological evolution of the fold-and-thrust belt based on onshore geological observations (e.g. Holtedahl 1924; Ohta 1985; Andresen *et al.* 1992; Braathen & Bergh 1995; Braathen *et al.* 1995, 1999; Harland 1997; CASE Team 2001; Mazur *et al.* 2009). An outline of the major structural units involving the Caledonian basement (Hecla Hook; Kulling 1934) as well as the younger sedimentary cover around Isfjorden has also been given in a series of geological maps (Major & Nagy 1972; Lauritzen *et al.* 1989; Ohta *et al.* 1992; Bergh *et al.* 2003). Offshore studies of the West Spitsbergen Fold-and-Thrust Belt based on seismic data were described in a seismic atlas (Eiken 1994) and utilized in the Isfjorden structural study by Bergh *et al.* (1997). The marine seismic reflection data, however, cover only parts of the shelf and some of the fjords along the western coast of Spitsbergen.

The present analysis is based on 2D multichannel seismic (MCS) lines that cover most of Isfjorden, which is the largest fjord of western Spitsbergen. Its central part crosses the core of the West Spitsbergen Fold-and-Thrust Belt, including a section through Oscar II Land to the north as well as the less deformed Tertiary sediments of the Central Basin of Nordenskiöld Land (Fig. 1). In this paper we present an analysis of the fold-and-thrust structures as seen in sediments at three distinct tectonostratigraphic levels, namely (1) the top of the metamorphic basement, (2) the base of the upper Carboniferous Nordenskiöldbreen Formation, and (3) the base of the Lower Cretaceous Helvetiafjellet Formation, as identified in available 2D seismic reflection lines in the study area. The seismic reflection lines are consistent so that the stratigraphic units can be confidently mapped across the study area, permitting the correlation of the structures with those already documented from onshore mapping. Analysis of shallow structures of Isfjorden and their expression on the sea floor has been described by Blinova *et al.* (2012).

Seismic data

A map of all available multichannel seismic data, comprising several 2D seismic surveys, is shown in Figure 2. The data acquisition was performed by Statoil (Norway) in 1985 and 1988, and by the University of Bergen (Norway) during the Svalex seismic surveys in 2004, 2005, 2006 and 2007. The data acquired by Statoil are open source data providing both stacked and migrated seismic lines.

The seismic lines acquired by Statoil in 1988 and Svalex 2006 and 2007 are the data of best quality. These data show strong and consistent reflections through the full stratigraphic section down to the top of the metamorphic basement. One exception to this is an area in the western part of Isfjorden, which is situated close to the area of basement-involved fold-and-thrust complexes.

Geology and tectonic setting

The basement of western Svalbard (Hecla Hook) incorporates igneous and metamorphic rocks of late Proterozoic to Silurian age (Peucat *et al.* 1989; Ohta 1994; Balashov *et al.* 1995; Gee *et al.*

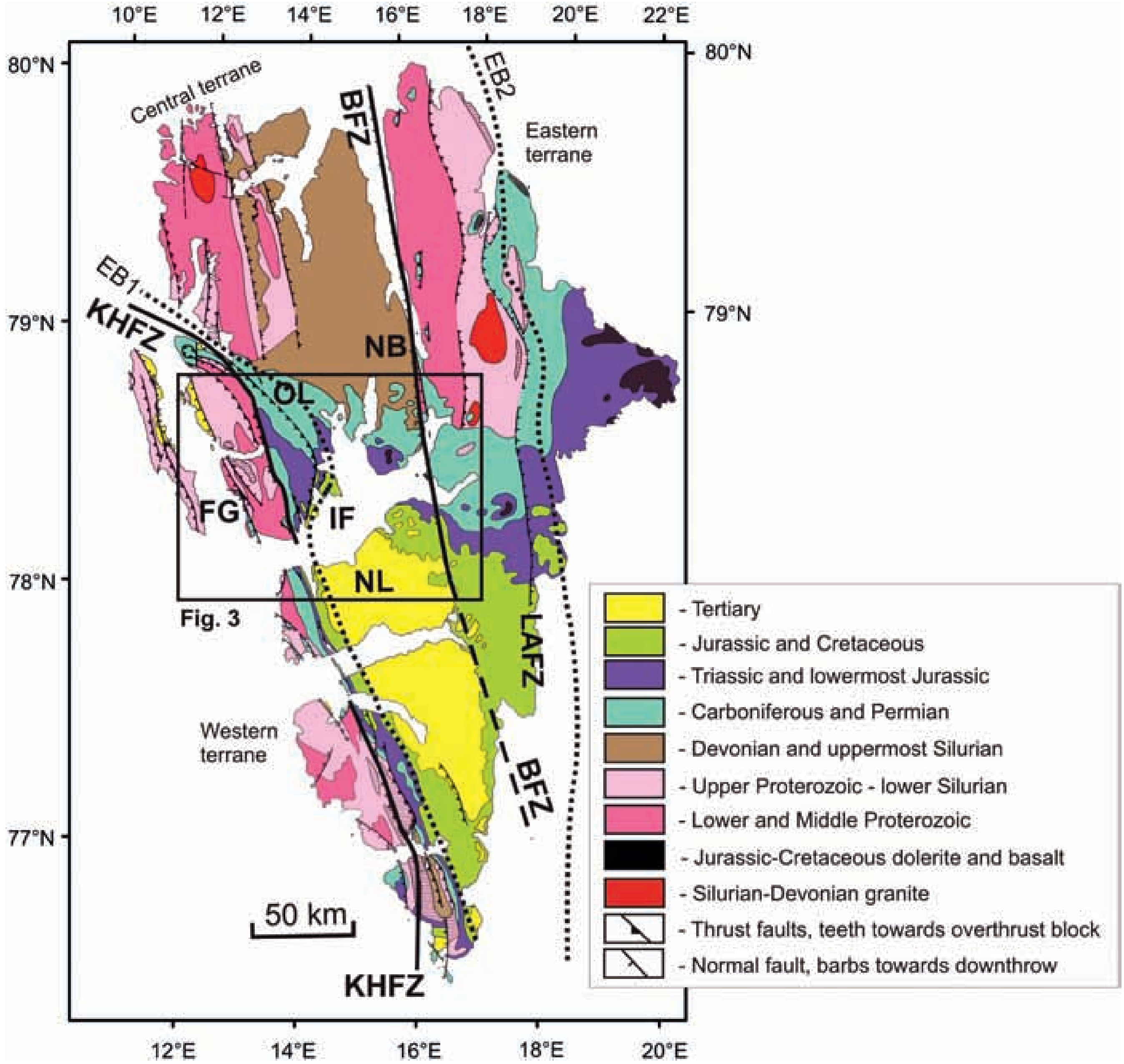


Fig. 1. Geological map of Spitsbergen (modified from Hjelle 1993; Harland 1997). KHFZ, Kongsfjorden–Hansbreen Fault Zone; BFZ, Billefjorden Fault Zone; LAFZ, Lomfjorden–Agardbukta Fault Zone; FG, Forlandsundet Graben; OL, Oscar II Land; IF, Isfjorden; NB, Nordfjorden block; NL, Nordenskiöld Land; EB1, boundary of the West Spitsbergen Fold-and-Thrust Belt structures; EB2, eastern boundary of observed Tertiary folding and thrusting (Dallmann *et al.* 1993; Dallmann 1999). Cross-section of the study area (outlined by black rectangle) is shown in Figure 3.

2008; Majka *et al.* 2008). During the mid-Silurian–early Devonian Caledonian Orogeny the basement rocks were highly deformed as a result of the collision of the North American and European continental plates (Hjelle 1993; Dallmann 1999; Gee *et al.* 2008). An 8000 m thick post-orogenic Old Red sandstone unit was deposited during the late Silurian–Devonian. These sediments are mainly preserved in a major graben structure within the basement in NW Spitsbergen and they were involved in Late Devonian contraction of the ‘Svalbardian phase’ (Dallmann 1999; Fossen *et al.* 2008; Gee *et al.* 2008; Bergh *et al.* 2011). Most of the Carboniferous (Mississippian to middle Pennsylvanian Epochs) was characterized by the formation of several fault-bounded basins. However, sinistral transpressional shear caused localized inversion in early to mid-Carboniferous times (Bergh *et al.* 2011), whereas the latest Carboniferous records the transition to a period with stable platform conditions (Worsley 1986, 2008; Dallmann 1999; Worsley & Nøttvedt 2008). The later Carboniferous to mid-Permian period was characterized by the accumulation of carbonates and evaporites in a shelf setting (Samuelsberg & Pickard 1999; Worsley & Nøttvedt 2008). The deposition of the Gipshuken Formation took place simultaneously with a mild extensional faulting (Harland 1997; Dallmann 1999), and the deposition of marine siliciclastic deposits with interbedded carbonates (Tempelfjorden Group) occurred during the late Permian. Regional uplift with the development

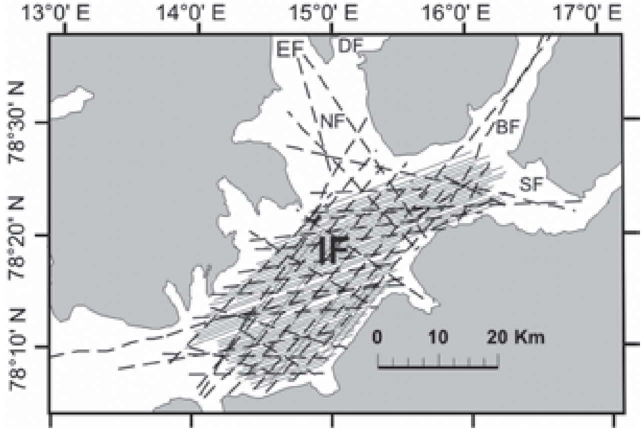


Fig. 2. Overview map of available seismic data. Continuous lines, surveys Svalex 2004, 2005, 2006 and 2007 (UIB); dashed lines, surveys ST8815 and ST8515 (Statoil). IF, Isfjorden; NF, Nordfjorden; ED, Ekmanfjorden; DF, Dicksonfjorden; BF, Billefjorden; SF, Sassenfjorden.

of an associated regional unconformity took place at the Permian–Triassic transition. A thick sequence of Mesozoic sediments was deposited in stable platform conditions and was characterized by sea-level fluctuations. The Lower–Middle Triassic sediments comprise the Sassedalen Group, which consists of marine shales passing upwards into sandstones. The Upper Triassic to Middle Jurassic strata of the Kapp Toscana Group consist mainly of deltaic sandstones, whereas the Middle Jurassic to lowermost Cretaceous deposits pertaining to the lower part of the Adventdalen Group consist of open-marine shales and thin sandstones. The upper part of the Lower Cretaceous sequence is dominated by shallow water and fluvio-deltaic sandstone evolving upward to open-marine shales and sandstones (Nemec *et al.* 1988). Intrusions of dolerites took place in Svalbard in the latest Jurassic and Early Cretaceous (Major & Nagy 1972; Steel & Worsley 1984; Lauritzen *et al.* 1989; Ohta *et al.* 1992; Harland 1997; Dallmann 1999; Worsley 2008). Regional uplift took place during the Late Cretaceous, generating a hiatus in the sedimentary succession. The uplift resulted in the generation of a land bridge between Svalbard and the adjacent North Greenland. This bridge remained throughout much of the Palaeocene (Steel & Worsley 1984; Harland 1997; Dallmann 1999; Worsley 2008).

The generation of the West Spitsbergen Fold-and-Thrust Belt is related to the Eocene opening of the Norwegian–Greenland Sea (Talwani & Eldholm 1977; Srivastava & Tapscott 1986; Eldholm *et al.* 1990; Tessensohn & Piepjohn 2000). Its development has been explained as a result of a time-constrained head-on collision between the Greenland and the Eurasian plate (Lyberis & Manby 1993*a*,*b*; CASE Team 2001; Saalmann & Thiedig 2002), whereas many researchers have advocated a mechanism related to transpression (Harland 1969; Lowell 1972) combined with strain partitioning (Faleide *et al.* 1988; Maher & Craddock 1988). The latter model has gained support from Leever *et al.* (2011a,b). Formation of the West Spitsbergen Fold-and-Thrust Belt was associated with uplift and erosion along the western coast of Spitsbergen and contemporaneous accumulation of clastic sediments in the Central Tertiary Basin to the east. This basin is a foreland basin (Steel *et al.* 1985; Dallmann 1999) filled by the deltaic deposits of the Van Mijenfjorden Group (Steel & Worsley 1984; Ohta *et al.* 1992; Harland 1997).

A cross-section of the West Spitsbergen Fold-and-Thrust Belt is displayed in Figure 3, showing that three main décollements were active during the top-to-the east Tertiary tectonic transport. Evaporites of the Permian Gipshuken Formation, shales of the Triassic Bravaisberget Formation and the organic-rich shales of the Jurassic–Cretaceous Janusfjellet Subgroup served as lubricants of the principal detachment in agreement with that documented by outcrop data (Braathen & Bergh 1995; Braathen *et al.* 1995; Bergh *et al.* 1997).

Seismic interpretation

The correlation of the stratigraphic and seismic units of Isfjorden (Fig. 4) is based on seismic reflection interpretations published by Nøttvedt (1994) and Bergh *et al.* (1997). A composite transect crossing Isfjorden from west to east was used as a key-line in the present interpretation (Fig. 5), which also gives an example of the typical seismic signature of the main units. Some of fold-and-thrust belt structures that are observed in outcrops of Spitsbergen close to the western hinterland show steep to vertical orientation of bedding (Fig. 3). Interpretation of such geometries from seismic data could be challenging, as they are not imaged by standard processing of

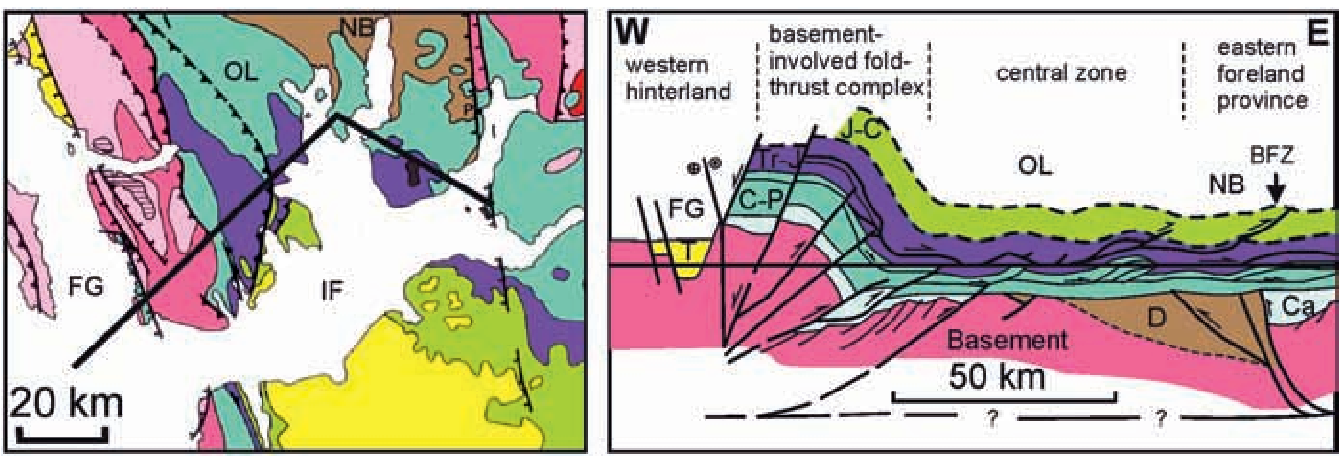


Fig. 3. Generalized cross-section of the West Spitsbergen Fold-and-Thrust Belt (Braathen *et al.* 1999). FG, Forlandsundet Graben; OL, Oscar II Land; IF, Isfjorden; NB, Nordfjorden block; BFZ, Billefjorden Fault Zone. D, Devonian; Ca, Lower–mid-Carboniferous; C-P, Carboniferous and Permian; Tr-J, Triassic and lowermost Jurassic; J-C, Jurassic and Cretaceous; T, Tertiary.

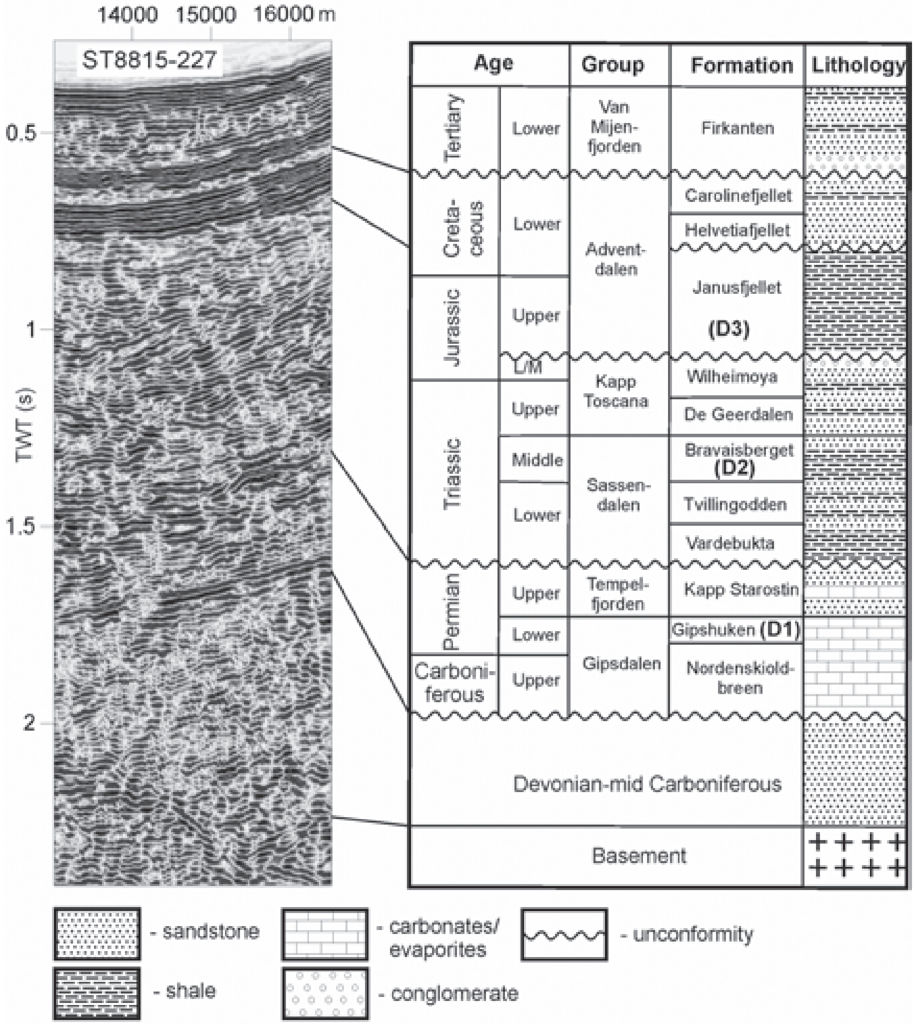


Fig. 4. Stratigraphic column tied with seismic units. Example of seismic line, ST8815-227. D1, D2 and D3 are formations comprising detachment layers. Correlation and lithology are based on stratigraphical tables published by Ohta *et al.* (1992), Nøttvedt (1994), Bergh *et al.* (1997) and Dallmann (1999).

the data. For instance, the seismic reflectivity pattern observed in the Isfjorden area becomes weaker and more diffuse as it approaches the mouth of Isfjorden (Festningen section) (Bælum & Braathen 2012). The unclear seismic image at the western end of profile ST8815-222 (Fig. 5) may indicate intense deformation and rotation of the rocks to very steep positions.

The lowermost two units, metamorphic Caledonian basement and Devonian to mid-Carboniferous sedimentary strata, are characterized by a scattered and discontinuous seismic signature of different signal intensity. The metamorphic Caledonian basement is characterized by a chaotic seismic character of stronger signal. This unit is overlain by a Devonian sedimentary section characterized by less pronounced reflections. Although the reflectivity pattern within the two deepest units is scattered and relatively weak, the top of the metamorphic basement is well imaged in the Statoil 1988 survey. The appearance of strong short reflectors within the seismic reflectivity picture of Devonian sedimentary filling might be related to dolerite sill intrusions.

The Devonian to mid-Carboniferous unit is overlain by a sequence characterized by strong and continuous reflections, representing the upper Carboniferous–Permian succession of mainly carbonates. On top of this, the shales of the Sassendalen Group are found. This unit displays weak and discontinuous reflections, but the sandstones of the Kapp Toscana Group stand out as a pile of strongly folded and overthrust reflections, well expressed to the east. A strong reflection indicating a sharp impedance contrast is observed between the low-velocity shales of the Janusfjellet subgroup, which is characterized by a chaotic and discontinuous seismic reflectivity pattern, and the overlying high-velocity sandstones of the Lower Cretaceous Helvetiafjellet Formation, which is seen as a sequence with strong and continuous reflections. A thin transparent seismic sequence below the strong double reflector and above the strong and continuous reflectivity pattern of the Helvetiafjellet Formation is related to the base of the Tertiary.

Three décollements were identified in the key section, within the Carboniferous–Permian, Triassic and Jurassic–Cretaceous sequences (Fig. 5). The seismic signatures of the décollements are characterized by separate sequences with contrasting styles and intensity of deformation and by the definition of surfaces from which thrust faults splay. The study of the shallow tectonic structures and their morphological expressions on the sea floor in Isfjorden (Blinova *et al.* 2012) suggests that thrust faults in the Isfjorden section are mainly foreland-directed in-sequence thrusts with mainly NW–SE strike directions.

The three well-pronounced and continuous seismic reflections identified in the available seismic data (the top of the metamorphic basement, base of the upper Carboniferous Nordenskiöldbreen Formation and base of the Lower Cretaceous Helvetiafjellet Formation) were chosen to produce time–structure maps for analysis of the structural architecture and tectonostratigraphy of the Palaeozoic–Cenozoic units of Isfjorden. The traces of the three

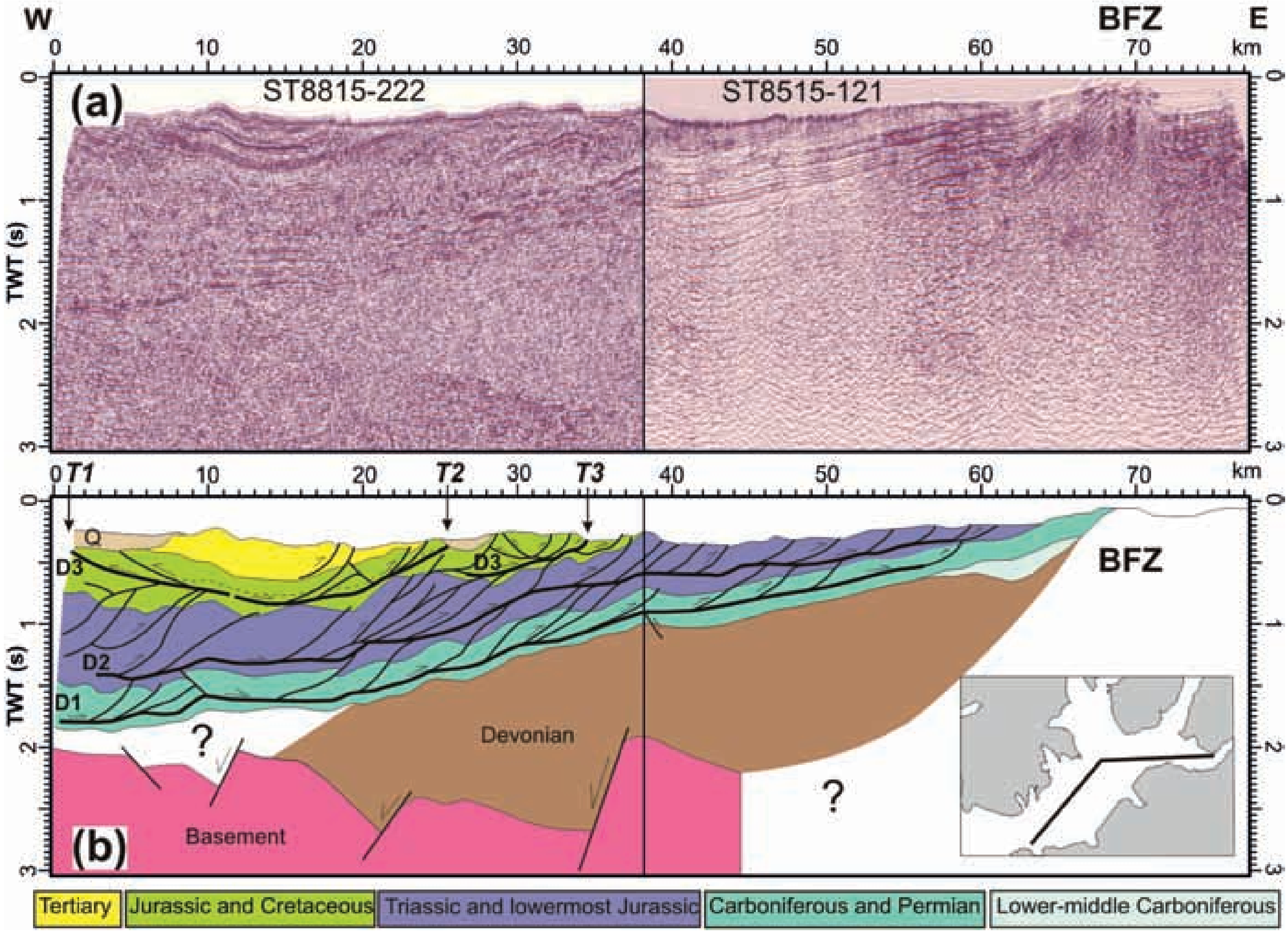


Fig. 5. Example of the seismic reflectivity along a transect line and line drawing of its interpretation. BFZ, Billefjorden Fault Zone; Q, Quaternary; T1, T2, T3, major thrust faults; bold lines, décollement layers; fine lines, thrust faults; dashed line within interpreted Jurassic–Cretaceous strata corresponds to base of the Helvetiafjellet Formation.

main thrust faults and geological boundaries (Figs 5 and 6) were superimposed on the time–structure maps of the interpreted reflectors for correlation of trends of the deep and shallow parts of the sections.

Top of the metamorphic basement

The top of the metamorphic basement was identified and mapped (Fig. 7a) over nearly the entire study area. However, the interpretation is somewhat uncertain for the westernmost part owing to more intense deformation in the central zone of the West Spitsbergen Fold-and-Thrust Belt (Leever *et al.* 2011*a*,*b*). Figure 7b shows examples of the seismic reflectivity along three seismic lines in the southwestern, central and northern part of Isfjorden. It is noteworthy that pronounced graben topography with a dominant north–south trend is clearly seen at top basement level. The normal faults delineating the grabens are well defined in the seismic sections and are marked by an abrupt change in the continuity of the seismic reflector (Fig. 7b). An interpretation of the geological boundaries and traces of the main thrust faults cropping out on the sea floor was superimposed on the map of the basement relief with the aim of comparing the geometry of deep and shallow structures (Fig. 7a). It is also noteworthy that the observed graben structures of the metamorphic basement and thrust structures of the shallow section have contrasting trends.

Base of the upper Carboniferous Nordenskiöldbreen Formation

The base of the upper Carboniferous Nordenskiöldbreen Formation is also associated with a reflection that can be correlated with certainty over the study area (Fig. 8a and b). This level corresponds to the unconformity between Devonian–mid-Carboniferous deposits and upper Carboniferous–Permian sedimentary cover. The base of the succession generates a well-pronounced reflection in most of the lines (Fig. 8b), whereas the top of the unit is difficult to define in the western part of Isfjorden owing to disturbance by thrusting above the décollement within the Gipshuken Formation. Uncertainties in the interpretation of the base of the upper Carboniferous Nordenskiöldbreen Formation occur particularly in the northeastern part of Isfjorden. The time–structure map demonstrates the gentle southwestward dip of the interpreted surface (Fig. 8a). The trend of isochrons on the map coincides with the direction of the sea-floor traces of the main thrust faults and geological boundaries. Furthermore, the base of the upper Carboniferous unit parallels the lowermost décollement, implying that the general inclination of the strata existed prior to the initiation

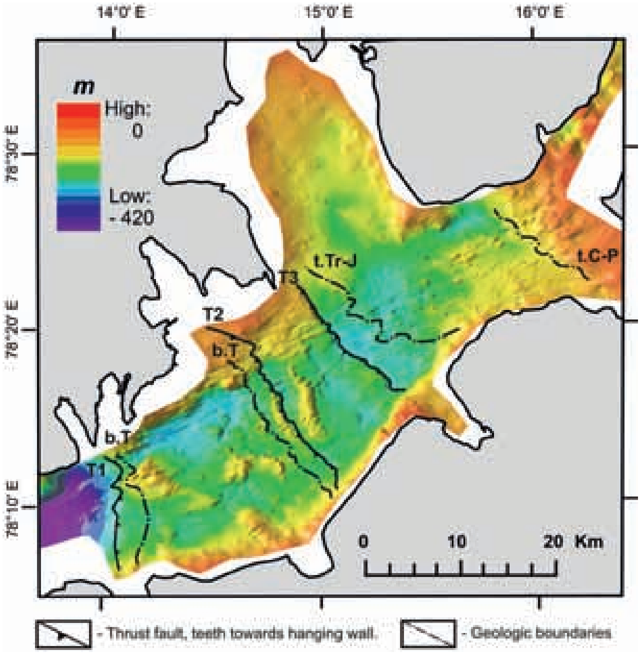


Fig. 6. Sea-floor relief (depth in metres) derived from interpretation of a dense grid of MCS data. T1, T2, T3, interpretation of the major thrust faults. Interpretation of outcrops: b.T, base Tertiary; t.Tr-J, top of Triassic and lowermost Jurassic strata; t.C-P, top of Carboniferous–Permian strata.

of the master thrusts. The presence of the Isfjorden–Ymerbukta Fault Zone in the SW part of the fjord may cause a relatively abrupt change in structural trend that is observed at the SW end of the horizon interpretation. Detailed discussion of the structures is difficult owing to the absence of clear signs of the transfer faults in the seismic data along with a poor reflectivity picture in that area.

Base of the Lower Cretaceous Helvetiafjellet Formation

The base of Lower Cretaceous Helvetiafjellet Formation coincides with the third easily identifiable décollement of the West Spitsbergen Fold-and-Thrust Belt of Isfjorden. The map view of the base of the Helvetiafjellet Formation and typical seismic cross-sections for these sequences are shown in Figure 9a and b. The surface defines the base of a foreland basin delineated by NW–SE-trending boundaries to the west and east, which are affiliated with the thrust faults cropping out on the sea floor. In some places the surface is disturbed by thrust faults emerged from the underlying décollement in shales of the Janusfjellet Formation (Fig. 9b).

Regional correlations

The Devonian Old Red molasse sediments are preserved in down-faulted crustal blocks and exposed in northern Svalbard (Fig. 1; Dallmann 1999, 2007). Based on interpretation of one seismic line in eastern Isfjorden, Eiken & Austegard (1994) reported a continuation of the Devonian grabens of northern Spitsbergen below Isfjorden. Their interpretation is supported by our observations of trends of basement structures as seen in the seismic lines in Isfjorden (Fig. 10). Thus, the westernmost normal faults in the Isfjorden area might represent southward continuation of the Raudfjorden and Breibogen faults.

Furthermore, a north–south-trending reverse fault is clearly defined in northeastern Isfjorden, cutting the base of the upper Carboniferous Nordenskiöldbreen Formation, probably corresponding to the Blomesletta Fault (Figs 10 and 11). The magnitude of vertical throw of this fault is *c*. 50 ms (*c*. 100 m). The Blomesletta Fault was described in onshore outcrop as a west-vergent high-angle reverse fault that upcast Devonian–Carboniferous strata westward by *c*. 200 ms on top of the Permian sequence (Dallmann *et al.* 1993; Bergh *et al.* 1997). It is noted that the offshore expression of the Blomesletta Fault differs from that seen onshore in that a thick sequence of sediments is preserved above the upper Carboniferous–Permian succession here. A pronounced eastward thrust is observed right above the inferred reverse fault. Its major décollement coincides with the lower Permian Gipshuken Formation evaporites and it abruptly cuts the extensional fault plane of the Blomesletta Fault, indicating severe structural inversion across this structure.

A comparison between the Blomesletta Fault and Gipshuken Fault (Ringset & Andresen 1988; Haremo *et al.* 1990) is shown in Figure 11 (cross-sections 3 and 6). The Gipshuken Fault is one of the main tectonic elements of the Billefjorden Fault Zone and is a contractional duplex-structure with a shallowly dipping ramp developed above a listric normal fault that seems to detach in the middle Carboniferous sediments. Ringset & Andresen (1988) related the initiation of the contractional part of the structure to the early Tertiary shortening. Evaporites of the Ebbadalen Formation at Gipshuken coincide with the low-angle, mainly bedding-parallel floor thrust, from which the thrust faults branch. The westerly ramping of the thrust faults in the system was caused by the pre-existing fault-related stepping topography and promoted by contrasts in lithology. Thus, the Gipshuken Fault was interpreted as a backthrust feature of general eastward-directed contraction. By analogy, it is therefore natural to ascribe the top-to-the-east shortening associated with the Blomesletta Fault to a similar mechanism.

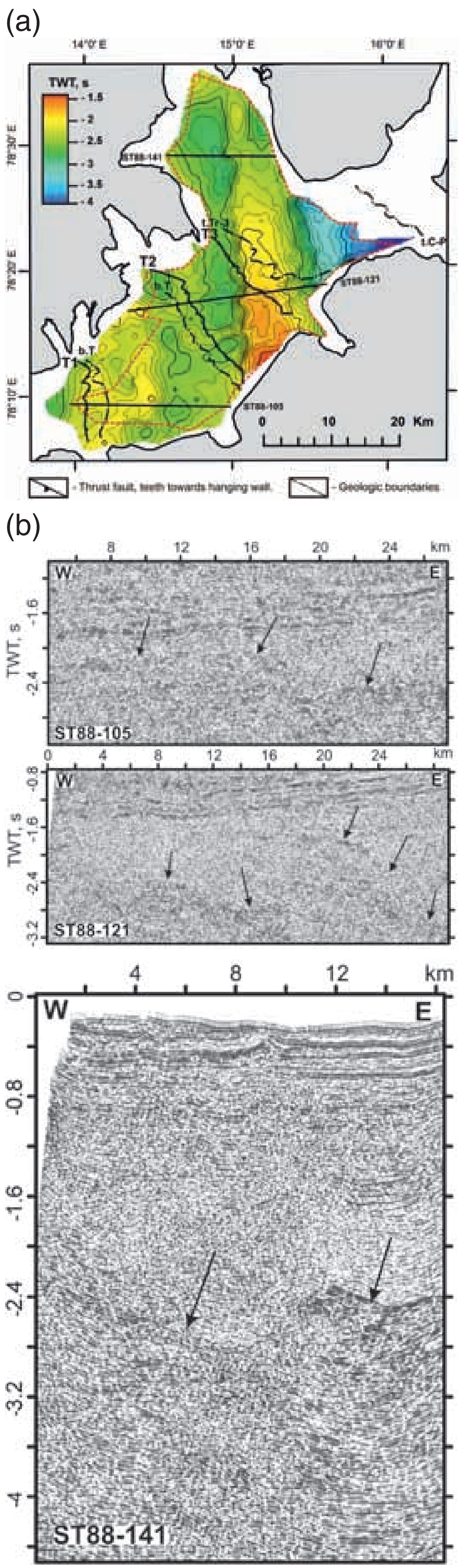
The isochron map of the base of upper Carboniferous Nordenskiöldbreen Formation shows a deviation in the pattern, with a SW–NE structural trend, in the SW part of Isfjorden.

Thrust kinematics

From the interpretation of the seismic data it is evident that, for the late Palaeozoic–Cenozoic sediments in the Isfjorden area, thrusting was associated with the development of three major tectonostratigraphic units. Each unit is characterized by a different structural style of deformation (Fig. 12) reflecting contrasting overburden, mechanical strength, layering and perhaps strain rate.

Figure 12a illustrates the earliest structural signature recognized in the present study, which includes normal faults affecting the metamorphic basement, the grabens of which became filled with Devonian Old Red sandstones. Down-faulted blocks of basement rocks coincide with the development of the Devonian graben faults as known onshore Svalbard, and thus may represent a direct link to the deep extensional structures of Isfjorden. The orientation of the graben structures is parallel to the Billefjorden Fault Zone and seems to be entirely unaffected by the Tertiary deformation. The interpreted horizon at the base of the upper Carboniferous Nordenskiöldbreen Formation is affected by reverse faulting (e.g. the Blomesletta Fault) that may be related to waning tectonic movements during the late Carboniferous and/or to Tertiary shortening (Fig. 12b).

Bergh *et al.* (1997) divided the West Spitsbergen Fold-and-Thrust Belt in the Isfjorden area into three major tectonic subareas or zones. These include the western, basement-involved (thick-skinned) zone, a central, mainly thin-skinned zone where large-scale, open-upright to overturned folds are found above the



master thrusts, particularly involving Triassic–Cretaceous shales and silt-dominated units, and a frontal, thin-skinned zone to the east, involving stacked and imbricated thrust sheets. In the central part, Bergh *et al.* (1997) identified three levels of décollements, similar to those reported in the present study.

The high strain associated with the Tertiary deformation is reflected by the thrust systems affecting the upper Carboniferous–Lower Cretaceous sequences (Fig. 12c). The thin-skinned central–eastern foreland fold-and-thrust belt evolved during the main Eocene transpressional event characterized by WSW–ENE-oriented shortening (Bergh & Andersen 1990; Braathen & Bergh 1995; Braathen *et al.* 1995; Bergh *et al.* 1997), activating the basal thrust (D1), which represents the mechanically weakest layer consisting of evaporites of the Gipshuken Formation. By continued movements shallower detachments became activated, involving the mechanically weak shales of the Mesozoic succession (Fig. 12c). The shortening associated with décollement D1 includes foreland-vergent, relatively widely separated thrust faults, probably reflecting a moderate amount of shortening combined with relatively low friction and moderate consolidation. The thrusting above the middle detachment (D2) is characterized by a complete duplex in its central part, steeper thrust faults, and a frontal imbricate fan on the foreland side (Fig. 12c). This is likely to represent more intense contraction, and is probably associated with the thrust climax. Finally, the thrust sheet above the upper detachment (D3) has again a different architecture from that seen for the sheets below, and is dominated by thrusts subcropping at the present sea floor and a lower frequency of faults (Fig. 12d). This suggests that the uppermost thrust sheet was developed during a stage of waning shortening.

The structural style in Isfjorden displays less intense deformation as compared with that seen onshore (e.g. in Oscar II Land north of the fjord; Bergh & Andresen 1990; Bergh *et al.* 1997). In Oscar II Land the complex fold–thrust geometry is characterized by tight folds, numerous thrusts and interaction between décollements at deep and high stratigraphic levels emplacing Permian strata on top of Triassic (e.g. Mediumfjellet; Bergh & Andresen 1990). In contrast, a relatively more simple style of deformation in a higher level thrust sheet, which involves Triassic and Jurassic shales (Dallmann *et al.* 1993), is observed in Nordenskiöld Land (south of Isfjorden). Hence, the Isfjorden–Ymerbukta Fault Zone in the southern part of Oscar II Land (Fig. 10) is suggested to be a boundary between the two structural regimes found north and south of Isfjorden respectively (Bergh & Andresen 1990; Bergh *et al.* 1997). This picture is supported by the present analysis, illustrating that the Isfjorden–Ymerbukta Fault separates thrust sheets of contrasting strain intensity and different structural styles (Figs 5 and 10), reflecting contrasts in lithology and tectonostratigraphic position as described above. Such configurations are not uncommon in central and frontal parts of fold-and-thrust belts, such as the Alps and the Pyrenees (e.g. Lacombe & Mouthereau 2002) and the Caledonides (Bruton *et al.* 2010).

The shallowest tectonic unit, which is situated above detachment D3 (Fig. 12d), comprises the Helvetiafjellet Formation, which corresponds to the Central Tertiary Basin. This unit defines a syncline structure with amplitude *c.* 900 m and wavelength *c.* 23 km,

Fig. 7. (**a**) Isochron, top of the metamorphic basement (TWT). T1, T2, T3, interpretation of the major thrust faults. Interpretation of outcrops: b.T, base Tertiary; t.Tr-J, top of Triassic and lowermost Jurassic strata; t.C-P, top of Carboniferous–Permian strata. The boundary for the confident interpretation is marked by a red dashed line. (**b**) Examples of reflectivity picture along seismic lines (for location see (**a**)). Arrows indicate the top of the metamorphic basement.

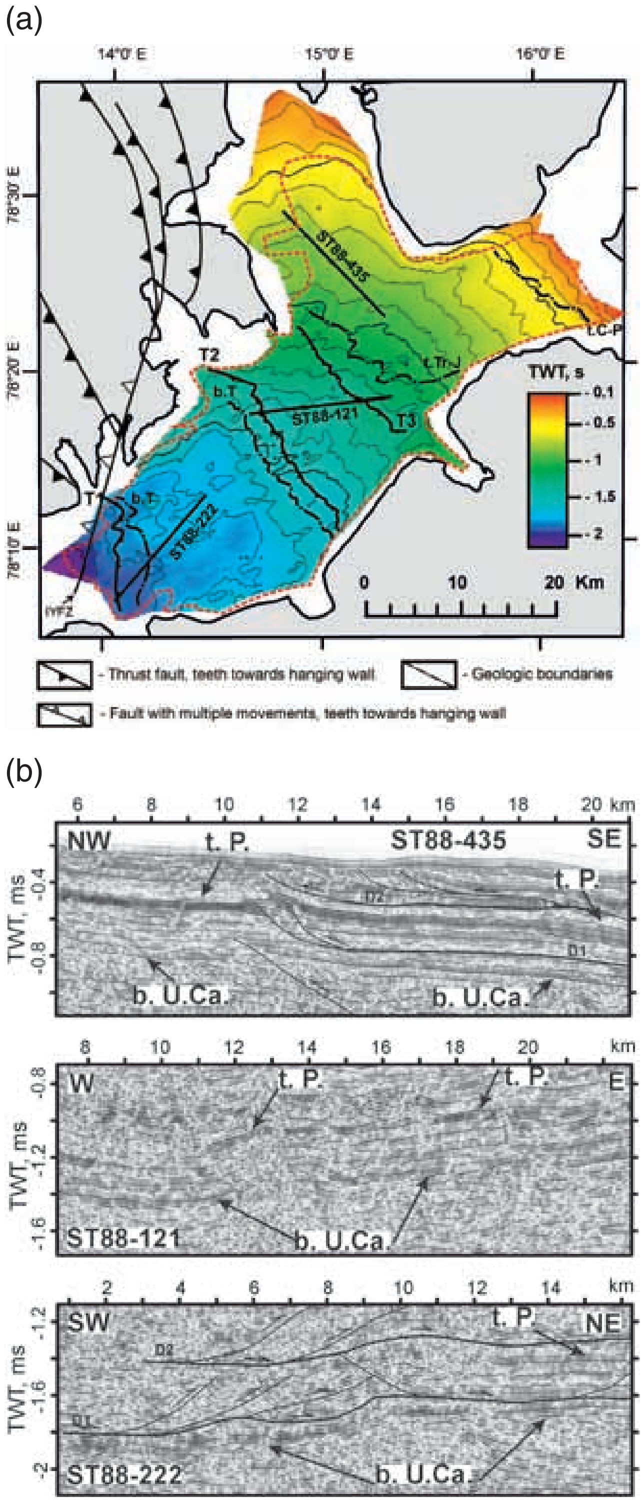


Fig. 8. (**a**) Isochron, base of the upper Carboniferous Nordenskiöldbreen Formation (TWT). T1, T2, T3, interpretation of the major thrust faults. Interpretation of outcrops: b.T, base Tertiary; t.Tr-J, top of Triassic and lowermost Jurassic strata; t.C-P, top of Carboniferous–Permian strata. IYFZ, Isfjorden–Ymerbukta Fault Zone. The boundary for the confident interpretation is marked by a red dashed line. (**b**) Examples of reflectivity picture along seismic lines (for location see (**a**)). t.P, top Permian; b.u.Ca., the base of the upper Carboniferous Nordenskiöldbreen Formation. D1, décollement layer in gypsum of Gipshuken Formation; D2, décollement layer in shales of Bravaisberget Formation (bold lines); fine lines, thrust faults.

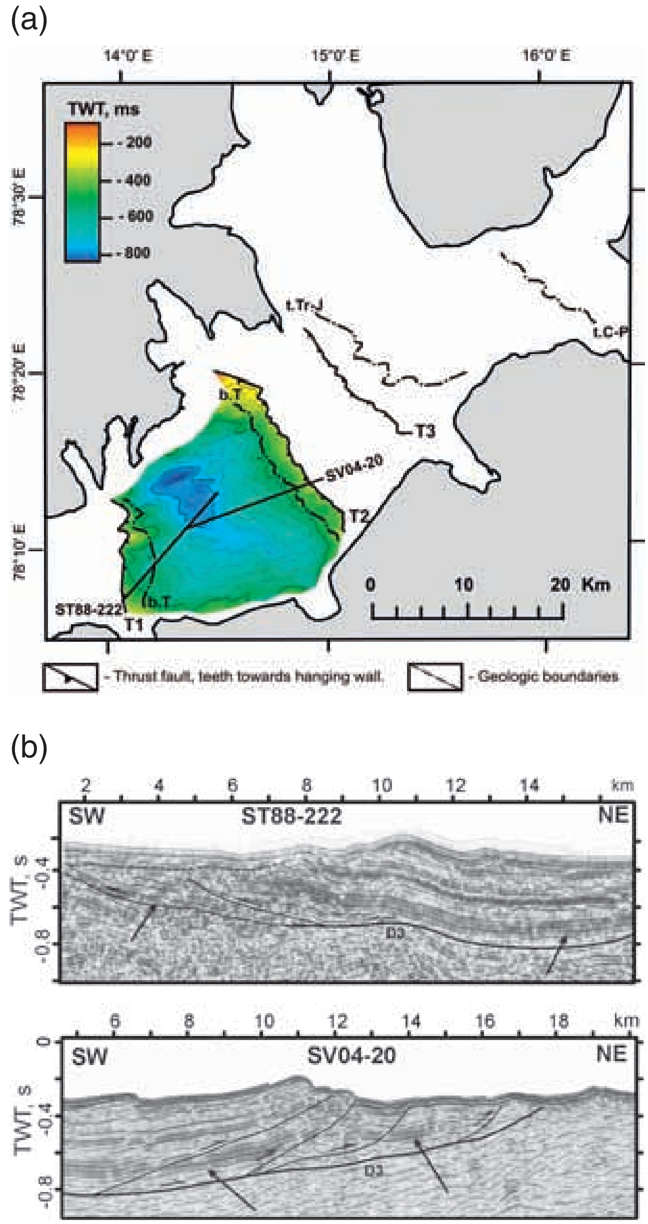


Fig. 9. (**a**) Isochron, base of the Lower Cretaceous Helvetiafjellet Formation (TWT). T1, T2, T3, interpretation of the major thrust faults. Interpretation of outcrops: b.T, base Tertiary; t. Tr-J, top of Triassic and lowermost Jurassic strata; t.C-P, top of Carboniferous-Permian strata. (**b**) Examples of reflectivity picture along seismic lines (for location see (**a**)). Arrows indicate the base of the Lower Cretaceous Helvetiafjellet Formation. D3, décollement layer in shales of Janusfjellet subgroup (bold lines); fine lines, thrust faults.

and has been shortened less than the thrust sheet below it, reflecting its status as a piggy-back basin.

Summary and conclusions

Three horizons were interpreted along 2D multichannel seismic lines and were used to generate time–structure maps. The lowermost horizon represents the top of the metamorphic basement and reflects graben structures that could be related to the Devonian grabens observed onshore in the northern part of Spitsbergen. The

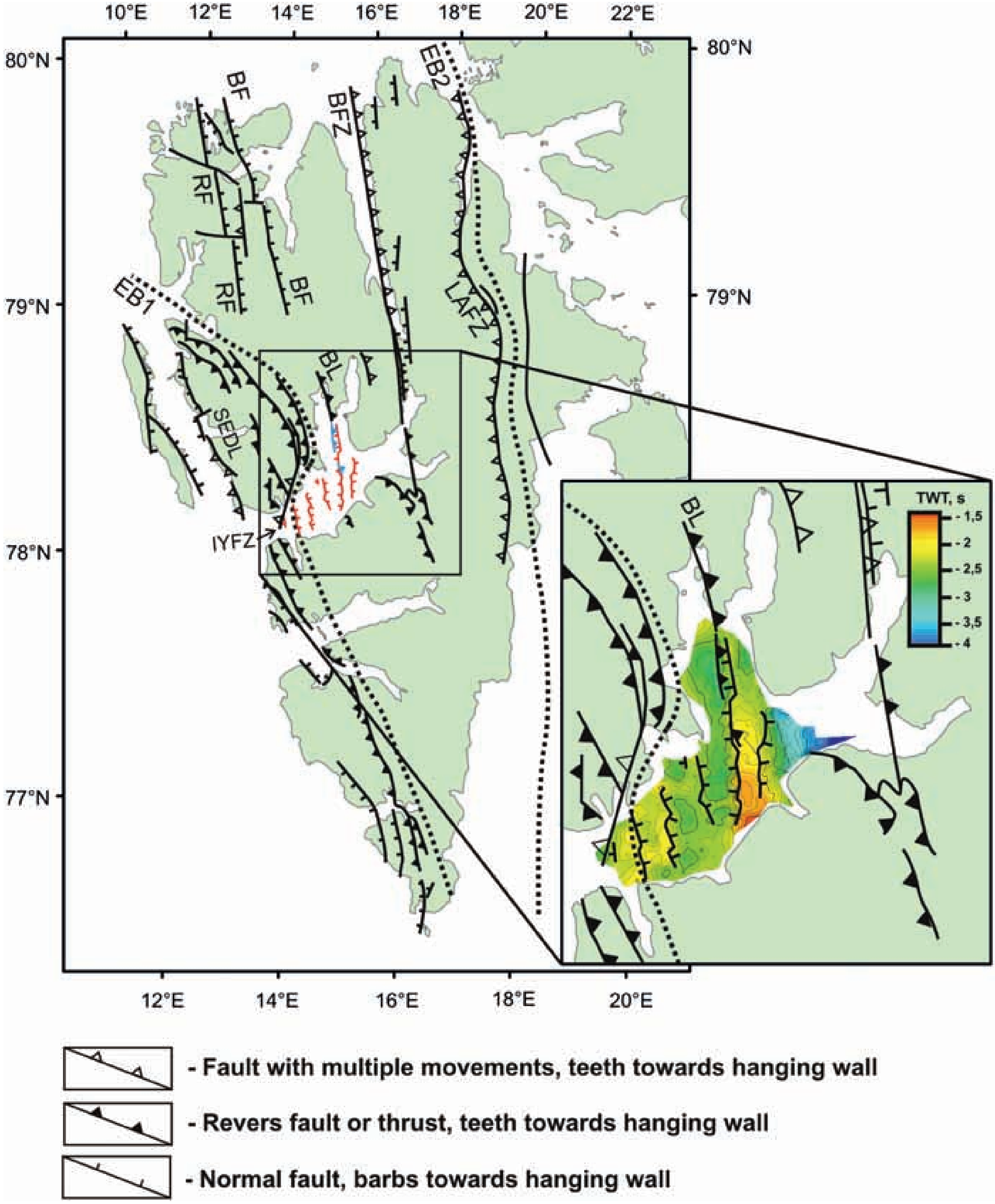


Fig. 10. Sketch map of basement tectonic structures and the Blomesletta Fault superimposed on a regional tectonic map of Spitsbergen (modified from Dallmann 1999). BFZ, Billefjorden Fault Zone; LAFZ, Lomfjorden–Agardbukta Fault Zone; SEDL, Svartfjella, Eidembukta and Daudmannsodden lineament; IYFZ, Isfjorden–Ymerbukta Fault Zone; BF, Breibogen Fault, RF, Raudfjorden Fault; BL, Blomesletta Fault; EB1, boundary of the West Spitsbergen Fold-and-Thrust Belt structures; EB2, eastern boundary of observed Tertiary folding and thrusting. Red lines on the map correspond to normal faults bounding graben and half-graben structures defined in the seismic data from the reflector separating metamorphic basement and Devonian sedimentary rocks; blue line, offshore continuation of the Blomesletta Fault.

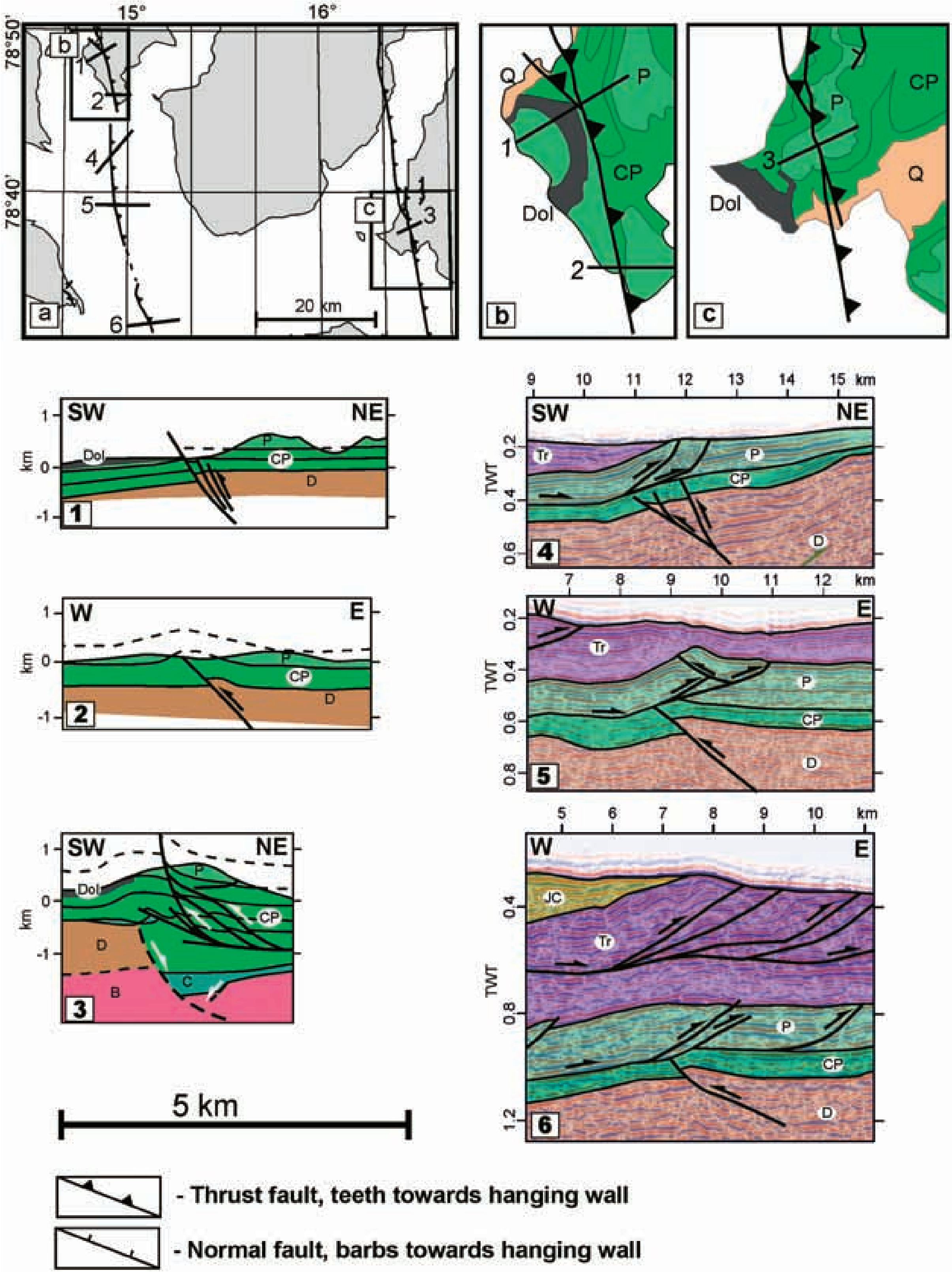


Fig. 11. Interpretation of the Blomesletta Fault. (**a**) Map view showing the Blomesletta Fault (**b**), Billefjorden Fault Zone (**c**) and locations of lines where the faults were observed. Onshore observations of the Blomesletta Fault ((**b**), cross-sections 1 and 2) and Gipshuken Fault of Billefjorden Fault Zone ((**c**), cross-section 3) are based on published data by Bergh *et al.* (2003, 1997) and Ringset & Andresen (1988) respectively. Examples of offshore continuation of the Blomesletta fault are based on interpretation of MCS data: line 4, seismic line ST88-241; line 5, ST88-141; line 6, ST88-127. JC, Jurassic–Cretaceous; Tr, Triassic; P, Upper Permian (Kapp Starostin Formation); CP, mid-Carboniferous to lower Permian; D, Devonian; C, Lower Carboniferous; B, basement; Dol, dolerite.

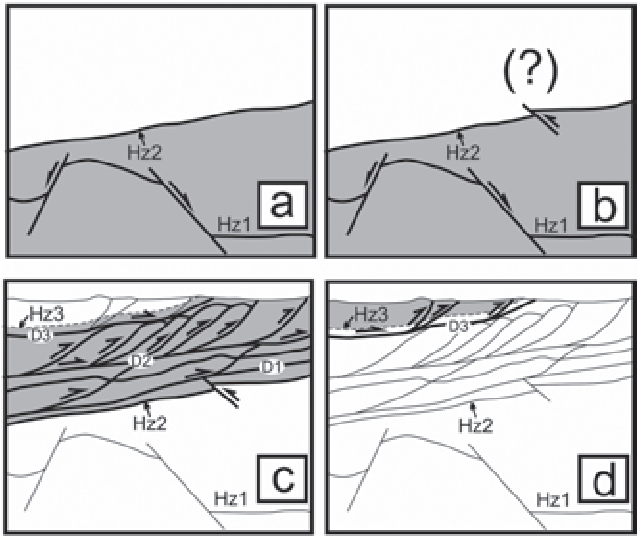


Fig. 12. Line drawing of three tectonostratigraphic units. Hz1, top of the metamorphic basement; Hz2, base of the upper Carboniferous Nordenskiöldbreen Formation; Hz3, base of Lower Cretaceous Helvetiafjellet Formation (dashed line); D1, décollement layer in gypsum of Gipshuken Formation; D2, décollement layer in shales of Bravaisberget Formation; D3, décollement layer in shales of Janusfjellet Formation.

interpreted structures show a different trend compared with the shallow part and thus seem to be unaffected by the Tertiary deformation. The transition between Devonian–mid-Carboniferous deposits that fill the grabens and overlying upper Carboniferous–lower Permian carbonate succession represents a second interpreted horizon. The southwestward dip of the base of the upper Carboniferous Nordenskiöldbreen Formation coincides with the trend of geological features that crop out at the sea floor. The reverse fault that cuts the horizon was interpreted as a southward continuation of the Blommesletta Fault observed onshore. The uppermost horizon was interpreted at the base of Helvetiafjellet Formation characterizing the syncline structures of the Central Tertiary Basin. The West Spitsbergen Fold-and-Thrust Belt structures evolved by means of three décollements defined within strata above the interpreted horizon base of the upper Carboniferous Nordenskiöldbreen Formation. A moderate rate of deformation is reflected in thrust structures above the lowermost décollement within evaporites of the Gipshuken Formation. Strata above the middle detachment developed within Triassic shales show structural features revealing the most intense deformation of the Eocene transpression. Thrusting above the uppermost décollement indicates a mild rate of deformation that could correspond to the later stage of the fold-and-thrust belt evolution. The sub-bottom structures observed within the Isfjorden area reflect the similar structural style to that defined to the south in Nordenskiöld Land. The Isfjorden–Ymerbukta Fault Zone located along the northwestern coast of Isfjorden represents a boundary separating the Isfjorden area from the more intense deformation that affected strata in Oscar II Land to the north.

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