RESEARCH ARTICLE

Devonian–Carboniferous extension and Eurekan inversion along an inherited WNW–ESE-striking fault system in Billefjorden, Svalbard [version 1; peer review: 1 approved, 2 not approved]

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Abstract

Background: The Billefjorden area in central Spitsbergen hosts thick Lower–lowermost Upper Devonian, late–post-Caledonian collapse deposits presumably deformed during the Late Devonian Svalbardian Orogeny. These rocks are juxtaposed against Proterozoic basement rocks along the Billefjorden Fault Zone and are overlain by uppermost Devonian–early Permian deposits of the Billefjorden Trough, a N–S-trending Carboniferous rift basin bounded by the Billefjorden Fault Zone.

Methods: We interpreted seismic reflection (also depth-converted), bathymetric, and exploration well data.

Results: The data show abundant Early Devonian, WNW–ESE-striking (oblique-slip) normal faults segmenting the Billefjorden Trough, and a gradual decrease in tectonic activity from the Early Devonian (collapse phase) to early Permian (post-rift phase). Early Devonian–Middle Pennsylvanian WNW–ESE-striking faults were mildly reactivated and overprinted and accommodated strain partitioning and decoupling in the early Cenozoic. This resulted in intense deformation of Lower Devonian sedimentary rocks and in the formation of bedding-parallel décollements, e.g., between the Lower Devonian Wood Bay and the uppermost Pennsylvanian–lowermost Permian Wordiekammen formations. This suggests that intense deformation within Devonian rocks in Dickson Land can be explained by Eurekan deformation alone. Eurekan deformation also resulted in the formation of WNW–ESE- and N–S- to NNE–SSW-trending, kilometer-wide, open folds such as the Petuniabukta Syncline, and in inversion and/or overprinting of Early Devonian to Early Pennsylvanian normal faults by sinistral-reverse Eurekan thrusts. WNW–ESE-striking faults merge at

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depth with similarly trending and dipping ductile shear zone fabrics in Proterozoic basement rocks, which likely formed during the Timanian Orogeny.
Conclusions: A NNE-dipping shear zone, which is part of a large system of Timanian thrusts in the Barents Sea, controlled the formation of WNW–ESE-striking Devonian–Mississippian normal faults and syn-tectonic sedimentary rocks in Billefjorden. Eurekan strain partitioning and decoupling suggest that the Svalbardian Orogeny did not occur in Svalbard.

Keywords
Svalbard, Billefjorden, Devonian, décollement, Timanian, Svalbardian, Eurekan, Cenozoic

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Introduction

The Svalbard Archipelago experienced a complex series of tectonic events during its geological evolution, including the latest Neoproterozoic Timanian Orogeny (Faehnrich *et al.*, 2020; Koehl, 2019; Koehl, 2020a; Koehl *et al.*, 2022a; Majka *et al.*, 2008; Majka *et al.*, 2012; Majka *et al.*, 2014; Mazur *et al.*, 2009), early Paleozoic Caledonian Orogeny (Gee *et al.*, 1992; Gee *et al.*, 1994; Harland *et al.*, 1966; Witt-Nilsson *et al.*, 1998), Devonian late- to post-orogenic extension (Braathen *et al.*, 2018; Braathen *et al.*, 2020; Friend *et al.*, 1997; Maher *et al.*, 2022; Manby & Lyberis, 1992), latest Devonian Svalbardian contraction (Dallmann & Piepjohn, 2020; Harland *et al.*, 1974; Piepjohn *et al.*, 1997; Vogt, 1938), Pennsylvanian to early Permian rifting (Braathen *et al.*, 2011; Cutbill & Challinor, 1965; Johannessen & Steel, 1992), and early Cenozoic Eurekan deformation (Dallmann *et al.*, 1993; Harland, 1969; Harland & Horsfield, 1974; Maher *et al.*, 1986). Apart from the Timanian Orogeny, these tectonic events contributed to form a prominent N–S-trending structural grain on the island of Spitsbergen. This grain consists of Caledonian foliation, thrusts and shear zones, Devonian normal faults, latest Devonian folds and thrusts, Pennsylvanian to early Permian normal faults and early Cenozoic thrusts, folds, and shear zones. The long-lived N–S trend of the dominant structural grain is thought to have played an important role in the assembly of Svalbard's three main basement terranes during the early to mid Paleozoic (Caledonian and Svalbardian orogenies), e.g., by accommodating strike-slip movements in a scale of hundreds to thousands of kilometers along brittle faults such as the Billefjorden Fault Zone (Harland *et al.*, 1974; Harland *et al.*, 1992). Nevertheless, N–S-trending structures alone, cannot explain all the sedimentary thickness variations within Carboniferous successions, such as the Hultberget Formation (e.g., locally absent in Brucebyen; Cutbill *et al.*, 1976) and coal-rich strata of the Billefjorden Group (e.g., thickest in Pyramiden, Sassenfjorden, and Tempelfjorden but almost absent in Yggdrasilkampen; Cutbill *et al.*, 1976; Dallmann *et al.*, 2004a; Koehl, 2021).

Other structural trends exist in Svalbard, among which the WNW–ESE trend is the most prominent (Bergh *et al.*, 2000; Koehl & Muñoz-Barrera, 2018; McCann, 2000; Piepjohn *et al.*, 2001; Saalmann & Thiedig, 2000; Saalmann & Thiedig, 2001). Structures of this trend have, thus far, been poorly studied and their role and implications for the tectonic history of Svalbard are poorly understood. The goal of this paper is to discuss newly identified WNW–ESE-striking structures on seismic and bathymetric data in Billefjorden, e.g., the Adolfbukta and Garmaksla faults, and their influence on well-studied N–S-striking basins and faults, e.g., the northern Spitsbergen Devonian Graben (Friend *et al.*, 1997; Manby & Lyberis, 1992) and the Carboniferous Billefjorden Trough (Braathen *et al.*, 2011; Gjelberg, 1984). The present contribution is part of a large study (Koehl *et al.*, 2020) aiming at investigating cryptic WNW–ESE-striking structures and fabrics in the Norwegian Arctic. The present contribution focuses on the offshore portion (seismic and bathymetric data) of the Billefjorden area, whereas Koehl *et al.* (2023a) and Koehl *et al.* (2023b) focus on onshore outcrops respectively on the western shore and the eastern shore of the fjord.

Geological setting

In the latest Neoproterozoic, the Svalbard Archipelago was truncated by several kilometers thick, thousands of kilometers long, dominantly top-SSW thrust systems during the Timanian Orogeny (Koehl, 2019; Koehl, 2020a; Koehl *et al.*, 2022a). In northern and central Spitsbergen, these thrusts are deeply buried, but some crop out in western Spitsbergen, where they were exhumed by subsequent E–W Caledonian and Eurekan contraction (e.g., Vimsodden–Kosibapasset Shear Zone in southwestern Spitsbergen; Faehnrich *et al.*, 2020; Majka *et al.*, 2008; Majka *et al.*, 2012; Majka *et al.*, 2014; Mazur *et al.*, 2009).

In the early Paleozoic, igneous and sedimentary Proterozoic basement rocks in northeastern Spitsbergen (Figure 1A) were subjected to c. E–W-oriented contraction during the Caledonian Orogeny resulting in the formation of a tens of kilometer wide, gently north-plunging antiform or antiformal thrust stack with well developed N–S-trending foliation (Gee *et al.*, 1992; Gee *et al.*, 1994; Witt-Nilsson *et al.*, 1998).

In late Silurian to Early Devonian times, late- to post-orogenic extensional collapse initiated, leading to the deposition of several kilometer-thick, reddish sedimentary successions in northern Spitsbergen made up with basal conglomerate units overlain by interbedded sandstones and shales (Friend & Moody-Stuart, 1972; Gee & Moody-Stuart, 1966; Manby & Lyberis, 1992; Manby *et al.*, 1994). These successions were deposited in the hanging wall of low-angle extensional detachments (Chorowicz, 1992; Roy, 2007; Roy, 2009), some of which accommodated coeval exhumation of basement rocks as metamorphic core complexes (Braathen *et al.*, 2018; Braathen *et al.*, 2020; Maher *et al.*, 2022). A description of the Devonian sedimentary units in northern and central Spitsbergen is provided in *Extended data*. In Billefjorden (Figure 1B), Devonian sedimentary rocks are believed to be present west and southwest of the Billefjorden Fault Zone as observed in onshore areas (e.g., Dallmann & Piepjohn, 2020; Piepjohn, 2000).

In the Late Devonian, Spitsbergen is commonly thought to have experienced a short-lived episode of contraction, the Svalbardian Orogeny, during which the Balliolbreen Fault segment of the Billefjorden Fault Zone presumably formed as a top-west reverse fault, juxtaposing Proterozoic basement rocks in the east against post-Caledonian (Devonian) sedimentary rocks in the west (Bergh *et al.*, 2011; Dallmann & Piepjohn, 2020; Harland *et al.*, 1974; McCann, 2000; Piepjohn *et al.*, 1997; Piepjohn, 2000; Vogt, 1938). The Balliolbreen Fault is thought to continue southwards across Billefjorden as a rectilinear NNW–SSE- to N–S-striking fault (Bælum & Braathen, 2012). Svalbardian tectonism is thought to have deformed Devonian sedimentary rocks of the Andrée Land Group and Mimerdalen Subgroup intensely in discrete narrow belts in Dickson Land (Dallmann & Piepjohn, 2020; Piepjohn & Dallmann, 2014). However, competing interpretations based on evidence from aerial photographs and field and seismic data suggest that Svalbardian folds and thrusts may partly have formed during extensional detachment folding in the Early to Middle Devonian (Chorowicz, 1992; Roy, 2007; Roy, 2009) and/or due to early

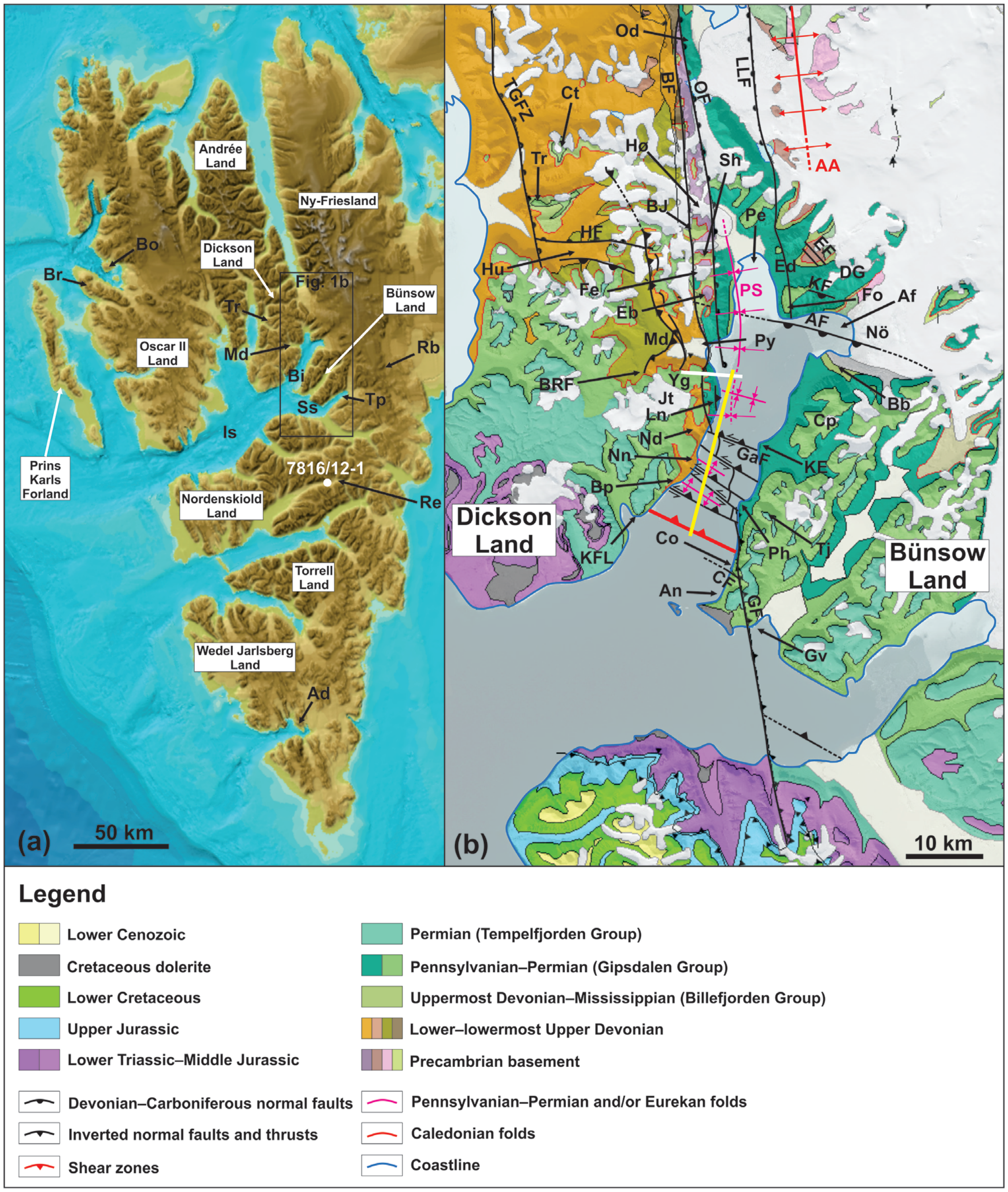

Figure 1. (**A**) Topographic and bathymetric map around Spitsbergen modified after Jakobsson *et al.* (2012) (originally published under CC-BY 4). Abbreviations: Ad – Adriabukta; Bi – Billefjorden; Bo – Blomstrandhalvøya; Br – Brøggerhalvøya; Is – Isfjorden; Md – Mimerdalen; Rb – Rembebreen; Re – Reindalspasset; Ss – Sassenfjorden; Tp – Tempelfjorden; Tr – Triungen; (**B**) Geological map modified from svalbardkartet.npolar.no showing the main tectono-stratigraphic units and structures in the study area in central Spitsbergen. The yellow line shows the location of the seismic line in Figure 4A–B and the white line the approximate location of the transect shown in Figure 6. Abbreviations: AA – Atomfjella Antiform; AF – Adolfbukta Fault; Af – Adolfbukta; An – Anservika; Bb – Brucebyen; BF – Balliolbreen Fault; BJ – Birger Johnsonfjellet; Bp – Brimerpynten; BRF – Blåvatnet Reverse Fault; CF – Cowantoppen Fault; Co – Cowanodden; Cp – Campbellryggen; Ct – Citadellet; DG – De Geerfjellet; Eb – Elsabreen; Ed – Ebbadalen; EF – Ebbabreen Faults; Fe – Ferdinandbreen; Fo – Fortet; GaF – Garmaksla fault; GF – Gipshuken Fault; Gv – Gipsvika; HF – Hugindalen Fault; Hu – Hugindalen; Hø – Hørbyebreen; Jf – Jotunfonna; KE – Kapp Eckholm; KF – Kampesteindalen Fault; KFL – Kapp Fleur de Lys; LLF – Lemströmfjellet–Løvehovden Fault; Ln – Lykteneset; Md – Mimerdalen; Mu – Mumien; Nd – Nidedalen; Nn – Narveneset; Nö – Nordenskiöldbreen; Od – Odellfjellet; OF – Odelfjellet Fault; Pe – Petuniabukta; PS – Petuniabukta Syncline; Ph – Phantomodden; Py – Pyramiden; Re – Reindalspasset; Sh – Svenbreenhøgda; TGFZ – Triungen–Grønhorgdalen Fault Zone; Tj – Tjosaasfjellet; Tr – Triungen; Yg – Yggdrasilkampen.

Cenozoic strain partitioning and decoupling along low-angle detachments and/or décollements, e.g., within weak Devonian to Mississippian shale- and coal-rich sedimentary strata (Koehl, 2021) and Pennsylvanian to Permian evaporites (Harland *et al*., 1988; Ringset & Andresen, 1988). In addition, there are many inconsistencies attached to the timing of the Svalbardian event throughout Spitsbergen (Koehl *et al*., 2022b).

In the latest Devonian to Mississippian (Lindemann *et al*., 2013; Marshall *et al*., 2015; Playford, 1962; Playford, 1963; Scheibner *et al*., 2012), fluvial, clastic- and coal-rich deposits of the Billefjorden Group (Figure 2) deposited during a period of tectonic quiescence (Braathen *et al*., 2011; Smyrak-Sikora *et al*., 2018) or within multiple mini-basins (Aakvik, 1981; Cutbill & Challinor, 1965; Cutbill *et al*., 1976; Gjelberg, 1984; Koehl & Muñoz-Barrera, 2018; see electronic supplement 1 for description of the stratigraphic units).

In the Earyl to Middle Pennsylvanian, sediment deposition (Gipsdalen Group) was restricted to the Billefjorden Trough and was accompanied by kilometer-scale normal faulting in a shallow marine environment with main depocenter between the Billefjorden Fault Zone and the Lemströmfjellet–Løvehovden Fault (Braathen *et al*., 2011; Smyrak-Sikora *et al*., 2018; Figure 2). In the latest Middle Pennsylvanian to early Permian, tectonic activity had almost completely ceased and a carbonate platform developed in a shallow sea (Ahlborn & Stemmerik, 2015; Braathen *et al*., 2011; Cutbill & Challinor, 1965; Gee *et al*., 1952; Keilen, 1992; Maher & Braathen, 2011 see electronic supplement 1 for description of the stratigraphic units).

In the early Cenozoic, the opening of the Labrador Sea and of Baffin Bay between Greenland and Canada (Chalmers & Pulvercraft, 2001; Oakey & Chalmers, 2012) resulted in an episode of contraction (transpression?) in Svalbard, the Eurekan tectonic event, during which east-verging thrusts formed in the West Spitsbergen Fold-and-Thrust Belt (Andresen *et al*., 1994; Dallmann *et al*., 1993; Harland, 1969; Harland & Horsfield, 1974; Maher *et al*., 1986) and a thick succession of sediments deposited in the Central Tertiary Basin (foreland basin; Larsen, 1988; Petersen *et al*., 2016). In Billefjorden, Eurekan deformation involved the NE-dipping Cowantoppen Fault, which accommodated up to 200 m of top-SW reverse movement, and the southern continuation of the Balliolbreen Fault, the east-dipping Gipshuken Fault, which offsets the Wordikammen and Gipshuken formations by up to 200 m of top-west (Bælum & Braathen, 2012; Dallmann *et al*., 2004a; Harland *et al*., 1974; Ringset & Andresen, 1988).

Methods

The study presents structural analysis of submarine escarpments on bathymetric data from the Norwegian Mapping Authority and the University Centre in Svalbard (Figure 3A–D and electronic supplement 2) and on Two-Way Time (TWT) seismic data from the Norwegian National Data Repository for Petroleum Data (DISKOS database) in Billefjorden (Figure 4A–H and electronic supplements 3 and 4). See *Underlying data* for full details of the datasets used. To interpret bathymetric and seismic data, we used Global Mapper (version 13) and Petrel (version 2021.3) respectively. QGIS and OpendTect are free, open source alternative software that can be used to perform similar functions to Global Mapper and Petrel respectively. CorelDraw 2017 (GIMP is a freely available open source alternative) was used to design the figures.

The depth and thickness of sedimentary units were obtained through interpretation of the main sedimentary unit boundaries and brittle faults and shear zones on seismic data (Figure 4A–H and electronic supplements 3 and 4). The interpretation of the various stratigraphic units is included in electronic supplement 5. Velocity data are taken from exploration well 7816/12-1 in Reindalspasset (electronic supplement 6; Eide *et al*., 1991) and from Gernigon *et al*. (2018, their Table 1), and were used to calculate estimates (minimum and maximum) of depths and thicknesses (in meters – m) from Two-Way Time seismic data. We used velocities from nine intervals (1850 to 2250 m; depths of intervals are specified *Extended data*) in well 7816/12-1 to calculate an average velocity for Pennsylvanian rocks in central Spitsbergen (c. 5940 m.s^{-1}) and used average velocities from Gernigon *et al*. (2018) of 5500 m.s^{-1} for Pennsylvanian and 5500 to 5800 m.s^{-1} for Devonian to Mississippian sedimentary rocks. For the depth conversion of the seismic section (electronic supplement 7), we used the velocities from Gernigon *et al*. (2018; electronic supplement 6). High-resolution versions of the manuscript's figures (necessary to identify the structures and stratigraphic units mentioned) can be found in *Underlying data* (Koehl *et al*., 2023c) and *Extended data* (Koehl *et al*., 2023d).

Results and interpretations

Bathymetric data

Description

In Adolfbukta, bathymetric data (Figure 3A; see high-resolution versions of the figure at *Underlying data*) the mouth of Nordenskiöldbreen show numerous narrow (several meters wide), undulating to arcuate, NNE–SSW- to N–S-trending, ice-margin parallel, typically 2 to 3 m high submarine ridges that were interpreted as moraines deposited during the most recent recession of Nordenskiöldbreen (dotted fuchsia lines in Figure 3B; Allaart *et al*., 2018). Farther south, the moraine ridges appear to abruptly bend into a NNW–SSE trend across localized WNW–ESE-trending submarine escarpments that accommodate gentle to moderate (typically 5 to tens of meters) drops in bathymetry (Figure 3B and electronic supplement 8). The WNW–ESE-trending escarpments align with but are distinct from widespread, smooth, WNW–ESE-trending, oval-shaped hills and parallel lineations and troughs, which were interpreted as glacially streamlined landforms (drumlins and glacial lineations) and mass transport deposits with associated channels (yellow lines in Figure 3B; Allaart *et al*., 2018; Baeten *et al*., 2010). Glacial lineations in the deepest portion of the fjord show arcuate geometries, bending from an E–W trend in the northeast to a NE–SW trend in the southwest, i.e., following the fjords attitudes. Oblique to the glacial lienations is a subtle WNW–ESE-trending lineament bounding

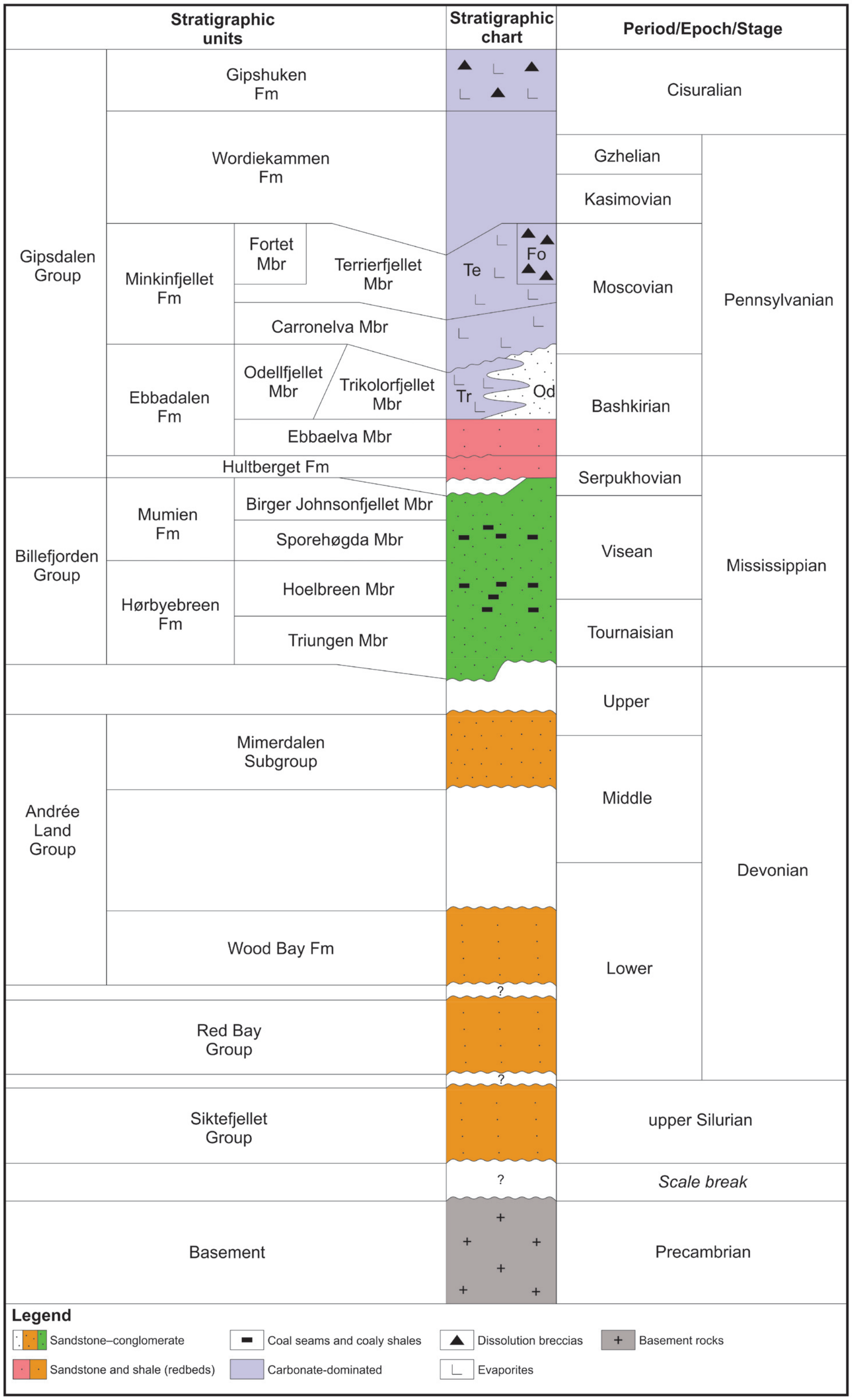

Figure 2. Litho-stratigraphic chart of mid to late Paleozoic (upper Silurian to lower Permian) sedimentary rocks of the Siktefjellet, Red Bay, Andrée Land, Billefjorden, and Gipsdalen groups in central Spitsbergen. The chart is based on descriptions by Aakvik (1981); Braathen *et al.* (2011); Cutbill & Challinor (1965); Cutbill *et al.* (1976); Dallmann *et al.* (1999); Friend *et al.* (1966); Friend & Moody-Stuart (1972); Friend *et al.* (1997); Gee *et al.* (1952); Gee & Moody-Stuart (1966); Gjelberg (1983); Gjelberg (1984); Gjelberg & Steel (1981); Holliday & Cutbill (1972); Johannessen (1980); Johannessen & Steel (1992); Lønøy (1981); Lønøy (1995); McWhae (1953); Murascov & Mokin (1979); Playford (1962), and Dallmann & Piepjohn (2020).

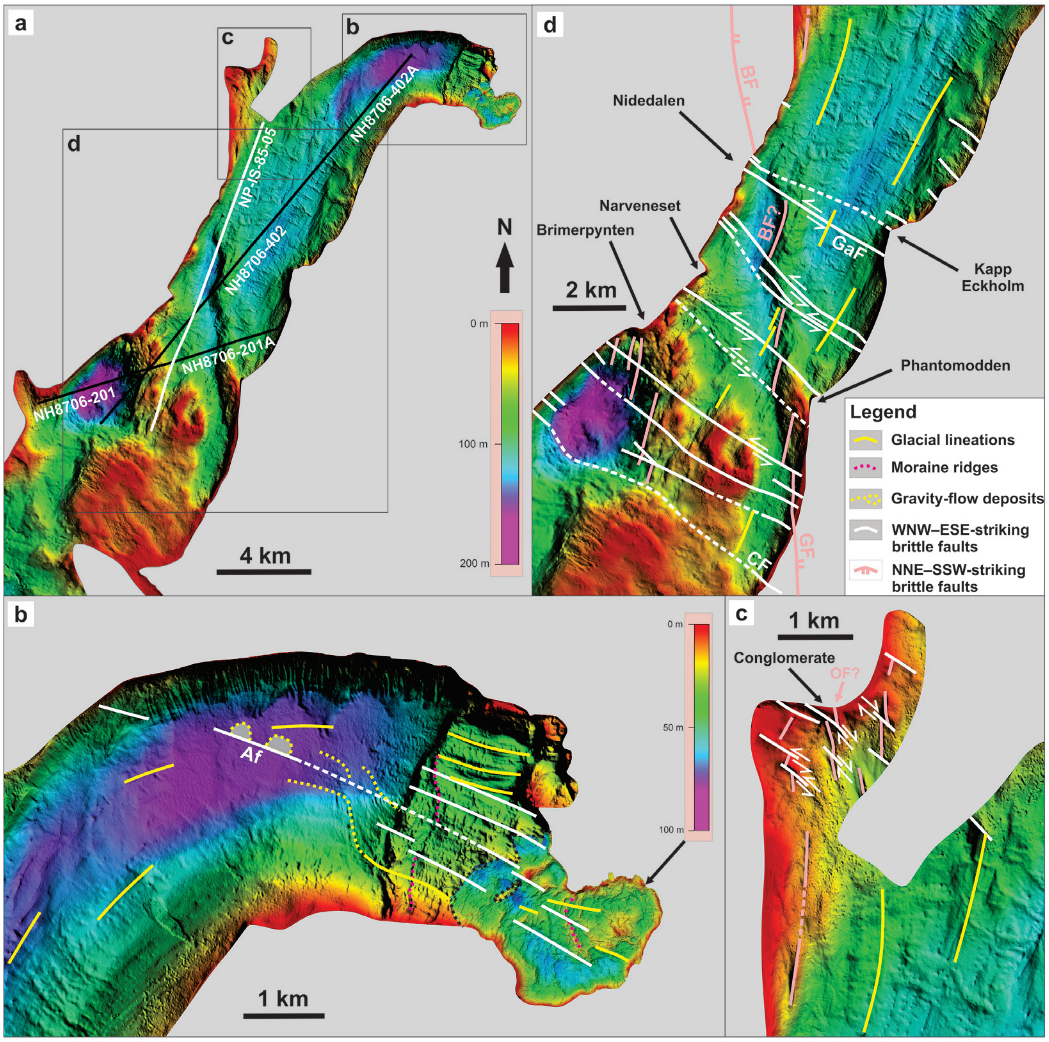

Figure 3. (**A**) Bathymetric data in Billefjorden (see Figure 1A for location) showing the location of seismic line NP-IS-85-05 (Figure 4A–B) as a white line and of other seismic lines included as supplements as black lines. (**B**–**D**) Zooms in (**B**) Adolfbukta and Nordenskiöldbreen, (**C**) Pyramiden, and (**D**) southern Billefjorden showing dominant WNW–ESE-trending, fault-related escarpments (white lines; including the Adolfbukta fault) offsetting (dominantly left-) laterally subsidiary NNW–SSE- to NNE–SSW-trending fault-related escarpments and ridges that parallel known major faults (e.g., Balliolbreen and Odellfjellet faults). Both sets of escarpments trend oblique to local glacial lineations (yellow lines). The reader is referred to Baeten *et al.* (2010) and Allaart *et al.* (2018) for detailed interpretation of glacial features in the area. Note the hundreds of meter- to kilometer-scale left-lateral offsets of a NNW–SSE-trending ridge consisting of NNE–SSW-striking, Z-shaped (possibly drag-folded) segments of the Balliolbreen Fault by WNW–ESE-striking faults in (**D**). Grey shading denotes areas with no data. The dotted black line in (**B**) indicates the boundary between the two bathymetric datasets with different color-scale. Abbreviations: Af – Adolfbukta fault; BF – Balliolbreen Fault; CF – Cowantoppen Fault; GaF – Garmaksla fault; GF – Gipshuken Fault; OF – Odellfjellet Fault. This figure was designed and copyright is held by the authors of the present manuscript.

two 200–300 m wide, 4–5 m high, WNW–ESE-trending, lens-shaped ridges (dotted yellow lines; Figure 3B), which coincide with the end of gravity flow tracks (Allaart *et al*., 2018).

In the northwestern part of Billefjorden near Pyramiden, bathymetric data show a few discontinuous, steep, N–S- and WNW–ESE-striking submarine escarpments abutting and/or crosscutting one another (Figure 3C). Notably, one of the main N–S-trending escarpment, which defines the western flank of a c. 1 km-long ridge, appears offset right-laterally by c. 100 m by a series of aligned, discontinuous, WNW–ESE- to NW–SE-trending lineaments and escarpments (Figure 3C).

In the southern part of Billefjorden, bathymetric data reveal a kilometer-wide, overall N–S-trending ridge that is bounded to the west by alternating steep, N–S- to NNE–SSW-trending escarpments and relatively smooth, arcuate (anticlockwise-bending), NNW–SSE-trending escarpments that define hundreds of meter- to kilometer-scale (500 to 2000 m) left steps along the ridge axis (Figure 3D). The smoother and arcuate

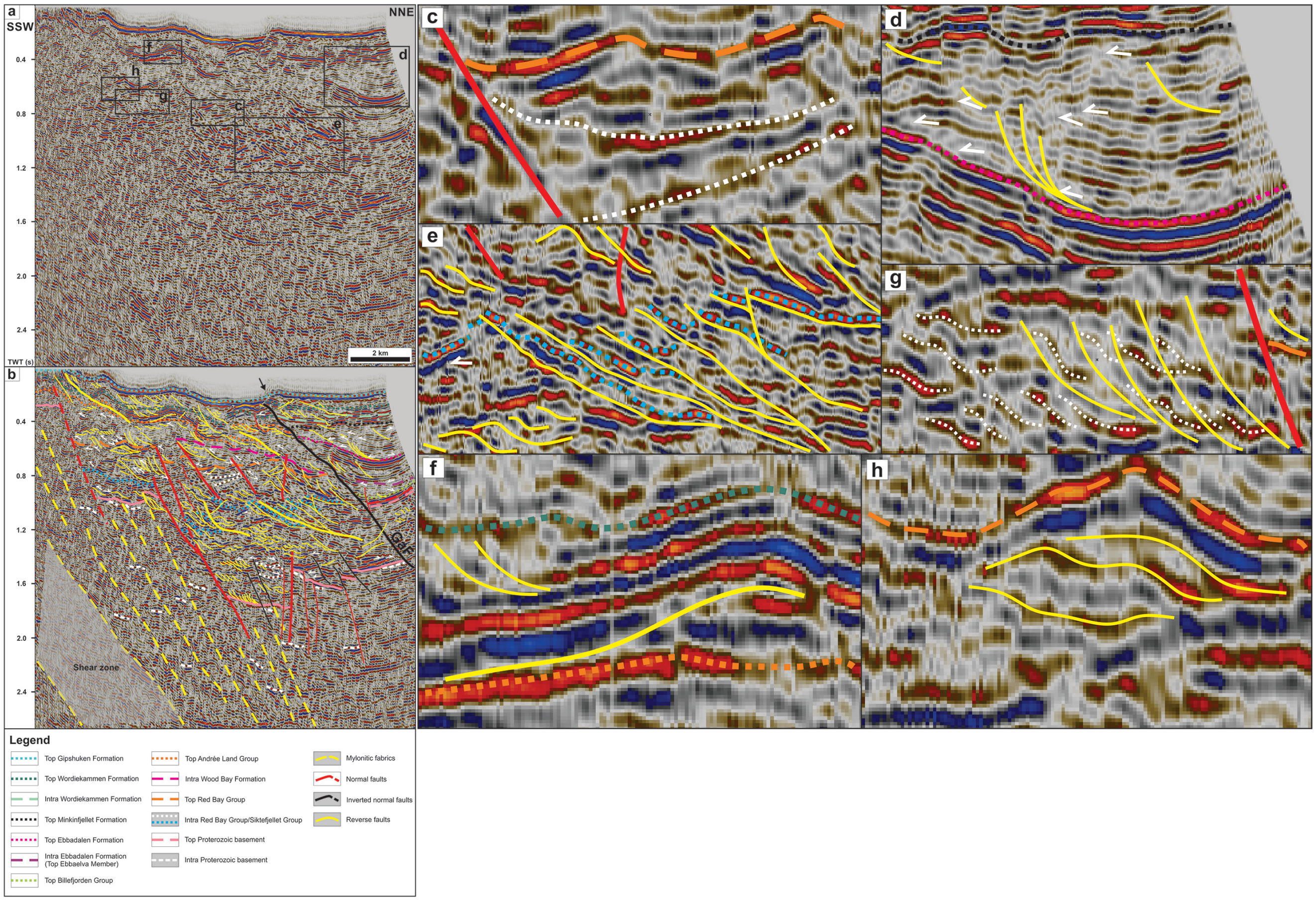

Figure 4. (**A**) Uninterpreted and (**B**) interpreted seismic line NP-IS-85-05 in Billefjorden showing dominant WNW–ESE-trending, NNE-dipping ductile fabrics in Proterozoic basement rocks, and Early Devonian to Pennsylvanian (mildly inverted) normal faults and associated early Cenozoic overprints in Lower Devonian to lower Permian sedimentary rocks. See Figure 1B for location. (**C**–**H**) Zooms in (**C**) a wedge of Lower Devonian sedimentary rocks (dotted white lines) thickening against a NNE-dipping, high-angle, Devonian normal fault (red line) that was partially inverted in early Cenozoic times as shown by gently folded seismic reflections (e.g., dashed orange line), (**D**) an imbricate thrust fan (yellow lines) and onlaps and toplaps (white half-arrows) within the Minkinfjellet Formation, (**E**) early Cenozoic low-angle thrusts (yellow lines) and thrust sheets (dotted blue lines) within Lower Devonian sedimentary rocks, (**F**) a top-NNE early Cenozoic Eurekan thrust (yellow line) flattening and soling into the stratigraphic boundary between the Wood Bay Formation and Wordiekammen Formation (dotted orange line), thus suggesting the presence of a décollement, (**G**) folded bedding surfaces (dotted white lines) offset by top-SSW thrust faults (yellow lines) and arranged into duplexes within Lower Devonian sedimentary rocks, and (**H**) an antiformal thrust stack or ramp anticline within Lower Devonian sedimentary rocks. Note that the bedding surfaces arranged in top-SSW duplexes shown in (**G**) are not displayed in (**B**) due to insuffiencient resolution. Abbreviations: GaF – Garmaksla fault. The seismic data in the figure is reproduced with permission from copyright holders, Norwegian Petroleum Directorate.

NNW–SSE-trending portions of this ridge line up with steep, subvertical, high-frequency, WNW–ESE- to NW–SE-trending escarpments on the edges of the fjord along a WNW–ESE- to NW–SE-trending axis on bathymetric data (Figure 3D).

Interpretation

The location of the N–S-trending escarpment near Pyramiden coincides with the suspected continuation of the Odellfjellet Fault (Braathen *et al.*, 2011; Smyrak-Sikora *et al.*, 2018) and with that of a Eurekan thrust (Dallmann *et al.*, 2004a) and is therefore interpreted as a brittle fault. In southern Billefjorden, the kilometer-wide, overall N–S-trending ridge and associated escarpments trend sub-orthogonal to and display significantly different geometries from smooth, undulating, WNW–ESE- to E–W-trending narrow ridges interpreted as recessional moraines (Baeten *et al.*, 2010). The ridge aligns with the speculated location and strike of the Balliolbreen Fault in Lykteneset (Braathen *et al.*, 2011; Dallmann *et al.*, 2004a; Harland *et al.*, 1974). The ridge may therefore represent the nearshore southern continuation of the Balliolbreen Fault. However, the ridge also coincides with landslides involving rocks of the Wordiekammen Formation onshore in the hanging wall of the Balliolbreen Fault (Dallmann *et al.*, 2004a; Koehl *et al.*, 2022 submitted, their supplement S8). Hence, the ridge may reflect east-dipping carbonate beds of the Wordiekammen Formation that are offset by the Balliolbreen Fault and/or are part of the western limb of the Petuniabukta Syncline (Braathen *et al.*, 2011; Maher & Braathen, 2011). The latter is supported by the smooth and gently east-dipping character of the top of the ridge and by the steeply dipping western flank of the ridge on bathymetric profiles (electronic supplement 9), and by the gently dipping attitude of sedimentary strata within the ridge on seismic data (see black arrow in Figure 4B).

WNW–ESE-trending escarpments in Billefjorden are interpreted as brittle faults. This is supported by the following arguments. First, WNW–ESE-trending escarpments parallel and, in places, align with onshore fault-related escarpments observed on satellite images and in the field (Figure 3B–D, electronic supplement 10, Koehl *et al*., 2023a their figure 3a–b, and Koehl *et al*., 2023b their figures 2, 3, 4a and d–e, and 5). Second, the geometry of the WNW–ESE-trending escarpments (steep and discontinuous) contrasts with that of smooth and continuous, WNW–ESE-trending ridges interpreted as recessional moraines (Baeten *et al*., 2010; Figure 3B–C). This is also the case for N–S-trending fault-related escarpments and NNE–SSW-trending lineations previously interpreted as glacial lineations in northwestern Billefjorden and (Baeten *et al*., 2010; Figure 3C). Third, the curving, abutting and crosscutting relationships of N–S- and WNW–ESE-striking escarpments suggest lateral tectonic offsets and/or stepping attitudes of brittle faults. Notably, in southern Billefjorden, the left-stepping and anticlockwise-bending geometry of the smoother and arcuate NNW–SSE-trending portions of the overall N–S-trending ridge (Balliolbreen Fault?) are interpreted to reflect 0.5 to 1.5 km wide offsets and drag-folding by NW–SE- to WNW–ESE-striking faults. Fourth, in places (e.g., northeastern Billefjorden), WNW–ESE-trending escarpments bound mass-flow deposits and are highly oblique to local glacial features (Figure 3B; Allaart *et al*., 2018).

The smoother, arcuate, NNW–SSE-striking portions of the Balliolbreen Fault link up segments characterized by well defined, steep, N–S- to NNE–SSW-trending escarpments (Figure 3D). Based on the numerous occurrences and, in places, dominance of N–S- to NNE–SSW-striking faults in Billeforden (Figure 3C; Koehl *et al*., 2023a their fig. 3A–B, 5a, c, and d, and 6b; Koehl *et al*., 2023b, fig. 2–6), we propose that NNE–SSW- to N–S-trending fault-related escarpments along the Balliolbreen Fault represent the actual strike of the fault, whereas relatively smoother and arcuate, NNW–SSE-striking segments represent portions of the fault that were drag-folded and offset by (c. 0.5 to 1.5 km-wide) left-lateral movements along WNW–ESE-striking faults (Figure 4A–B).

Seismic data

Structures in Proterozoic basement rocks

Description

Highly reworked basement rocks commonly display chaotic facies in seismic data (e.g., Ji & Long, 2006; Koehl *et al*., 2018; Phillips & McCaffrey, 2019). However, the deepest portions of seismic sections in Billefjorden show sub-horizontal to gently NNE-dipping, undulating, low to moderate-amplitude reflections (dashed white lines in Figure 4B). These are extensively disrupted and truncated by moderately to steeply NNE-dipping (gently dipping once depth-converted; electronic supplement 7), sub-planar and sub-parallel, moderate-amplitude reflections (dashed yellow lines in Figure 4B), which dominate in the south-southwest at a depth > 1.2 second TWT, i.e., > 7 km (grey-shaded area in Figure 4B and electronic supplement 7; see high-resolution versions of the figure in *Underlying data*). Upwards, these sub-horizontal to gently NNE-dipping low to moderate-amplitude reflections are truncated at an angle by a mildly undulating, moderate to high-amplitude, negative reflection interpreted as the Top Proterozoic basement reflection.

Interpretation

The sub-horizontal undulating reflections are interpreted as lithological transitions within folded Proterozoic basement rocks. These attitudes are similar to intra-unit lithological transitions in folded metasedimentary rocks and metaigneous rocks crosscut by intrusions in nearby onshore areas (Bayly, 1957; Christophersen, 2015; Dallmann *et al*., 2004a; Koehl *et al*., 2023b), and to folded basement rocks on seismic data worldwide and in Svalbard (Ji & Long, 2006; Koehl & Allaart, 2021).

The disruptive and truncating character of moderately to steeply (gently when depth-converted; electronic supplement 7) NNE-dipping, moderate-amplitude reflections suggests that they represent pervasive WNW–ESE-trending, NNE-dipping, brittle to ductile, possibly mylonitic fabrics within Proterozoic basement rocks. This is supported by the dominance of WNW–ESE-trending brittle to ductile fabrics in Proterozoic basement rocks in adjacent onshore areas and on bathymetric data in Billefjorden (e.g., Figure 3B and Koehl *et al*., 2023b their figures 2–6), and by the strong influence of preferred mineral orientation on seismic velocity (Christensen, 1965; Fountain *et al*., 1984; Hurich *et al*., 1985). The high concentration of potential mylonitic surfaces within a kilometer-thick zone in the south-southwest (gray-shaded area in Figure 4A–B) indicates that these deformation surfaces are probably aggregated into a major NNE-dipping shear zone, which displays a similar seismic facies to other mylonitic shear zones worldwide (e.g., Christensen & Szymanski, 1988; Clerc *et al*., 2018; Fazlikhani *et al*., 2017; Fisher *et al*., 1989; Hajnal *et al*., 1996; Hedin *et al*., 2016; Koehl *et al*., 2018; Lenhart *et al*., 2019; Osagiede *et al*., 2020; Phillips *et al*., 2016; Phillips & McCaffrey, 2019; Wang *et al*., 1989; Wrona *et al*., 2020).

Structures in post-Caledonian sedimentary rocks

Devonian to Carboniferous extensional normal faults and folds

Description

Stratigraphic units and sub-units and internal reflections within Devonian to Carboniferous sedimentary rocks are offset by several high-angle (moderately dipping when depth converted; electronic supplement 7), sub-planar disruption surfaces that bound north-northeastward-thinning wedge- to fan-shaped seismic sub-units interpreted as alluvial fans (see also electronic supplement 5). Most of these disruption surfaces dip north-northeastwards, terminate upwards within the Wood Bay Formation or the Hultberget and/or Ebbadalen formations, and coincide with abrupt northwards thickening of overlying and adjacent wedge- to fan-shaped stratigraphic units and sub-units. In places, the disruption surfaces are subvertical, dip to the south-southwest, terminate in the lower part of the Devonian succession, and offset seismic reflections interpreted as stratigraphic boundaries and bedding surfaces down-SSW (Figure 4A–B). Both NNE- and SSW-dipping disruption surfaces crosscut stratigraphic (sub-) unit boundaries and bedding surfaces (e.g., dotted blue lines) at a high-angle (Figure 4A–C). Downwards, NNE-dipping disruptions surfaces dip slightly more gently (subtle listric geometry) and merge with parallel mylonitic fabrics in the hanging wall of the kilometer-thick shear zone in underlying and adjacent Proterozoic basement rocks (Figure 4A–B).

In the north-northeast near Pyramiden, Pennsylvanian strata of the Hultberget and/or Ebbadalen and Minkinfjellet formations are involved in a 4 to 5 km-wide, open, E–W- to WNW–ESE-trending syncline (Figure 4A–B & D). There, strata of the Minkinfjellet Formation are thickest near the center of the syncline and terminate as toplaps on the edge of the syncline against a flat-lying Top Minkinfjellet Formation reflection.

Interpretation

Based on their listric geometries, on their high-angle crosscutting relationships with bedding surfaces and stratigraphic (sub-) unit boundaries, on the normal offsets of stratigraphic (sub-) units boundaries across these surfaces, on abrupt thickening of stratigraphic units and sub-units over these surfaces (i.e., possibly representing syn-tectonic deposits), and on their absence in Middle Pennsylvanian to lower Permian strata of the Minkinfjellet, Wordiekammen and Gipshuken formations, we interpret the high-angle (modetarely dipping when depth converted; electronic supplement 7) disruption surfaces as Early Devonian to Early Pennsylvanian normal faults. Normal offsets along these faults are in the range of hundreds of meters to 2 km. For example, the second southernmost of these faults displays the largest offset and potentially offsets the Top Basement reflection by c. 0.7 second (TWT), i.e., ca. 1.9 to 2.0 km, and reflections within the Siktefjellet and/or Red Bay groups (e.g., dotted blue line reflection) by up to ca. 0.3 second (TWT), i.e., c. 825 to 870 m (electronic supplement 6) down-NNE (Figure 4A–B). These brittle, dominantly NNE-dipping normal faults show similar parallel and merging relationships to preexisting basement fabrics as normal faults in Devonian to Carboniferous collapse basins in the Barents Sea (Koehl *et al.*, 2018; Koehl *et al.*, 2022a) and North Sea (Fazlikhani *et al.*, 2017; Lenhart *et al.*, 2019; Osagiede *et al.*, 2020; Phillips *et al.*, 2016). They are therefore interpreted to reflect late- to post-Caledonian Devonian (to Early Pennsylvanian?) collapse along partly reactivated, inherited, NNE-dipping basement fabrics.

The synclinal fold structure most likely partly reflects the contrasting characters of syn-tectonic Lower Pennsylvanian rocks and latest to post tectonic sedimentary strata of the Minkinfjellet Formation. The former were deposited as a potential alluvial fan along a NNE-dipping normal fault, which dies out in the middle to upper part of the Lower Pennsylvanian succession, whereas the latter passively filled accommodation space created by down-NNE normal faulting. This is supported by northward thickening of the Minkinfjellet Formation and northwards thinning of Lower Pennsylvanian strata of the Hultberget and/or Ebbadalen formations on the southern limb, and by southward thickening of the Minkinfjellet Formation and southwards tilting (and northward thinning) of Lower Pennsylvanian strata against a NNE-dipping normal fault on the northern limb (Figure 4A–B).

Early Cenozoic thrusts and contractional duplexes

Description

Interpreted stratigraphic units and sub-units and intra-unit reflections are truncated and offset by numerous low-angle disruption surfaces showing diverse geometries including low-angle and sub-planar, listric and fan-shaped, Z-like, and upwards-convex geometries. Low-angle and sub-planar, dominantly NNE-dipping disruption surfaces commonly show top-SSW reverse offsets and, occasionally, (S-like) bending of stratigraphic (sub-) units boundaries (e.g., Top Red Bay Group reflection) and bedding surfaces (e.g., dotted blue lines in Figure 4B & E). In places, these disruption surfaces merge with bedding surfaces (e.g., dotted blue lines) but die out rapidly laterally, extending less than 3 km from north-northeast to south-southwest (Figure 4A–B & E).

Z-like reflections extending laterally for tens to hundreds of meters are particularly abundant within Devonian (Siktefjellet and/or Red Bay groups and Wood Bay Formation) and lower Permian (Wordiekammen and Gipshuken formations) units. These reflections mostly occur as groups of several adjacent reflections bounded upwards and downwards by planar reflections (Figure 4A–B & G).

Interpretation

The low-angle disruption surfaces are interpreted as early Cenozoic thrust faults locally bounding and detaching thin (<< 0.1 s TWT thick) thrust sheets and soling into bedding-parallel décollements (Figure 4A–B & E–F). This is suggested by the low-angle relationship with bedding surfaces and stratigraphic (sub-) unit boundaries, the reverse offsets of stratigraphic boundaries and related seismic reflections, the narrow (< 3 km) lateral extent of thrust faults, and their presence in all stratigraphic units. The only exception to the limited lateral extent is a thrust detaching a c. 1 km-wide, open, SSW-verging anticline fold structure in the hanging wall involving a ca. 0.2 s (TWT) thick succession of strata of the Wood Bay, Wordiekammen and Gipshuken formations. In the north-northeast, this thrust fault merges with the Top Andrée Land Group (top of Lower Devonian) stratigraphic boundary that potentially hosts a local, bedding-parallel décollement detaching the overlying SSW-verging anticline (Figure 4A–B & F). This suggests that this fold structure corresponds to a ramp anticline. In places, low-angle thrusts display listric and downwards merging geometries, forming fan-shaped structures that may represent imbricate thrusts (Figure 4A–B & D). Offsets along low-angle thrusts are in the range of (tens to hundreds of) meters and may reach up to 1 to 2 km in places (e.g., offset dotted blue line in Figure 4B & E).

Z-like reflections may well correspond to tilted prograding sedimentary systems. However, since the rounded edges of these Z-like reflections seems to coincide with subtle bends in bounding planar reflections (Figure 4A–B & G), and considering their geometrical similarity with low-angle thrusts and their occurrence as packages of adjacent Z-shaped reflections, we propose that they correspond to brocken-up, stacked bedding surfaces in contractional duplexes (Boyer & Elliott, 1982) most likely consisting of roof- and floor-thrusts (McClay, 1992) connected by link thrusts (McClay & Insley, 1986). The seismic expression and geometry of these structures is very similar to contractional duplex structures in uppermost Devonian to Mississippian coal-rich sedimentary deposits of the Billefjorden Group onshore in Pyramiden and nearshore in Sassenfjorden and Tempelfjorden (Koehl, 2021). Aggregates of contractional duplexes commonly align with the imaginary downwards and upwards prolongation of low-angle subplanar thrusts, seemingly connecting them and, thus, possibly acting as hard- to soft-linking transfer structures (Figure 4A–B). In places, Z-shaped reflections show upwards-convex geometries (Figure 4A–B & H), which may also represent contractional duplexes, but that potentially suggest tilting and reworking of the duplexes into local antiformal thrust stacks.

Contractional inversion structures

Description

Devonian to Permian strata in Billefjorden are also deformed into multiple kilometer-scale fold structures. Notably, Devonian and lower Permian strata in the south are involved into a 1 to 2 km-wide open anticline, which location coincides with that of the tip of high-angle normal faults terminating within the Wood Bay Formation (Figure 4A–B).

In the north-northeast, a major, moderately NNE-dipping, gently undulating disruption surface abuts near the seafloor reflection and merges at depth with the main NNE-dipping fault bounding uppermost Devonian to Pennsylvanian sedimentary strata (Figure 4A–B). This disruption surface coincides with a break and a minor (c. 500 m-wide) bump in the seafloor reflection, and with a top-SSW, ca. 0.1 second (TWT) (i.e., c. 250 to 325 m; electronic supplement 6) reverse offset of the Top Wordiekammen reflection (Figure 4A–B and electronic supplement 5).

Interpretation

It is possible that the 1 to 2 km-wide open anticline is related to upwards propagation of normal faults in post-Carboniferous times. However, considering its occurrence at the same depth and its proximity to the interpreted ramp anticline in the hanging wall of an early Cenozoic low-angle thrust 1 to 2 km farther south, it is more probable that this broad anticline reflects mild inversion of preexisting Devonian normal faults during early Cenozoic contraction.

Considering the merging relationship with the high-angle normal fault at depth, reverse offset of the Top Wordiekammen Formation, and minor break and bump in the seafloor reflection (Figure 4A–B), we argue that the major, moderately NNE-dipping, gently undulating disruption surface represents an early Cenozoic top-SSW thrust overprint of a major (Devonian? to) Early Pennsylvanian down-NNE normal fault. Based on the absence of Pennsylvanian sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations south of this fault on seismic data and on a subtle (c. 250 to 325 m, i.e., ca. 0.1 s TWT; electronic supplement 6) thickness increase of the Wordiekammen Formation in the fault hanging wall, the fault is thought to have initiated as a Pennsylvanian to earliest Permian normal fault, accommodating as much as 1.1 to 1.2 km of down-NNE normal displacement (i.e., ca. 0.4 s TWT; electronic supplement 6) and was later reactivated as a thrust in the early Cenozoic. This fault is associated with a 4 to 5 km-wide, open, E–W- to WNW–ESE-trending syncline in rocks of the Billefjorden and Gipsdalen groups in the hanging wall (Figure 4A–B & D). Though this fold is partly thought to reflect the late- to post-tectonic character of Middle Pennsylvanian deposits of the Minkinfjellet Formation, involvement of the Top Basement and Top Billefjorden Group reflections in the folding (Figure 4A–B) suggest that it (at least partly) formed due to Eurekan contraction in the early Cenozoic.

Correlation of seismic and bathymetric data and satellite images

The locations of dominantly NNE-dipping brittle faults on seismic data (Figure 4A–B) correlate well with WNW–ESE-striking fault-related escarpments on bathymetric data (Figure 3D). Notably, (1) the main NNE-dipping, inverted normal fault bounding uppermost Devonian to Pennsylvanian strata on seismic data in Billefjorden and presently named the Garmaksla fault (250 to 325 m top-SSW offset; electronic supplement 6), (2) the system of hard- to soft-linked early Cenozoic, Eurekan, top-SSW thrusts (250 to 325 m top-SSW offset; electronic supplement 6), and (3) the major low-angle, early Cenozoic, NNE-dipping partial décollement (c. 1 km top-SSW offset; Figure 4A–B) coincide with WNW–ESE-striking fault-related escarpments with associated drag folding and left-lateral offsets of the Balliolbreen Fault that extend respectively (1) from a few hundreds of meters north of Nidedalen to Kapp Eckholm (0.5 to 1.5 km offset), (2) from Nidedalen to c. 1 km northeast of Phantomodden (offset up to 1.5 km), and (3) from southwest of Brimerpynten to southwest of Phantomodden (offset of up to c. 500 m; Figure 3D). The drag-folding in map view and both horizontal (Figure 3D) and vertical offsets across these faults (Figure 4A–B) suggest that they accommodated oblique-slip sinistral-reverse movements in the early Cenozoic.

Alternatively, the apparent left-lateral offset of the ridge on bathymetric data (Figure 3D) may reflect vertical offset of gently dipping sedimentary strata of the Wordiekammen Formation, as suggested from bathymetric profiles (electronic supplement 9) and onshore studies in Garmdalen and Lykteneset (Dallmann *et al.*, 2004a; Koehl *et al.*, 2022 submitted). If they were purely vertical, the offsets along WNW–ESE-striking faults must therefore be normal down-NNE or reverse top-NNE because of the east-dipping character of sedimentary strata. Seismic data show that WNW–ESE-striking faults offsetting the ridge dip to the north-northeast and accommodated top-SSW offset of the Wordiekammen Formation (e.g., Garmaksla fault; Figure 4A–B), therefore suggesting that the WNW–ESE-striking faults in Billefjorden did accommodate some sinistral strike-slip movement component. This is further supported by slickenside lineations indicating sinistral to sinistral-reverse movement along WNW–ESE-striking faults in Narveneset (electronic supplement 11).

Considering the NNE–SSW strike of the Balliolbreen Fault (Figure 3A & D), i.e., parallel to the NNE–SSW-trending seismic line in Figure 4A–B, it is very likely that the fault should appear as a horizontal reflection or alignment of reflection disruptions, at least in the northern half of the seismic line since the laterally offset northern segment of the Balliolbreen Fault dips ESE and, thus, most likely intersects with the seismic section at depth. Taking into account previous studies of the Balliolbreen Fault in the area (e.g., Harland *et al.*, 1974; Koehl, 2021), it is probable that the Balliolbreen Fault actually localized within weak, coal-rich sedimentary deposits of the Billefjorden Group (see dashed red line in Figure 4B) as observed in Pyramiden (Koehl, 2021), or simply separates the Billefjorden Group from Proterozoic basement rocks (i.e., dashed light red line in Figure 4B).

Discussion

The discussion (1) reviews evidence for the presence of a fault in northern Billefjorden, the Adolfbukta fault and (2) evaluates the impact of newly identified WNW–ESE-striking faults on the Billefjorden Trough and related faults. Then, the discussion addresses the implications of the present study for (3) post-Caledonian extension at a regional scale (a detailed discussion of further implications for Devonian–Carboniferous normal faulting is included as electronic supplement 12), (4) the Svalbardian Orogeny and the Eurekan tectonic event, and (5) the Petuniabukta Syncline. Finally, a brief account on (6) the orogin of the WNW–ESE-striking faults in Billefjorden is given.

The Adolfbukta fault

In Pyramiden, relatively recent studies (e.g., Bergh *et al.*, 2011; Michaelsen *et al.*, 1997; Piepjohn *et al.*, 1997; Piepjohn, 2000) suggested the presence of Proterozoic basement rocks in outcrops below the entrance of the Russian coal mine of Pyramiden, although older works showed only Devonian to Mississippian sedimentary rocks (Harland *et al.*, 1974; Lamar *et al.*, 1986; Sirotkin, pers. comm. 2019). Recent fieldwork and thin section analysis on both sides of the speculated trace of the Balliolbreen Fault in this area further supports the absence of basement in Pyramiden (Koehl, 2021). The contact between Proterozoic basement and uppermost Devonian to Permian sedimentary rocks, which crop out at a maximum altitude of c. 500 m in Elsabreen 2 to 2.5 km north of Pyramiden (Figure 1B), is therefore located below ground level in Pyramiden, i.e., at least below an altitude of 100 m. Similarly in eastern Billefjorden, the unconformity between Proterozoic basement rocks and overlying uppermost Devonian to Mississippian rocks of the Billefjorden Group shows a comparable southwards altitude decrease across Adolfbukta, from > 200 m altitude in De Geerfjellet (Dallmann *et al.*, 2004a; svalbardkartet.npolar.no) to a depth of 116 m in Brucebyen (Cutbill *et al.*, 1976).

In addition, several stratigraphic units thicken southwards across Adolfbukta. For example, the thickness of the Billefjorden Group increases from < 40 m in De Geerfjellet (see location in Figure 1B) to 85 to 100 m-thick in Brucebyen (Figure 1B; Cutbill *et al.*, 1976). The uppermost Devonian to Middle Pennsylvanian sedimentary infill (Billefjorden Group and Hultberget, Ebbadalen, and Minkinfjellet formations) in Petuniabukta is c. 1.3 km thick based on exploration wells of Trust Arktikugol (Senger *et al.*, 2019). These successions thicken to the south to c. 1.65 to 1.78 km based on depth conversion of seismic data near Pyramiden (ca. 0.6 s TWT; Figure 4A–B; electronic supplement 6). Such significant and abrupt thickening to the south may reflect c. 350 to 480 m of syn-sedimentary, down-SSW normal movements along an E–W- to WNW–ESE-striking fault zone in Adolfbukta, including up to 45 to 60 m during the deposition of the Billefjorden Group based on thickness variations (Cutbill *et al.*, 1976). A potential candidate is the Kampesteindalen Fault (Smyrak-Sikora *et al.*, 2018). However, the estimated total normal displacement along the Kampensteindalen Fault is thought to be around 50 m in the Early Pennsylvanian (Smyrak-Sikora *et al.*, 2018), i.e., much smaller than total southward sedimentary thickness increase across Adolfbukta. Displacement along the Kampesteindalen Fault is also much smaller than the 300 to 400 m southward altitude drop of the contact between Proterozoic basement rocks and the Billefjorden Group. It is therefore unlikely that the Kampesteindalen Fault is, alone, responsible for such southwards deepening and thickening. This therefore suggests the presence of a larger SSW-dipping normal fault extending between Adolfbukta and Pyramiden, the Adolfbukta fault. This is further supported by numerous WNW–ESE-striking fault-related escarpments in Proterozoic basement rocks on satellite images, in the field (Koehl *et al.*, 2023b, figure 2, 3, 4a, d–e, and 5) and on bathymetric data in Nordenskiöldbreen (Figure 3A–D), and in nearby onshore areas in Billefjorden (Witt-Nilsson *et al.*, 1998, figure 3; Christophersen, 2015; Koehl & Muñoz-Barrera, 2018; Koehl *et al.*, 2023a, figure 3A–B; Koehl *et al.*, 2023b, figure 2, 3, 4a, d–e, and 5). It is also supported by similarly striking normal faults on seismic data in Billefjorden, which show comparable, several hundreds of meter- to kilometer-scale normal offsets of uppermost Devonian to Permian sedimentary successions (Figure 4A–B).

The inferred SSW-dipping Adolfbukta fault defines a WNW–ESE-trending lineament that is highly oblique to glacial features and bounds two, several meters high, WNW–ESE-trending lensoidal ridges in the deepest part of the fjord in Adolfbukta (dotted yellow lines in Figure 3B). In the west, the Adolfbukta fault may continue in Hugindalen where Piepjohn *et al.* (1997, figure 4) and Piepjohn (2000, figure 3) mapped a south- to SSW-dipping brittle normal fault that aligns with the inferred trace of the Adolfbukta fault in Adolfbukta and between Elsabreen and Pyramiden (Figure 1B). East of Billefjorden, the Adolfbukta fault may extend as far as Rembebreen based on mapping by the Norwegian Polar Institute (svalbardkartet.npolar.no), which shows a WNW–ESE-striking fault in the area.

Alternatively or complementarily to the Adolfbukta fault, the 300 to 400 m altitude drop of the top of the Proterozoic basement and base of the Billefjorden Group from Elsabreen to Pyramiden and from De Geerfjellet to Brucebyen may be related to the presence of a several kilometers wide, WNW–ESE-trending, SSW-verging fold structure. Seismic data document the presence of multiple WNW–ESE-trending, open, upright fold structures, including a 4 to 5 km-wide, open, E–W- to WNW–ESE-trending syncline within rocks of the Billefjorden and Gipsdalen groups in northern Billefjorden (Figure 4A–B & D), which are most likely (at least partly) related to mild early Cenozoic inversion of Early Devonian to Carboniferous normal faults during Eurekan deformation. In addition, recent field studies reveal that the N–S-trending, west-verging Mimerelva Syncline (Piepjohn, 2000) bends into a WNW–ESE-trending, SSW-verging geometry in Munindalen (Koehl & Stokmo, 2021a; Koehl & Stokmo, 2021b; Koehl *et al.*, in prep.), i.e., in the west-northwestwards prolongation of the inferred SSW-verging fold between Elsabreen and Pyramiden. E–W- to WNW–ESE-trending early Cenozoic fold structures in Billefjorden would also explain the enigmatic attitude of gently NNE-dipping bedding surfaces and stratigraphic boundaries within the Lower Devonian Wood Bay Formation and uppermost Devonian–Mississippian Billefjorden Group above the entrance of the coal mine in Pyramiden (Koehl, 2021). Nonetheless, the presence of numerous WNW–ESE-trending fault-related escarpments on bathymetric (Figure 3B) and in the field in Adolfbukta (Koehl *et al.*, 2023b, figures 4a and d–e, and 5b) and the horst-and-graben geometries defined by WNW–ESE-striking faults at Top Proterozoic basement level on seismic data (Figure 4A–B) suggest that initial basin geometry bounded by WNW–ESE-striking normal faults played a role in the observed variations. Therefore, the more likely scenario is an interplay between a Devonian to Carboniferous (SSW-dipping) normal fault and a related early Cenozoic, SSW-verging fold structure (e.g., electronic supplement 13).

Segmentation of the Billefjorden Trough by WNW–ESE-striking faults

The overall N–S-trending ridge in southern Billefjorden (Figure 3D) was interpreted as the uplifted (i.e., inverted) hanging wall of NNE–SSW-striking fault segments of the Billefjorden Fault Zone (most likely the Balliolbreen Fault) and/or as east-dipping carbonate beds of the Wordiekammen Formation. The ridge is offset left-laterally and drag-folded by WNW–ESE-trending fault-related escarpments on bathymetric data that correlate with early Cenozoic Eurekan thrusts overprinting and/or that formed parallel to NNE-dipping, inverted, oblique-slip sinistral-normal Devonian to Carboniferous faults (Figure 4A–B). This suggests that the Billefjorden Fault Zone and the Billefjorden Trough are segmented by sub-orthogonal oblique-slip faults and shear zones, most likely since the Early Devonian (Figure 5A), which is supported by a 410 Ma U–Th–Pb age for sinistral strike-slip movements along NW–SE-striking mylonitic shear zones in Proterozoic basement rocks in Oscar II Land (Ziemniak *et al.*, 2020), and possibly earlier as suggested by the basement-seated character of the NNE-dipping mylonitic shear zone (Figure 4A–B). Segmentation is also supported by numerous WNW–ESE-trending fault-related escarpments on satellite images and in the field within Lower Devonian rocks of the Wood Bay Formation in Brimerpynten and Narveneset (electronic supplement 10 and 11).

Segmentation by WNW–ESE-striking faults would explain the gently SW- to south-dipping attitudes of bedding surfaces in Lower Devonian strata of the Wood Bay Formation in Triungen (Dallmann *et al.*, 2004b and electronic supplement 14) through syn-sedimentary Devonian down-faulting to the north along a NNE-dipping fault analogous to those observed on seismic data in Billefjorden (Figure 4A–B). The presence of inverted Devonian NNE-dipping faults in Billefjorden further accounts for anomalous subvertical, E–W-trending bedding surfaces in the Wood Bay Formation in southern Mimerdalen on the northern slope of Yggdsrasilkampen (i.e., suborthogonal to elsewhere in Mimerdalen; Dallmann & Piepjohn, 2020) through a combination of Early Devonian, down-NNE, syn-sedimentary normal faulting and southwards tilting, and subsequent top-SSW Eurekan folding and inversion and/or overprinting along (a) NNE-dipping fault(s) like those observed on seismic data in Billefjorden (Figure 4A–B) and onshore northwestern Spitsbergen (Friend *et al.*, 1997, figure 12B–C; McCann, 2000). This interpretation is supported by occurrences of subvertical, E–W- to WNW–ESE-trending bedding surfaces within Lower Devonian sedimentary rocks of the Wood Bay Formation in the fjord (Figure 4A–B and dotted white lines in Figure 4G).

Segmentation of the N–S-trending Billefjorden Trough may explain the significant thickness variations of coal-rich sedimentary deposits of the Billefjorden Group in central Spitsbergen. This stratigraphic unit, which comprises thickened coal seams in Pyramiden (Livshits, 1966) and Brucebyen (Aakvik, 1981; Cutbill *et al.*, 1976), is very thin (<50 m) to absent in Yggdrasilkampen in the south (Dallmann *et al.*, 2004a), and thinner northwards in Elsabreen and De Geerfjellet (Aakvik, 1981, figure 8.1.3; Cutbill *et al.*, 1976; Gjelberg, 1984). Notably, in Yggdrasilkampen, very thin portions of the Billefjorden Group succession are unconformably overlain by Upper Pennsylvanian to lowermost Permian sedimentary strata of the Wordiekammen Formation (Dallmann *et al.*, 2004a; Koehl *et al.*, 2022; Manby *et al.*, 1994). Whether uppermost Devonian to Mississippian sedimentary strata of the Billefjorden Group were deposited and subsequently eroded prior to the latest Mississippian or never or partly deposited because this area was exposed to continental erosion, a potential explanation for such thinning of the succession in Yggdrasilkampen and for the limited extent of thick coal-rich deposits in Pyramiden might be normal movements along (a) NNE-dipping brittle fault(s) downthrowing the Pyramiden block to the north during the latest Devonian to Middle Pennsylvanian, i.e., prior to the deposition of the Wordiekammen Formation, which is of comparable thickness in Pyramiden and

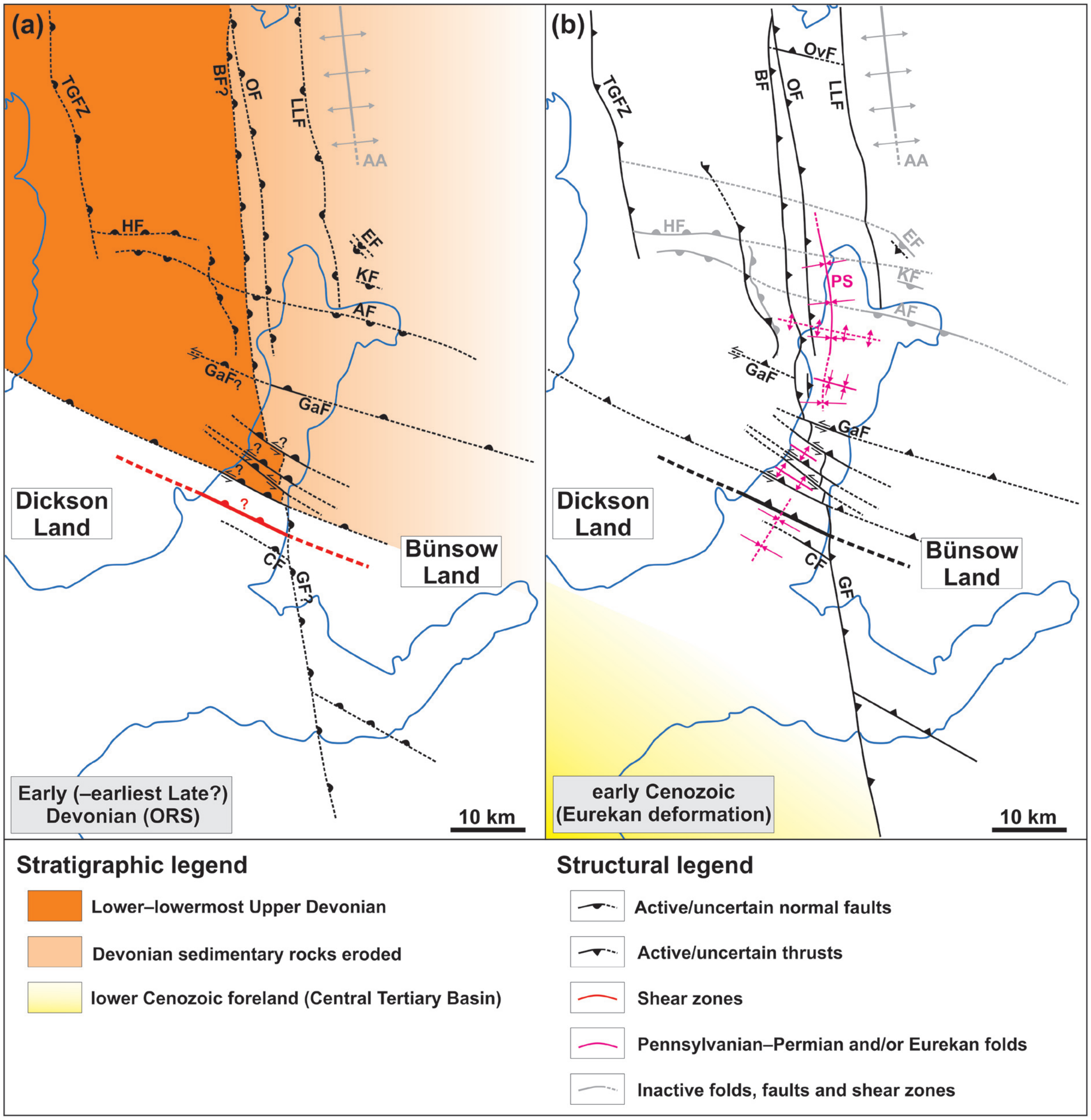

Figure 5. Post-Caledonian tectonic history of the Billefjorden and Sassenfjorden areas including (**A**) (late Silurian? to) Devonian extensional collapse along major NNE-dipping normal faults reactivating/overprinting WNW–ESE-striking (Timanian?) basement fabrics, and (**B**) early Cenozoic formation of the Petuniabukta Syncline and Eurekan reactivation and/or overprint of (Timanian?) basement fabrics and Devonian to Carboniferous normal faults dominantly as top-west and top-SSW thrusts and deposition of lower Cenozoic sedimentary strata in the Central Tertiary Basin south of major NNE-dipping and west of major east-dipping basement-seated shear zones and inverted Devonian to Carboniferous normal faults. Left-lateral offset of the Balliolbreen Fault by NNE-dipping Devonian normal faults may have occurred in the Devonian to Mississippian due to normal-sinistral oblique-slip movements (**A**) and/or in early Cenozoic times due to sinistral-reverse inversion of Devonian to Carboniferous normal faults (**B**). Abbreviations: AA – Atomfjella Antiform; Af – Adolfbukta fault; BF – Balliolbreen Fault; CF – Cowantoppen Fault; EF – Ebbabreen Faults; GaF – Garmaksla fault; GF – Gipshuken Fault; HF – Hugindalen Fault; KF – Kampesteindalen Fault; OF – Odellfjellet Fault; ORS – Old Red Sandstone; OvF – Overgangshytta fault; PS – Petuniabukta Syncline; TGFZ – Triungen–Grønhorgdalen Fault Zone.

Yggdrasilkampen (Dallmann *et al.*, 2004a). This interpretation is supported by the presence of several NNE-dipping faults in Billefjorden such as the Garmaksla fault, which bounds a NNE-thinning, wedge- to fan-shaped unit of uppermost Mississippian to Lower Pennsylvanian sedimentary rocks of the Hultberget and Ebbadalen formations in northern Billefjorden and is therefore believed to have accommodated normal movement at that time (Figure 3D and Figure 4A–B).

Segmentation of the Billefjorden Trough by WNW–ESE-striking fautls is further supported by the calculated surface slope angle (in a critical wedge taper; e.g., Dahlen, 1990) between outcrops of the base Wordiekammen Formation in Pyramiden and Yggdrasilkampen (c. 6.50°), which is 3.5 times higher than between Yggdrasilkampen and Asvindalen farther south (c. 1.99°; electronic supplement 13) where the contact crops out at sea level (Dallmann *et al.*, 2004a). The calculated angle suggests that the uplift of the base Wordiekammen Formation in Pyramiden (located at an altitude of c. 850 m, i.e., higher than the c. 350 to 400 m altitude in Yggdrasilkampen) may be related to top-SSW early Cenozoic movements (folding; Figure 4A–B). Of the c. 475 m high southward down-drop in altitude of the base of the Wordiekammen Formation, about 145 m are related to the local 1.99° dip angle. This indicates that c. 330 m of the southward down-drop are imputable to top-SSW Eurekan folding in Mimerdalen (electronic supplement 13).

Thickening of uppermost Devonian to Mississippian sedimentary strata of the Billefjorden Group in Birger Johnsonfjellet, Petuniabukta, and Triungen, and thinning farther north in Faraofjellet and Citadellet (Aakvik, 1981, figures 8.1.1–8.1.3; Cutbill *et al.*, 1976; Verba, 2013, exploration well 116) may indicate further segmentation of the Billefjorden Trough and an architecture consisting of at least two WNW–ESE-trending, latest Devonian to Mississippian (to Early to Middle Pennsylvanian?), minor horsts and grabens interfering with the main N–S-trending half graben. The southern graben may extend from Brucebyen to Pyramiden and is bounded to the north by the SSW-dipping Adolfbukta fault (Figure 3B and Koehl *et al.*, 2023b, figures 4a and d–e, and 5b) and to the south by the NNE-dipping Garmaksla fault (Figure 4A–B). The northern graben may extend from Petuniabukta and Birger Johnsonfjellet to Triungen and is bounded to the south by the NNE-dipping Hugindalen Fault and, to the north, either by the SW-dipping Ebbabreen faults (McCann & Dallmann, 1996; Piepjohn *et al.*, 1997; Piepjohn, 2000) or by the SSW-dipping McCabefjellet fault zone (Koehl *et al.*, 2023b).

Segmentation of the Billefjorden Trough is also suggested by the presence of Proterozoic basement rock crosscut by abundant WNW–ESE-striking fault-related escarpments west of the speculated trace of the Balliolbreen Fault in Ferdinandbreen (Koehl *et al.*, 2023b, figure 5C). This outcrop of Proterozoic basement rocks is located within the possible horst structure bounded by the WNW–ESE- to E–W-striking (normal) Hugindalen and Adolfbukta faults (Figure 1B; see also Piepjohn, 2000, figure 3), and it is therefore possible that the Balliolbreen Fault is laterally and/or vertically offset by both horst-bounding faults.

Implications for post-Caledonian extension in central and northwestern Spitsbergen

Interpretation of seismic data and depth conversion in Billefjorden, and earlier field studies in Billefjorden and seismic interpretation in Sassenfjorden and Tempelfjorden support kilometer-scale (up to 4.35 km) down-NNE normal displacement along NNE-dipping faults and shear zones. Normal movement was coeval with the deposition of Lower Devonian to Early (Middle?) Pennsylvanian strata of the Siktefjellet, Red Bay, and Andrée Land groups (Figure 4A–B), Billefjorden Group (Koehl, 2021, e.g., figure 4A–B), and (lower) Gipsdalen Group (at least Hultberget Formation and lower part of the Ebbadalen Formation; Figure 4A–B). This is shown by the presence of large, fault-bounded, wedge- to fan-shaped seismic units thinning towards the north (Figure 4A–B; Koehl, 2021, e.g., figure 4A–B). Previous field studies in Lower Devonian sedimentary rocks onshore northernwestern Spitsbergen already suggested that sediments from the Siktefjellet and Red Bay groups and of the Wood Bay Formation were sourced from the south (Dallmann & Piepjohn, 2020; Friend *et al.*, 1966; Friend & Moody-Stuart, 1972; Murascov & Mokin, 1979) and deposited along NNE-dipping normal faults through kilometer-scale normal movements (McCann, 2000), thus supporting our datasets (Figure 5A).

Recently, Braathen *et al.* (2018) argued for significant top-north (> 50 km?) movements along the Keisarhjelmen Detachment in northwestern Spitsbergen based on the consistent SSW-tilting of strata of the Siktefjellet and Red Bay groups and on kilometer-scale normal offsets along NNE-dipping faults (some of which are thought to root into the Keisarhjelmen Detachment) showing slickensides indicating top-NNE normal movements (Friend *et al.*, 1997; McCann, 2000). Such interpretation is strongly disputed by Dallmann & Piepjohn (2018), mostly because some (most?) E–W- to WNW–ESE-striking faults seem to crosscut and left-laterally offset Proterozoic basement rocks of the Bockfjorden Anticline (e.g., Gee, 1972) instead of rooting into the Keisarhjelmen Detachment. Analogously to Braathen *et al.* (2018), McCann (2000) suggested that NNE-dipping normal faults in Haakon VII Land accommodated c. 30 km of north–south extension based on up to 45° SSW-tilting of Devonian rotated fault-blocks. However, inversion of analogous Devonian normal faults and the presence of numerous early Cenozoic top-SSW thrusts in equivalent Lower Devonian strata in Billefjorden (Figure 4A–H) suggest that NNE-dipping Devonian normal faults in Haakon VII Land may have been inverted and that Lower Devonian deposits were (at least partly) reworked (i.e., further tilted) by early Cenozoic top-SSW thrusting. This is also supported by the proximity of NNE-dipping faults in Haakon VII Land to the West Spitsbergen Fold-and-Thrust Belt, i.e., much closer to the collision zone between Greenland and Svalbard than their equivalents in Billefjorden, the latter of which were extrensively reworked by Eurekan deformation (Figure 4A–H). Thus, it is conceivable that the steep SSW-tilt of Lower Devonian strata in Haakon VII Land is actually the product of Devonian normal block-faulting and superimposed early Cenozoic thrusting (Figure 7 and Friend *et al.*, 1997, figure 12B–C), i.e., that the amount of north–south extension suggested by McCann (2000) and Braathen *et al.* (2018) was overestimated.

Implications for Svalbardian and Eurekan deformation events

Seismic and bathymetric data show the occurrence of major vertical and lateral offsets of stratigraphic units and possibly of the Balliolbreen Fault (if present at all; see also Koehl, 2021 and Koehl *et al*., 2022 for discussion of the onshore trace of the Balliolbreen Fault) across major NNE-dipping inverted Devonian normal faults and related top-SSW décollements and thrusts with ramp anticline and contractional duplexes in southern Billefjorden (Figure 3D & Figure 4A–H). Since many of these thrusts and duplexes crosscut Permian strata of the Wordiekammen and Gipshuken formations, they most likely formed during Eurekan contraction in the early Cenozoic. It is conceivable that some of the observed contractional structures in Lower Devonian strata represent Svalbardian structures, but it is not possible to distinguish these from Eurekan structures. However, based on the geometrical similarities and on comparable amounts of top-SSW offset along contractional structures in both Lower Devonian and lower Permian strata in Billefjorden, it is more probable that all these structures formed together in the early Cenozoic. A synchronous formation of all contractional structures is also supported by the possible (hard to soft) linkage of deep low-angle thrusts in Lower Devonian rocks with analogous shallow thrusts crosscutting strata of the Wordiekammen and Gipshuken formations by aggregates of top-SSW contractional duplexes (Figure 4A–B). This is further supported by a revision of the ages of multiple stratigraphic units and a reinterpretation of the significance of Late Devonian–Mississippian geochronological ages suggesting that the Svalbardian Orogeny did not occur in Svalbard (see discussion and references in Koehl *et al*., 2022b).

The dominant WNW–ESE strike and top-SSW (and subsidiary top-NNE) transport direction of Eurekan décollements, and contractional duplexes and folds within Devonian to Permian sedimentary strata in southern Billefjorden (Figure 4A–B and electronic supplements 3 and 4) diverge from the dominant N–S-striking Eurekan gra in Spitsbergen (e.g., Dallmann *et al*., 1993; Haremo & Andresen, 1992; Haremo *et al*., 1990; Harland *et al*., 1974). Nonetheless, WNW–ESE-trending Eurekan structures exist both in central (e.g., top-SW inversion of the Cowantoppen Fault; Harland *et al*., 1974; Figure 1B) and western Spitsbergen (e.g., in Brøggerhalvøya; Figure 1A). Notably, in Brøggerhalvøya, Eurekan contraction resulted in the formation of low-angle top-NNE thrusts with imbricate-fan geometries bounding hundreds of meter-thick thrust sheets, and forming contractional duplexes and antiformal stacks with bedding-parallel décollements and detachments localized along rheological boundaries and within weak sedimentary beds, e.g., carbonate and evaporitic succession of the Gipshuken Formation (Bergh *et al*., 2000; Piepjohn *et al*., 2001; Saalmann & Brommer, 1997; Saalmann *et al*., 1997; Saalmann & Thiedig, 2000; Saalmann & Thiedig, 2001). In addition, top-SSW imbricate thrusts in Blomstrandhalvøya showing comparable geometries and sizes to Eurekan thrusts in southern Billefjorden (Figure 4A–B & D–H) and initially ascribed to latest Devonian Svalbardian contraction (Buggisch *et al*., 1994; Kempe *et al*., 1997; Thiedig & Manby, 1992) likely formed in the early Cenozoic (Koehl, 2020b; Koehl *et al*., 2022b). Another similar structure is the NNE-dipping Overgangshytta fault in Odellfjellet (central–northern Spitsbergen), which formed or was reactivated as a top-SSW Eurekan thrust (Koehl & Muñoz-Barrera, 2018).

Lower Devonian sedimentary rocks of the Siktefjellet, Red Bay and Andrée Land groups in southern Billefjorden are considerably more deformed than strata of the Hultberget, Ebbadalen and Minkinfjellet formations and experienced a more intense early Cenozoic reworking than adjacent and underlying Proterozoic basement rocks as shown by the significantly higher number of Eurekan thrust and duplex structures within Lower Devonian strata (Figure 4A–H). This suggests that the thick (maximum c. 3.85 to 4.06 km) Lower Devonian sedimentary rocks may have acted as a buffer and localized the formation of most contractional structures during Eurekan tectonism. Hence Lower Devonian rocks (partially) decoupled basement rocks, which are crosscut by gently dipping basement-seated mylonitic shear zones, from overlying sedimentary rocks, which are truncated by low-angle brittle thrusts. Eurekan deformation was therefore partitioned between the intensely deformed belt of Lower Devonian rocks in the south and poorly deformed Pennsylvanian to Permian sedimentary units in the north (Figure 4A–H and electronic supplement 7). If strain decoupling and partitioning of Eurekan deformation occurred within Lower Devonian sedimentary successions in the Billefjorden area, this process is also very likely to have occurred elsewhere in Spitsbergen and the Barents Sea where Devonian to Mississippian successions are up to 8.6 to 9.675 km thick and most likely of similar composition (Friend *et al*., 1997; Murascov & Mokin, 1979). Strain partitioning of Eurekan deformation in Devonian to Mississippian sedimentary rocks notably occurred in Pyramiden, Sassenfjorden–Tempelfjorden (Koehl, 2021), and Garmdalen in central Spitsbergen (e.g., top-west thrusts localized within weak coals of the Billefjorden Group, Balliolbreen Fault flattening into a bedding-parallel décollement, and brecciated unconformities between the Wood Bay Formation, the Billefjorden Group and the Wordiekammen Formation; Manby *et al*., 1994, their Figure 12; Koehl *et al*., 2022, their Figure 2), and in Adriabukta in southern Spitsbergen (Koehl, 2020b; Koehl *et al*., 2022b). This strongly suggests that the Svalbardian Orogeny is not required to explain the strong deformation differences between intensely deformed Lower Devonian rocks and relatively undeformed Carboniferous to Permian strata in central Spitsbergen.

More specifically, contractional deformation intensity within thick Lower Devonian sedimentary rocks of the Siktefjellet and/or Red Bay and Andrée Land groups varies greatly. On the one hand, these units are crosscut by abundant thrusts and contractional duplexes and tightly folded in the lower part, which consists of highly heterogeneous (interbedded conglomerate, sandstone, siltstone, and mudstone; Friend *et al*., 1997; Gee & Moody-Stuart, 1966; McCann, 2000; Murascov & Mokin, 1979) deposits of the Siktefjellet and/or Red Bay groups. On the other hand, relatively homogeneous upper stratigraphic intervals like the Wood Bay Formation (Dallmann & Piepjohn, 2020; Friend *et al*., 1966; Friend & Moody-Stuart, 1972; Murascov & Mokin, 1979) are only mildly deformed into open upright folds, e.g., wedge- to fan-shaped alluvial fan deposits (Figure 4A–B). The numerous pronounced lithological heterogeneities in the Siktefjellet and Red Bay groups likely facilitated the localization of duplex structures bounded by roof- and floor-thrusts acting as décollements within weak shaly units (Figure 4G) and, thus, accommodated extensive amounts of deformation in the early Cenozoic compared to overlying more homogeneous deposits (i.e., strain partitioning and decoupling).

Early Cenozoic strain decoupling in Billefjorden is also particularly well illustrated by low-angle Eurekan thrusts merging downwards with a local décollement with detached ramp anticline along the stratigraphic boundary between the Wood Bay and Wordiekammen formations, which decoupled the Upper Pennsylvanian to lower Permian overburden from the Lower Devonian sedimentary successions during Eurekan deformation (Figure 4A–B & F), i.e., further suggesting that Svalbardian deformation is not needed to explain (inter-stratigraphic) variations in deformation patterns and intensity in central Spitsbergen. Early Cenozoic décollements at the base of the Wordiekammen Formation explain the presence of top-west folds and thrusts in deposits of the Billefjorden Group, Hultberget and Ebbadalen formations (Koehl *et al.*, 2022), and of the Minkinfjellet Formation (Senger *et al.*, 2018), whereas unconformably overlying strata of the Wordiekammen Formation in Garmdalen and Lykteneset are apparently undeformed (flat-lying; see Figure 1B for location).

In addition, recent analysis of seismic data in Sassenfjorden and Tempelfjorden showed the presence of similar WNW–ESE- and N–S-striking, top-SSW to top-NNE and top-west early Cenozoic Eurekan thrusts in sedimentary strata of the Billefjorden and Gipsdalen groups (Koehl, 2021, figure 4A–F). Top-SSW thrusts are restricted to the Hultberget, Ebbadalen, Minkinfjellet and Wordiekammen formations, whereas top-NNE and top-west thrusts occur dominantly within lower Permian strata of Gipshuken Formation. The former flatten downwards and sole into thin uppermost Devonian to Mississippian coal-rich strata of the Billefjorden Group known for their weak behavior and propensity to localize deformation (Koehl, 2021, figures 3B & 4B), and the latter into the stratigraphic boundary between the Wordiekammen and Gipshuken formations (Koehl, 2021, figure 4A–C). These observations therefore suggest the presence of bedding-parallel décollements in at least two stratigraphic levels in this area and, thus, a strong influence of strain decoupling in central Spitsbergen during Eurekan deformation. Such a strong effect of strain partitioning was predicted earlier (but not documented) by critical wedge taper models by Braathen *et al.* (1999).

Seismic and bathymetric data in Billefjorden show that numerous Eurekan décollements, thrusts, contractional duplexes, and folds strike WNW–ESE and accommodated dominant sinistral-reverse, top-SSW (and subsidiary top-NNE) movements (Figure 4A–H, and electronic supplements 3 and 4). Some of these thrusts and inverted Devonian to Carboniferous normal faults (and possibly related mylonitic shear zone at depth) accommodated hundreds of meter- to kilometer-scale (950 to 2350 m cumulated) top-SSW reverse offset of the Top Basement reflection as shown by the abrupt southwards deepening of this reflection across multiple faults from c. 2540 to 2850 m depth (i.e., ca. 1.1 s TWT) in the hanging of the northermost NNE-dipping fault to a depth of c. 4780 to 4920 m (i.e., ca. 1.4 s TWT) below the thickest portion of Lower Devonian sedimentary deposits in Billefjorden (Figure 4A–B and electronic supplement 6). Such large offsets along WNW–ESE-striking faults suggest that other N–S kilometer-scale variations in the depth of the top of the Proterozoic basement in Billefjorden may, as well, be related to top-SSW movements along yet-to-be-mapped, NNE-dipping (Eurekan thrust and/or inverted Devonian to Carboniferous normal) faults. Notably, the southward deepening of Proterozoic basement rocks from a 1290 m depth in Petuniabukta (well 116 of Trust Arktikugol; Senger *et al.*, 2019; Verba, 2013) to a depth of c. 2540 to 2850 m near Pyramiden, where the seismic line shown in Figure 4A–B terminates, suggests as much as c. 1250 to 1550 m of combined top-SSW Eurekan reverse offset along NNE-dipping faults and/or down-SSW normal movements along potential Devonian to Carboniferous faults between these two areas, including at least 300 to 480 m down-SSW movements along SSW-dipping normal faults (e.g., Adolfbukta and Kampesteindalen faults). This is further supported by the occurrence of top-SSW Eurekan and/or NNE-dipping, inverted Devonian–Carboniferous faults in Odellfjellet (e.g., Overgangshytta fault; Koehl & Muñoz-Barrera, 2018).

Eurekan thrusts and décollements, and Devonian–Carboniferous faults (and related mylonitic shear zones?) inverted in the early Cenozoic typically show 500 to 2000 m wide sinistral displacement of upper Paleozoic stratigraphic units including the Wordiekammen Formation (Figure 3D and Figure 4A–B and electronic supplement 9). Although recent geochronological studies in western Spitsbergen suggest that sinistral strike-slip movements along WNW–ESE-striking shear zones occurred in the Early Devonian (Ziemniak *et al.*, 2020; Figure 5A), the left-lateral offsets of east-dipping strata of the Wordiekammen Formation and their involvement into sinistral drag-folding indicate that sinistral movements also occurred along WNW–ESE-striking faults and shear zones in the early Cenozoic (Figure 5A–B).

The eastward dip of stratigraphic boundaries and bedding surfaces onshore western Billefjorden (Dallmann *et al.*, 2004a; Koehl *et al.*, 2022) and in the fjord (Figure 3D and electronic supplement 9) is most likely related to top-west early Cenozoic folding and thrusting along the Balliolbreen Fault and related faults (Figure 6). Top-west Eurekan structures and east-dipping strata are known from onshore areas in Billefjorden (Harland *et al.*, 1988; Koehl, 2021; McCann & Dallmann, 1996; Ringset & Andresen, 1988) and nearshore areas in Sassenfjorden–Tempelfjorden (Koehl, 2021).

Implications for the Petuniabukta Syncline

In the area of Pyramiden, Elsabreen and Svenbreenhøgda, the top-basement unconformity and sedimentary strata of the Ebbadalen Formation (Braathen *et al.*, 2011) and of the Minkinfjellet Formation dip gently to the east-southeast to

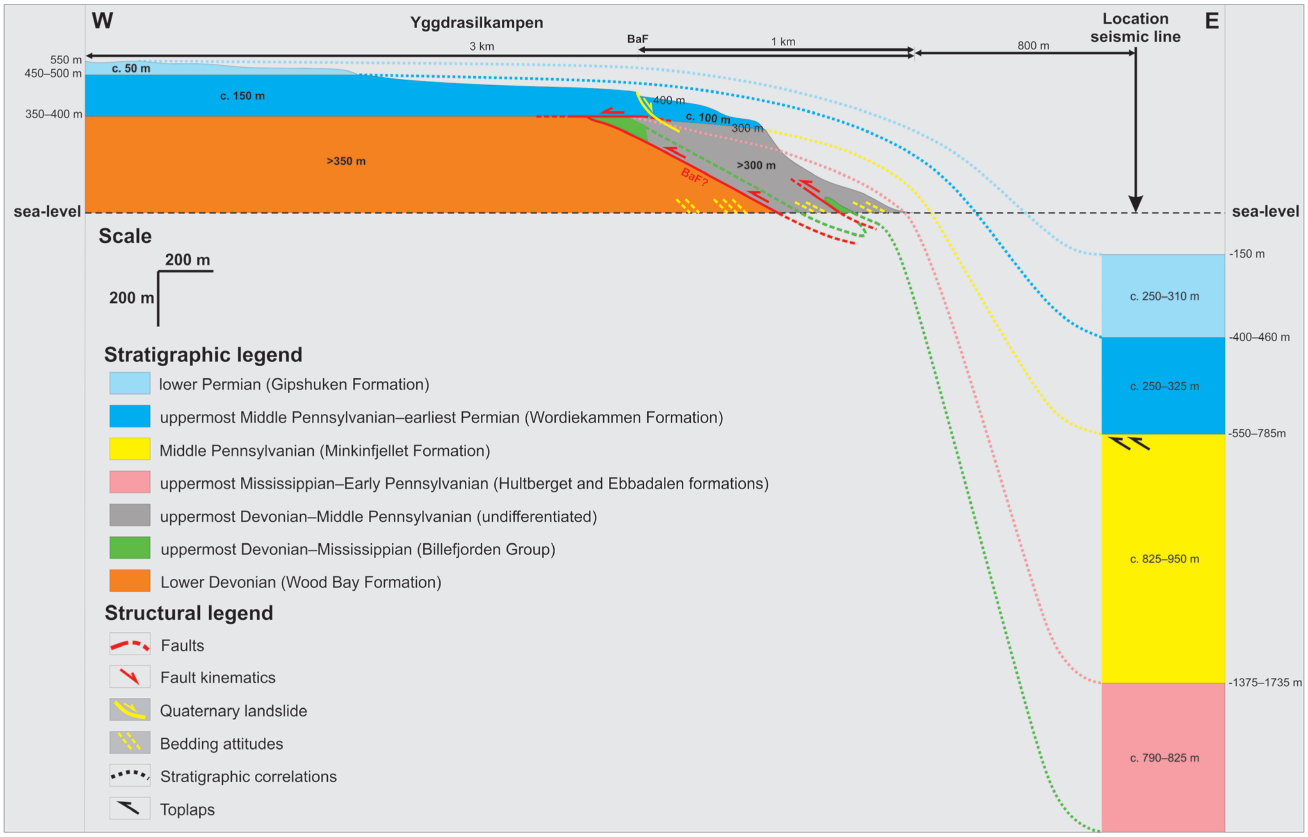

Figure 6. Onshore–offshore correlation between Garmdalen and Lykteneset and seismic interpretation in the hanging wall of the Garmaksla fault in nearshore fjord areas (see Figure 4A–B for seismic interpretation). The geology of onshore areas is based on Manby *et al.* (1994) and Koehl *et al.* (2022). Note that vertical and horizontal scales are the same.

southeast, and graben structures within the Minkinfjellet Formation just east of Pyramiden are tilted east-southeastwards to southeastwards (Koehl *et al.*, 2016; Koehl *et al.*, 2023a). (Braathen *et al.* (2011) ascribed these southeastward to east-southeastward dips and tilts to the presence of a SE- to SSE-dipping relay zone between the Balliolbreen and Odellfjellet faults in Pyramiden and Elsabreen, possibly including the Pyramiden Fault (Smyrak-Sikora *et al.*, 2018). However, the dip of strata of the Ebbadalen Formation does not appear to change across (i.e., because of) this fault (Smyrak-Sikora *et al.*, 2018, figure 7). Another possibility is that the observed dip and tilts are related to early Cenozoic inversion of both N–S- and WNW–ESE-striking faults such as the east-dipping Balliolbreen and Odellfjellet faults and the SSW-dipping Adolfbukta fault. For example, early Cenozoic reverse reactivation of the east-dipping segments of the Billefjorden Fault Zone may have tilted Pennsylvanian sedimentary strata of the Ebbadalen and Minkinfjellet formations (dominantly) to the east and superimposed (preceding, simultaneous or subsequent) reverse movement along the SSW-dipping Adolfbukta fault at depth would have resulted in an overall east-southeastward to southeastward tilt of the strata and graben structures (Figure 7). Alternatively, the ESE-dip of Pennsylvanian sedimentary strata in Pyramiden, Elsabreen and Svenbreenhøgda might be related to the actual strike of fault segments of the Billefjorden Fault Zone being NNE–SSW instead of N–S to NNW–SSE (Figure 3D; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b), and to tilting of the strata during Eurekan inversion of NNE–SSW-striking faults segments of the Billefjorden Fault Zone (and minor folding). This is supported by the similar dip of uppermost Devonian to Mississippian sedimentary strata of the Billefjorden Group and by the dominant top-WNW sense of shear of early Cenozoic Eurekan contractional duplexes and thrust faults (which are possibly part of the Balliolbreen Fault) within this stratigraphic unit in Pyramiden (Koehl, 2021).

In southern Billefjorden, the Gipshuken Formation crops out at sea level onshore Kapp Fleur de Lys and Anservika (Dallmann *et al.*, 2004a; Dallmann, 2015; Harland *et al.*, 1974), and close to the surface in the fjord between Kapp Fleur de Lys and Anservika (Figure 4A–B). However, farther north, this stratigraphic unit crops out at up to 450 to 500 m altitude in Yggdrasilkampen (west of the Billefjorden Fault Zone), at an altitude of 600 m east of the Billefjorden Fault Zone in Campbellryggen (Figure 1B; Dallmann *et al.*, 2004a), and at a depth of c. 150 to 310 m in the fjord (Figure 4A–B). This

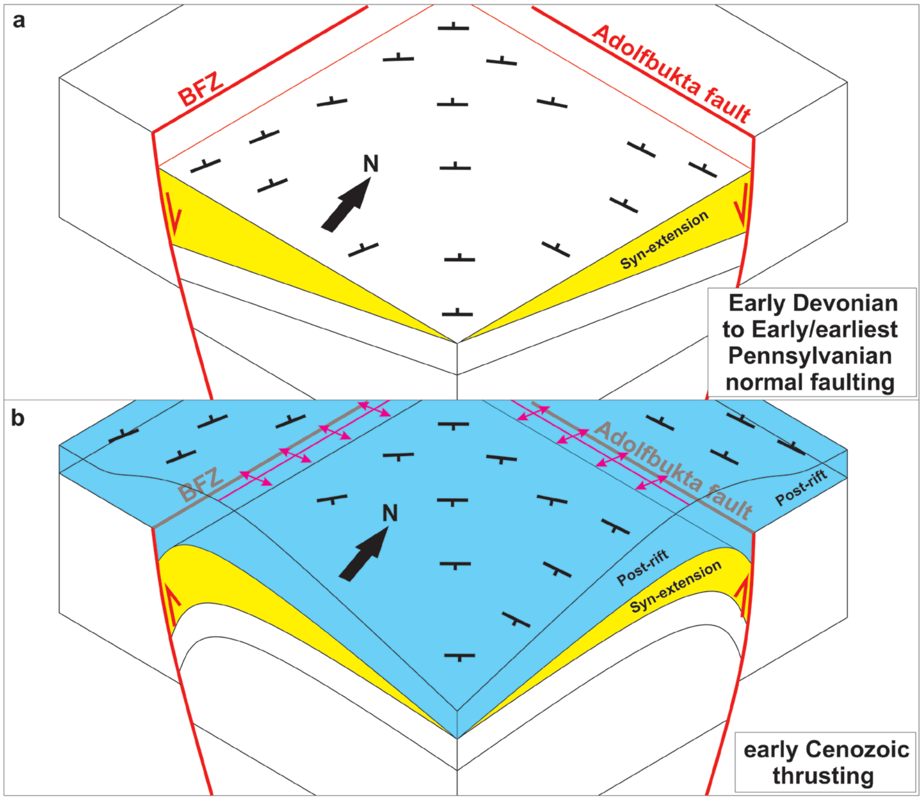

Figure 7. Schematic sketches showing (**A**) tilting of syn-tectonic, Early Devonian to earliest/Early Pennsylvanian sedimentary strata along coeval ESE- and SSW-dipping normal faults (red lines), and (**B**) back-tilting overall to the east-southeast to southeast due to inversion of post-Caledonian normal faults during early Cenozoic Eurekan deformation. Notice the formation of kilometer-wide, open folds above major inverted normal faults (fuchsia lines). Black symbols reflect bedding attitude. Abbreviations: BFZ – Billefjorden Fault Zone. Modified after Koehl *et al.*, 2023a (originally published under CC-BY 4).

configuration reflects an overall south to southwestwards dip of these sedimentary strata onshore on both sides of the fjord, as well as a 600 to 900 m negative topographic relief at Gipshuken Formation level in the fjord between Yggdrasilkampen and Campbellryggen. This suggests that, in addition to being offset by (up to 200 m of) top-west reverse movement along the Gipshuken segment of the Billefjorden Fault Zone in Cowanodden and Gipsvika (Dallmann *et al.*, 2004a; Dallmann, 2015; Harland *et al.*, 1974; see locations in Figure 1B), the Gipshuken Formation is either (1) offset with a top-west reverse sense of shear by (a) N–S- to NNE–SSW-striking fault(s) between the seismic section shown in Figure 4A–B and the eastern coastline of Billefjorden (e.g., the Odellfjellet Fault and/or Gipshuken Fault) or (2) by normal faults forming a (rectangular) mini-basin within the fjord, and/or (3) involved into a kilometer-wide, N–S- to NNE–SSW-trending, gently north- to northeastwards-plunging open syncline. The present analysis of bathymetric and seismic data in Billefjorden does not support the presence of any major N–S-striking fault in the fjord other than the Balliolbreen Fault (Figure 3D and Figure 4A–B and electronic supplements 3 and 4). However, previous study of the kilometer-wide Petuniabukta Syncline indicates the occurrence of Eurekan contractional folding in northern Billefjorden (Figure 5B; McCann & Dallmann, 1996). It is therefore most probable that the observed variations result from early Cenozoic folding related to the Petuniabukta Syncline (Figure 6). This is further supported by the 600 to 900 m topographic relief at Gipshuken Formation level between Yggdrasilkampen and Campbellryggen, which is comparable to the >700 m relief defined by the Wordiekammen Formation in the Petuniabukta Syncline in Petuniabukta (Maher & Braathen, 2011).

Similar topographic reliefs are recorded for the Top Wood Bay Formation and Top Wordiekammen Formation in the footwall of the Balliolbreen Fault in the south. There, the top of these formations crop out respectively at altitudes of c. 150 to 250 and c. 350 m onshore (in Nidedalen and Narveneset; see location in Figure 1B; Dallmann *et al.*, 2004a; Dallmann & Piepjohn, 2020) and are located at respective depths of c. 720 to 860 and c. 470 to 530 m in the fjord (i.e., topographic reliefs of 870 to 1110 and 820 to 880 m; Figure 4A–B and electronic supplement 6). This suggests that synclinal folding continues in the footwall of the (offset) southern portion of the Balliolbreen Fault (i.e., south of the Garmaksla fault in Figure 4A–B) and, therefore, precludes that folding in this area was influenced by Carboniferous to Permian, normal-fault propagation folding (Figure 5B). Since the Gipshuken Formation crops out at sea-level onshore Kapp Fleur de Lys and Anservika and reaches near-surface level within the fjord near these areas (Figure 4A–B), the Petuniabukta Syncline most likely dies out southwards (Figure 5B) or may, like the Billefjorden Fault Zone, be offset laterally by WNW–ESE-striking faults (Figure 3D).

Possible origin for WNW–ESE-striking faults and shear zones in Billefjorden

Seismic data in Billefjorden show a dominance of WNW–ESE-striking early Cenozoic Eurekan thrusts and (inverted) Devonian to Carboniferous normal faults. At depth, these faults merge and root into thick packages of sub-parallel moderate-amplitude reflections interpreted as mylonitic ductile shear zones and associated fabrics in adjacent and underlying Proterozoic basement rocks (Figure 4A–B). These observations suggest strong control of preexisting WNW–ESE-trending basement grain on post-Caledonian Devonian to Carboniferous extensional faulting and their early Cenozoic inversion and overprinting.

The NNE-dipping basement-seated shear zones are highly oblique to sub-orthogonal to N–S-trending Caledonian fabrics. Considering evidence supporting the presence of WNW–ESE-striking Timanian ductile structures and fabrics in southwestern (Gayer *et al.*, 1966, their samples 49 and 50, and their hypotheses 1 and 2 also discussed in Harland *et al.*, 1966; Majka *et al.*, 2008; Manecki *et al.*, 1998; Majka *et al.*, 2012; Mazur *et al.*, 2009), western (Horsfield, 1972), northwestern (Gayer *et al.*, 1966, their samples 53 and 60; Gromet & Gee, 1998; Koglin *et al.*, 2022; Ohta *et al.*, 2003; Peucat *et al.*, 1989), and northeastern Spitsbergen (Gayer *et al.*, 1966; Hamilton & Sandford, 1964, their samples 19–22; Johansson *et al.*, 2004; Johansson *et al.*, 2005), such as the Vimsodden–Kosibapasset Shear Zone (Faehnrich *et al.*, 2020; Mazur *et al.*, 2009, their sample 16-73A), we propose that WNW–ESE-striking basement-seated mylonitic shear zones and fabrics in southern Billefjorden formed during the Timanian Orogeny (Figure 4A–B). Recent studies reveal the presence of deep, crustal-scale, WNW–ESE- to NW–SE-striking shear zones and thrust systems in the northern Barents Sea, Svalbard and Storfjorden that merge with Timanian faults in northwestern Russia (Klitzke *et al.*, 2019; Koehl, 2019; Koehl, 2020a; Koehl *et al.*, 2022a). Since WNW–ESE-striking faults and fabrics in basement rocks in Billefjorden align with and strike parallel to some of the main Timanian thrusts and shear zones mapped in northern Storfjorden and Sassenfjorden (Koehl *et al.*, 2022a, e.g., their Kongsfjorden–Cowanodden fault zone), it is probable that they are part of the same fault system. A Timanian origin was also proposed for WNW–ESE-striking faults in Proterozoic basement rocks in Mittag-Lefflerbreen and potential late Paleozoic to early Cenozoic overprints in Odellfjellet (e.g., Overgangshytta fault; Koehl & Muñoz-Barrera, 2018).

Furthermore, it is probable that a major, crustal-scale, WNW–ESE-trending, basement-seated zone of weakness exists at depth, and that this zone separates northern from southern Spitsbergen and is responsible for the local dominance of WNW–ESE-trending structures. This is based on the presence of numerous and dominant WNW–ESE-striking brittle faults and shear zones within Proterozoic basement rocks and Lower Devonian to lower Cenozoic sedimentary strata in central (Figure 3A–D & Figure 4A–B and electronic supplements 3 and 4; Koehl *et al.*, 2023a, figure 3a–b; Koehl *et al.*, 2023b, figure 2, 3, 4a and d–e, and 5) and western Spitsbergen (Bergh *et al.*, 2000; Piepjohn *et al.*, 2001; Saalmann & Brommer, 1997; Saalmann *et al.* 1997; Saalmann & Thiedig, 2000; Saalmann & Thiedig, 2001). It is also supported by the WNW–ESE-trending alignment of outcrops of uppermost Devonian to Permian sedimentary rocks of the Billefjorden and Gipsdalen groups between Dickson Land and Brøggerhalvøya (including in James I Land), and by the alignment of major WNW–ESE-striking faults in Billefjorden and Sassenfjorden (present contribution and Koehl, 2021) with major WNW–ESE-striking faults in Brøggerhalvøya. Such a deep weakness zone was previously suggested in western Spitsbergen by Harland & Horsfield (1974; e.g., Kongsvegen Fault and Lappsdalen Thrust), Harland & Wright (1979; e.g., Kongsvegen Fault Zone and Central-West Fault Zone) and Harland *et al.* (1993; e.g., Kongsfjorden–Hansbreen Fault Zone), though with various extents, trends, and geometries. This major zone of weakness is referred to as the NNE-dipping Kongsfjorden–Cowanodden fault in ongoing works (Koehl, 2019; Koehl, 2020a; Koehl *et al.*, 2022a).

Conclusions

1) The several kilometer-thick successions of Lower Devonian sedimentary strata in Billefjorden and southeastern Dickson Land were deposited along syn-sedimentary WNW–ESE-striking faults comparable to faults in northwestern Spitsbergen.

2) The Billefjorden Trough and associated major N–S- to NNE–SSW-striking faults, like the Billefjorden Fault Zone, are segmented and offset by major WNW–ESE-striking faults, like the Adolfbukta fault, forming trough-oblique systems of grabens and horsts that localized the deposition of thickened coal-rich deposits of the Billefjorden Group during synchronous evolution of N–S- to NNE–SSW- and WNW–ESE-striking normal faults.

3) Eurekan strain partitioning and decoupling by thick Lower Devonian sedimentary successions acting as a weak buffer, the involvement of both Devonian and post-Devonian rocks in contractional deformation, and bedding-parallel décollements show that Late Devonian Svalbardian deformation is not required to explain differential deformation between folded Devonian and relatively undeformed Carboniferous to Permian rocks in Billefjorden.

4) The N–S- to NNE–SSW-trending Petuniabukta Syncline formed during early Cenozoic Eurekan deformation.

5) WNW–ESE-striking faults in Proterozoic basement and post-Caledonian sedimentary rocks in Billefjorden are following and, in places, merge with preexisting Timanian shear zones.

6) The dominance of WNW–ESE-striking faults and fabrics in Proterozoic basement rocks and Lower Devonian to lower Cenozoic sedimentary rocks both in central and western Spitsbergen suggests the presence of a major WNW–ESE-trending zone of weakness extending from Billefjorden–Sassenfjorden to Kongsfjorden and potentially merging with Timanian thrust systems in Storfjorden and the northern Barents Sea.

Data availability

Underlying data

The source data used in this study is not available publicly as it is under license by third parties. Please see below descriptions of the data sources and the information required to request access to the data directly from the third parties.

- The bathymetric data analysed in study (Figure 3A–D and electronic supplement 2) was sourced from:
    - The Norwegian Mapping Authority: Access to the data for research purposes can be requested by contacting the Norwegian Mapping Authority at https://www.kartverket.no/en/about-kartverket/contact-us.
    - The University Centre in Svalbard: Access to the data for research purposes can be requested by contacting the University Center in Svalbard at post@unis.no.
- The Two-Way Time (TWT) seismic data analysed in this study was sourced from the DISKOS (Norwegian National Data Repository for Petroleum Data) database in Billefjorden. Access to the data for research purposes can be requested by contacting the Norwegian Petroleum Directorate at https://www.npd.no/fakta/om-oss/kontakt-oss/.
- Velocity data were sourced from exploration well 7816/12-1 in Reindalspasset (discussed in Eide *et al*., 1991, and from Gernigon *et al*., 2018). Access to the data for research purposes can be requested by contacting the third party companies that own the data, namely:
    - Equinor A.S.A. at https://www.equinor.com/about-us/contact-us and
    - Store Norske Spitsbergen Kulkompani at https://www.snsk.no/kontakt/ansatte (in this case the authors contacted Malte Jochmann; malte.jochmann@snsk.no).

DataverseNO: Replication Data for: Devonian–Carboniferous extension and Eurekan inversion along an inherited WNW–ESE-striking fault system in Billefjorden, Svalbard. https://doi.org/10.18710/UCRW4L. (Koehl *et al*., 2023c).

This project contains the following underlying data:

- 00_ReadMe.txt.
- Figures 1-7 (high resolution versions of the figures included in this manuscript, in jpg format. All copyright permissions granted).
- Supplement figures 2–4, 7–9, 10–14 (high-resolution versions of the supplementary figures included in the extended dataset, Koehl *et al*., 2023d, in jpg format. All copyright permissions granted).

Extended data

DataverseNO: Supplements for Devonian–Carboniferous extension and Eurekan inversion along an inherited WNW–ESE-striking fault system in Billefjorden, Svalbard. https://doi.org/10.18710/1WTNQB. (Koehl *et al*., 2023d).

This project contains the following extended data:

- 00_ReadMe.txt.
- Koehl_*et_al.*_supplements.docx (supplementary information and data to the present contribution including an extended description of the late Paleozoic sedimentary successions in central Spitsbergen from the literature, uninterpreted versions of the figures, additional seismic data, and extended description and interpretation of the upper Paleozoic sedimentary successions on seismic data in Billefjorden, depth-converted seismic data and details about the depth-conversion process, additional bathymetric profiles in the fjord, satellite photographs, outcrop photographs, and an extended discussion of the implications of the present study for tectonic extension in the study area. All copyright permissions granted).
- Koehl_*et_al.*_supplements.pdf (pdf version of the above-described document).

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An earlier, non-peer reviewed preprint manuscript including the present contribution can be found on ResearchGate (DOI: 10.13140/RG.2.2.35857.97129).

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Open Peer Review

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✗

Alexander Peace
McMaster University, Hamilton, Ontario, Canada

This is a review of “Devonian–Carboniferous extension and Eurekan inversion along an inherited WNW–ESE-striking fault system in Billefjorden, Svalbard” by Jean-Baptiste P. Koehl *et al*. Overall, I found that the paper addresses an interesting topic but that it contains serious problems that in its current state make it unsuitable for indexing. Having said that I think that these issues can be fixed, and that the resultant manuscript will be a good contribution.

One of my main issues with the manuscript is the description of the data and methods. I felt that this section was not adequate for readers to fully understand the interpretations and limitations of the work. First, the manuscript needs better figures showing the locations of the seismic data used. I think some of this information is on figure 3 but it isn’t clear. Also, the acquisition, processing and interpretation parameters are not described. For example, what approach was taken with interpretation? This prevents a reader from fully evaluating the resultant geological models presented. I don’t think just naming the software used is enough. Regarding the bathymetric data, what is meant by 'high resolution' as noted in the text?

Also regarding methods, I feel that the results could have been bolstered by integration with the openly available gravity and magnetic data. This would allow the authors to place more constraints on the interpretations presented. Why didn’t the study utilise such potential field data? Has this work already been done?

I found that generally the manuscript is longer than it needs to be. Some sections in particular are much too long and the main points are lost in the text. For example, the Geological Setting section gives an excellent overview of the area, but how necessary is all of this information for the study? On the other hand, the Methods section only contains two paragraphs and nowhere near enough detail is given (as described above). Also regarding these introductory sections, I felt that the scientific rationale behind the work wasn’t particularly clear, i.e. what was the purpose of the study? Similarly, the discussion and interpretation sections are also overly long in my opinion.

Finally, I found that place names/locations are not well shown on figures for readers not familiar with the setting.

Other points:

- Figure 1: Overall, this is a good and useful figure but is there a colour scale for part 1 of this figure?

- Figure 3: Why are different colour scales used for A and B but no colour scale is given for D and C? What I mean by this is that I am not sure which scale I should be reading for C and D. Also what is the highshade direction used?

- Figure 4: A better location map is needed for the seismic data, as noted above. It is unclear to me where this line is from. The text on legend is too small on this figure. The boxes on part a are very hard to see and read too against the seismic line. Also, the interpretation process leading to the yellow horizons shown needs describing further.

- Discussion, The Adolfbukta fault: I am not sure that papers from 1997 count as recent. Even the most 'recent' one cited (2011) is 12 years old! Despite being referred to as 'older' the personal communication is the most recent item here.

- Figure 5 (and associated text): The figures that present the model are of good quality, but I don’t feel that the text explains the model sufficiently. It isn’t that the text isn’t long enough, more that the way it is explained is quite convoluted and overly long. I suggest refining the discussion so that it is more focused.

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and does the work have academic merit?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

No

If applicable, is the statistical analysis and its interpretation appropriate?

Not applicable

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Structural geology, tectonics, applied geophysics

I confirm that I have read this submission and believe that I have an appropriate level of

expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 14 Oct 2023

Jean-Baptiste Koehl

Reply to Alexander Peace Dear Sir, Madam, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

Comments by the reviewer

Comment 1: One of my main issues with the manuscript is the description of the data and methods. I felt that this section was not adequate for readers to fully understand the interpretations and limitations of the work.

Response: Agreed. This is partly addressed by the sentences added to the methods chapter. The authors of the present manuscript stress the importance of the Extended data section (notably Supplement S5, which details the interpretation of the stratigraphy) in understanding the interpretation presented. In addition, a solution will be discussed with the journal editorial team to enlarge Figure 4a–b. The authors of the present manuscript are open to Splitting Figure 4 into 2 separate figures should it be required by the journal's standards. This way, Figure 4a–b would be enlarged to an entire page and so would the new figure 5a–f (currently Figure 4c–h). Also see response to comment 2 for the addition of the entire database used in the interpretation.

Changes: Added "Supplementary data (e.g., calculations related to depth conversion and topographic variations, bathymetric profiles, and further field evidence and extended discussion) are available as Extended data.". Awaiting decision by the editorial team to split Figure 4a–h into Figure 4a–b and Figure 5a–f or leave as is but anyway enlarge Figure 4a–b to a full page. Also added information on the bathymetric data to the method chapter: "(the resolution of the data is 10 m laterally and 5 m vertically)" and "resolution: 0.05 m in all directions;".

Comment 2: First, the manuscript needs better figures showing the locations of the seismic data used. I think some of this information is on figure 3 but it isn't clear.

Response: Agreed.

Changes: Changed the names of the seismic lines in Figure 3 in the present manuscript into "Figure 4a–b" and "Supplement S3a & S4a" and "Supplements S3b & S4b". In addition, the entire seismic database used was included in Figure 1a in the present manuscript and added "showing the database of seismic reflection data used for the present study. The map is" to the caption of Figure 1a.

Comment 3: Also, the acquisition, processing and interpretation parameters are not described. For example, what approach was taken with interpretation? This prevents a reader from fully evaluating the resultant geological models presented. I don't think just naming the software used is enough.

Response: Agreed. Many more details about the interpretation (notably of the stratigraphy) are included in Supplement S5 in the Extended data section. A direct tie was established with the nearby onshore geology, which is summarized extensively in Supplement S1. See also response to comment 1. Regarding the acquisition and processing of the seismic surveys used, these can be accessed from the DISKOS database of the Norwegian Petroleum Directorate, and are not the focus of the present manuscript.

Changes: See response to comment 1.

Comment 4: Regarding the bathymetric data, what is meant by 'high resolution' as noted in the text?

Response: Agreed. High-resolution means 10 m by 10 m laterally and 5 m vertically for the bathymetric data of the Norwegian Polar Institute and 0.05 m in all three directions for the data of the University Centre in Svalbard. Regarding the meaning of the term "high-resolution" when referring to the versions of the figures included in the Open Access online dataset of the Underlying data section, it really means "full resolution". Journals can rarely include hundreds of MB-large figures in the pdf file of articles. Hence, the versions of the figures included in the manuscript file/pdf are mostly of lower resolution than the original figures and therefore do not always allow the reader to properly view the interpreted structures (e.g., on the bathymetric and seismic data in Figure 3a–d and Figure 4a–b). The authors of the present manuscript therefore insist again on the crucial importance of both the Underlying data and the Extended data sections and agree that this is not stressed enough in the present manuscript.

Changes: Added ", including high-resolution versions of the figures and supplements, which are necessary to view the presented interpretation in detail" and "Supplementary data (e.g., calculations related to depth conversion and topographic variations, bathymetric profiles, and further field evidence and extended discussion) are available as Extended data." to the method chapter.

Comment 5: Also regarding methods, I feel that the results could have been bolstered by integration with the openly available gravity and magnetic data. This would allow the authors to place more constraints on the interpretations presented. Why didn't the study utilise such potential field data? Has this work already been done?

Response: Agreed. However, the gravimetric and magnetic data mentioned by the reviewed are of too coarse resolution to be of any use in the detailed present study. The lead author of the present manuscript is currently writing a regional manuscript about the Kongsfjorden–Cowanodden fault zone, a top-SSW Timanian thrust, which extends from northwestern Russia (where it is called the Baidaratsky Fault Zone; Lopatin et al., 2001; Korago et al., 2004) and transects Spitsbergen between Sassenfjorden and Kongsfjorden and is very well imaged both by seismic data, and by gravimetric and magnetic anomalies in Svalbard (Koehl and Schiffer, in prep.).

Changes: None.

Comment 6: I found that generally the manuscript is longer than it needs to be. Some sections in particular are much too long and the main points are lost in the text. For example, the Geological Setting section gives an excellent overview of the area, but how necessary is all of this information for the study?

Response: All the information specified in the Geological setting chapter is reused in the discussion.

Changes: None.

Comment 7: On the other hand, the Methods section only contains two paragraphs and nowhere near enough detail is given (as described above).

Response: Agreed. However, as mentioned in earlier comments, the supplementary data (doi.org/10.18710/1WTNQB; also found under the "Extended data" section) include extensive details about the interpretation of the stratigraphy and many more details about corresponding rocks in nearby onshore areas (see notably Supplements S1 and S5). The authors of the present manuscript concede that the importance of the Underlying data and Extended data sections should be strongly emphasized in the method chapter. See also response to comments 1 and 4.

Changes: See response to comments 1 and 4.

Comment 8: Also regarding these introductory sections, I felt that the scientific rationale behind the work wasn't particularly clear, i.e. what was the purpose of the study?

Response: Agreed.

Changes: Added "The paper notably explores an alternate scenario to the post-Caledonian tectonic history of Svalbard by suggesting that all post-Caledonian contractional structures may be explained by early Cenozoic Eurekan contraction alone, thus downplaying the role of the Late Devonian Svalbardian Orogeny." to the Introduction chapter.

Comment 9: Similarly, the discussion and interpretation sections are also overly long in my opinion.

Response: Agreed. However, the interpretation section needs to be detailed enough in order to provide robust arguments supporting the interpretation presented, especially because of the lack of well control in the southern part of the fjord. The length of the interpretation section is partly making up for the short method chapter in that much of the reasoning associated with the interpretation of the data by the authors of the present manuscript is explained in the interpretation section instead of in the method chapter. This is done this way because of the subjectivity involved in the interpretation of seismic data, which does not fit the method chapter. Regarding the discussion, much more could have been discussed as shown by the extended discussion of the tectonic evolution of the study area included in Supplement S12. The present manuscript is the first to approach the impact of reactivated Timanian thrust systems on post-Caledonian sedimentary rocks and basins in Svalbard and therefore needs sufficient discussion of the new evidence and interpretation presented in order to fully highlight their implications.

Changes: None.

Comment 10: Finally, I found that place names/locations are not well shown on figures for readers not familiar with the setting.

Response: Agreed. See response to comment 12.

Changes: See response to comment 12.

Comment 11: Other points: Figure 1: Overall, this is a good and useful figure but is there a colour scale for part 1 of this figure?

Response: The basemap of the figure is the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2012) and the reader is referred to this publication/map for the color scale. The authors of the present manuscript are open to adding the color scale from the IBCAO of Jakobsson et al. (2012) but feel that this would needlessly overcrowd the figure with a color scale from a map widely known by Arctic scientists.

Changes: None yet.

Comment 12: Figure 3: Why are different colour scales used for A and B but no colour scale is given for D and C? What I mean by this is that I am not sure which scale I should be reading for C and D. Also what is the highshade direction used?

Response: Agreed.

Changes: Added “. The color scale shown in (B) and encircled in a dotted black frame is that of the easternmost portion of the fjord (dataset bounded by the dotted black lines in B). The color scale shown in (A) applies to all areas in Figure 3A–D, except the dataset bounded by dotted black lines at Nordenbskiöldbreen in easternmost Billefjorden in (B). The light source of the hills shading in (A–D) is from the northeast” in the caption of Figure 3. Also modified Figure 3 to add the geological map of Dallmann et al. (2004) in onshore areas and the corresponding stratigraphic legend, enlarged locality names and added a white frame so they appear clearer in Figure 3b–d, encircled the UNIS bathymetric dataset (which is associated with a discrete color scale) with a thicker dotted black line and did so for the corresponding color scale too in Figure 3b, and added the locality name “Nordenskiöldbreen” in Figure 3b.

Comment 13: Figure 4: A better location map is needed for the seismic data, as noted above. It is unclear to me where this line is from. The text on legend is too small on this figure. The boxes on part a are very hard to see and read too against the seismic line. Also, the interpretation process leading to the yellow horizons shown needs describing further.

Response: Agreed. See response to comments 1 and 2 regarding the better localization of the interpreted seismic data and the seismic lines displayed in Figure 4 and the supplements and regarding the discussion with the editorial team to enlarge Figure 4a–b to an entire page. Regarding the interpretation of the yellow horizons, the reviewer is referred to Supplements S1 and S5 of the Extended data section. See also response to comments 1, 3, and 7.

Changes: See also response to comments 1, 2, 3, and 7.

Comment 14: Discussion, The Adolfbukta fault: I am not sure that papers from 1997 count as recent. Even the most 'recent' one cited (2011) is 12 years old! Despite being referred to as 'older' the personal communication is the most recent item here.

Response: Disagreed. It is specified “relatively recent”, because these studies are more recent than the older works by Harland et al. (1974), Lamar et al. (1986), and the Russians in Pyramiden (Russian data from 1988–1993 provided by Sirotkin pers comm., 2019). The authors of the present manuscript are open to adding the year of collection of the Russian data provided by Prof. Sirotkin (1988–1993), but are uncertain if and how to do this by the standard of the journal.

Changes: None yet. Awaiting further instructions from the journal.

Comment 15: Figure 5 (and associated text): The figures that present the model are of good quality, but I don’t feel that the text explains the model sufficiently. It isn’t that the text isn’t long enough, more that the way it is explained is quite convoluted and overly long. I suggest refining the discussion so that it is more focused.

Response: Partly agreed. However, as previously mentioned, this is the first attempt at discussing the impact of the newly identified Timanian thrust systems on post-Caledonian basins and faults, and an extensive discussion of the data, interpretation, and their implications is therefore needed. See also response to comment 9.

Changes: None.

Competing Interests: None.

Reviewer Report 12 September 2023

https://doi.org/10.21956/openreseurope.17210.r34347

✗

Keith Dewing
Geological Survey of Canada Atlantic, Dartmouth, Nova Scotia, Canada

Comments on Devonian–Carboniferous extension and Eurekan inversion along an inherited WNW–ESE-striking fault system in Billefjorden, Svalbard by JB Koehl, L Allaart & R Noormets
Keith Dewing, Geological Survey of Canada

This paper explores the geology of the Billefjorden area in central Spitsbergen using a seismic line and bathymetric maps. From these data, the authors conclude that pre-existing structures controlled the location of Paleozoic normal faults, and that compression is exclusively Cenozoic in age.

The paper has a number of issues, centered around the incredibly detailed, but poorly constrained, interpretation of bathymetric and seismic datasets. These datasets are then combined with a number of the lead author's previous studies to make broad conclusions about the regional tectonic history. The paper is hard to follow as there is a lot of detailed discussion that is not supported by maps and diagrams.

The main issue I have with the paper is the amount of interpretation on both the bathymetric and seismic figures but that are not well supported. For instance, the interpretation of the bathymetric maps are not supported by any information from dredged samples or drilling, and the onshore geological map is not shown. The small strike-slip faults interpreted from the apparent steps in the ridge on Fig. 2D should also show up on the surface mapping. If they don't then maybe there's another explanation for the steps in the submarine escarpment, like scalloping due to submarine erosion or the effects of ice? If the strike slip faults only show up where there is no actually rock observation, then it would be worrisome!

The seismic figure 4 is even more difficult to accept without a leap of faith. Firstly, why are the two overview panels so small and the inserts so big? The stratigraphic column takes a whole page yet this figure, which is critical to the arguments made in the paper, is <1/2 page. Make 4A and 4B larger. Second, there are countless interpretations that could be made on this seismic section, especially given the lack of a drill hole in the line of the section, and the absence of cross lines. I've marked up the figure with many comments, but I really cannot see many of the small faults that the authors have put on the figure. Not every little gap in a reflection indicates tectonic movement – there is such a thing as poor data quality. I would hesitate to interpret anything below 1.6 seconds on this section. The figure would be easier to follow if there were another panel that showed the main stratigraphic packages with partially transparent colour blocks. Trying to follow the many colours of dotted and dashed lines is tricky.

So while I really support new ideas being introduced into the literature, this paper needs some big improvements. There needs to be clarifying text added to the introduction that this paper presents an alternate view of the geological history that downplays the Svalbardian Orogeny and provides an interpretation where the structures can be explained by a combination of Proterozoic-

Early Devonian-Cenozoic deformation and reactivation. The authors need to be clear that there are other, much more widely accepted models and that this paper presents one possibility for another tectonic interpretation.

The bathymetric interpretation should be tied to the surface geology by showing the geological map in conjunction with the bathymetry. If the features interpreted on the bathymetric map are not shown on the surface geology map, then some explanation needs to be given as to why these features are not visible at the surface.

The seismic figure needs to be resized, a panel is needed that shows the stratigraphic packages clearly, so the reader isn't hunting for various dotted lines. Many of the smaller faults are pretty questionable. I don't think most 3D cubes get this level of interpretation! Look at the literature and use a similar density of interpretation that other seismic interpreters use. I especially question 4C – why curve the upper white dotted line up rather than connect to the brown straight along trend. That would make the two white dotted lines parallel; 4D – the grouping of three reverse faults could easily be interpreted as a small graben that offsets the strong reflections at the top of the image; 4E – how can you be certain that the dotted blue lines are all the same horizon?; 4G – I just don't see the faults you mark, why not interpret the beds as just following through? Tie the seismic to surface geology more clearly, and explain how the stratigraphic picks are made. Is it by projecting surface geology down? Recognition of seismic facies? Wishful thinking?

It seems like the authors' tectonic model is driving the interpretation of the seismic to a very large degree. This leads to a house of cards effect, where the questionable interpretation is presented, which in turn is supported by reference to a lot of the author's own (often unpublished) work. Presenting citations to abstracts and unpublished work gives unjustified credence by making it look like a statement is supported by references, but those citations are not peer-reviewed.

Reorganize discussion to focus only on the study area, cut out the regional implications that have been discussed in many of Koehl's other papers and need not be repeated here. The discussion is very jumpy between local and regional implications and may be better organized if it were shorter and more focused. The ratio of interpretation text to data text in this paper is lop-sided in favour of interpretation. Explain the implications within the study area first, then what any new interpretation can be used in regional interpretation. Don't just re-iterate what you've already published elsewhere. What is new from the study area, does it add to or support your published models? No need to spell out your previously published models in the discussion. If what you are discussing is not in the area of Figure 1, then seriously consider deleting it. The discussion could readily be cut in half.

I have issue with citing your own unpublished work and abstracts as a back up for your interpretation. See detailed comments and editorial changes on the marked up pdf linked.

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and does the work have academic merit?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Arctic tectonics; stratigraphy; petroleum systems

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 14 Oct 2023

Jean-Baptiste Koehl

Reply to Keith Dewing Dear Sir, Madam, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

Comments by the reviewer

Comment 1: This paper explores the geology of the Billefjorden area in central Spitsbergen using a seismic line and bathymetric maps. From these data, the authors conclude that pre-existing structures controlled the location of Paleozoic normal faults, and that compression is exclusively Cenozoic in age.

Response: Mostly agreed, although the authors of the present manuscript would like to add that they argue that most of the post-Caledonian contraction is Cenozoic in age. In addition to Cenozoic Eurekan contractional deformation, the authors of the present manuscript recognize Timanian contraction and acknowledge the widespread occurrence of Caledonian contraction in the area.

Changes: None.

Comment 2: The paper has a number of issues, centered around the incredibly detailed, but poorly constrained, interpretation of bathymetric and seismic datasets. These datasets are then combined with a number of the lead author's previous studies to make broad conclusions about the regional tectonic history. The paper is hard to follow as there is a lot of detailed discussion that is not supported by maps and diagrams.

Response: Disagreed. From this comment and other comments by the reviewer, it is clear that he has not had a look at the Extended data and Underlying data sections available open access on DataverseNO (https://doi.org/10.18710/1WTNQB and https://doi.org/10.18710/UCRW4L respectively). It is therefore crucial that these sections are further highlighted and the reader better encouraged to look there early on. See response to comments 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 65, and 67, and the "Other changes" section at the end of the present document.

Changes: Added ", including high-resolution versions of the figures and supplements, which are necessary to view the presented interpretation in detail" and "Supplementary data (e.g., calculations related to depth conversion and topographic variations, bathymetric profiles, and further field evidence and extended discussion) are available as Extended data." in the method chapter. See response to comments 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17 65, and 67, and the "Other changes" section at the end of the present document.

Comment 3: The main issue I have with the paper is the amount of interpretation on both the bathymetric and seismic figures but that are not well supported. For instance, the interpretation of the bathymetric maps are not supported by any information from dredged samples or drilling, and the onshore geological map is not shown.

Response: No drilling and no dredging were ever done in the fjord. Therefore, the authors of the present manuscript have to proceed without such data.

Changes: None.

Comment 4: The small strike-slip faults interpreted from the apparent steps in the ridge on Fig. 2D should also show up on the surface mapping. If they don't then maybe there's another explanation for the steps in the submarine escarpment, like scalloping due to submarine erosion or the effects of ice? If the strike slip faults only show up where there is no actually rock observation, then it would be worrisome!

Response: The small strike-slip faults depicted by the offset of the ridge on bathymetric data in the fjord do indeed show on adjacent onshore areas on the western shore of the fjord. For this, the reader is referred to the supplementary data attached to the present manuscript. Notably supplements S10 and S11 show evidence for WNW–ESE-striking faults onshore Billefjorden on satellite images (S10) and in the field (S11) at Narveneset and Brimerpynten (see Figures 1b and 3d for location). Furthermore, supplement S11 clearly documents sinistral strike-slip kinematics along these faults in the field, thus supporting that the interpreted apparent offset of the N–S- to NNW–SSE-striking ridge in the fjord is at least partly related to sinistral strike-slip tectonic fault offset.

Changes: None required.

Comment 5: The seismic figure 4 is even more difficult to accept without a leap of faith. Firstly, why are the two overview panels so small and the inserts so big? The stratigraphic column takes a whole page yet this figure, which is critical to the arguments made in the paper, is <1/2 page. Make 4A and 4B larger.

Response: The format the journal chose to display the figure may hopefully be adapted after discussion with the editorial team.

Changes: Awaiting further discussion with the editorial team to enlarge figure 4a–b potentially to an entire page.

Comment 6: Second, there are countless interpretations that could be made on this seismic section, especially given the lack of a drill hole in the line of the section, and the absence of cross lines. I've Open Research Europe Page 26 of 29 Open Research Europe 2023, 3:124 Last updated: 22 SEP 2023 marked up the figure with many comments, but I really cannot see many of the small faults that the authors have put on the figure.

Response: The authors of the present manuscript concede that it is not possible to identify all the small faults interpreted in Figure 4a–b in the pdf file of the manuscript. However, the authors of the present manuscript made both supplementary data (see Extended data section at the end of the present manuscript; https://doi.org/10.18710/1WTNQB) and underlying data (see Underlying data section at the end of the present manuscript; https://doi.org/10.18710/UCRW4L) available so that the readers may fully zoom in and out of each figure, exploring the interpretation presented with full resolution. The high-resolution versions of the figures of the present manuscript are several hundreds of MB to several GB large and therefore cannot be included as such in the manuscript's pdf file. Nevertheless, the authors of the present manuscript argue that the high-resolution versions of the figures provide ample opportunity to the reader to zoom in specific structures on the seismic and bathymetric data.

Changes: None.

Comment 7: Not every little gap in a reflection indicates tectonic movement – there is such a thing as poor data quality. I would hesitate to interpret anything below 1.6 seconds on this section.

Response: Partly agreed. However, the seismic data presented in Figure 4a–b is of relatively high quality for the area and shows an incredible wealth of tectonic structures. This specific seismic line does not show any of the typical seismic artifacts (e.g., multiples, diffraction rays), that are often observed on poor-quality seismic data in the area (e.g., supplement S3 and S4 in which the authors of the present manuscript clearly avoided interpreting any reflection past 0.6 seconds TWT because of the poor quality of the data and the clear artifacts present on the data, e.g., multiples). Again, the reader is referred to the Underlying data section of the present manuscript, which is fully accessible on DataverseNO (Open Access online data repository; https://doi.org/10.18710/UCRW4L).

Changes: None.

Comment 8: The figure would be easier to follow if there were another panel that showed the main stratigraphic packages with partially transparent colour blocks. Trying to follow the many colours of dotted and dashed lines is tricky.

Response: Agreed.

Changes: Redesigned Figure 4b to include colored polygons for each stratigraphic unit.

Comment 9: So while I really support new ideas being introduced into the literature, this paper needs some big improvements. There needs to be clarifying text added to the introduction that this paper presents an alternate view of the geological history that downplays the Svalbardian Orogeny and provides an interpretation where the structures can be explained by a combination of ProterozoicEarly Devonian-Cenozoic deformation and reactivation. The authors need to be clear that there are other, much more widely accepted models and that this paper presents one possibility for another tectonic interpretation.

Response: Agreed.

Changes: Added “The paper notably explores an alternate scenario to the post-Caledonian tectonic history of Svalbard by suggesting that all post-Caledonian contractional structures may be explained by early Cenozoic Eurekan contraction alone, thus downplaying the role of the Late Devonian Svalbardian Orogeny.”.

Comment 10: The bathymetric interpretation should be tied to the surface geology by showing the geological map in conjunction with the bathymetry. If the features interpreted on the bathymetric map are not shown on the surface geology map, then some explanation needs to be given as to why these features are not visible at the surface.

Response: Agreed.

Changes: Added the geological map by Dallmann et al. (2004) in figure 3a, c, and d in the present manuscript, as well as the corresponding legend. Regardless of this change, very little can be extracted from the onshore geological map because it is way too detailed and will anyway require the reader/reviewer to refer to the map by Dallmann et al. (2004) and zoom in and out to identify specific stratigraphic units amongst the numerous units in the area.

Comment 11: The seismic figure needs to be resized, a panel is needed that shows the stratigraphic packages clearly, so the reader isn’t hunting for various dotted lines.

Response: Agreed. See response to comments 5 and 8.

Changes: See response to comments 5 and 8.

Comment 12: Many of the smaller faults are pretty questionable. I don’t think most 3D cubes get this level of interpretation! Look at the literature and use a similar density of interpretation that other seismic interpreters use.

Response: The present manuscript is not about doing seismic interpretation the same way many scientists have done in the past, but about advancing geological research by using the cutting-edge, ground-breaking leap made by the first authors in his correlation of geological structures in the field to their equivalent on seismic reflection data, e.g., Koehl (2020, 2021) and Koehl et al. (2022a, 2023). In these contributions, the lead author of the present manuscript notably describes a correlation of S-shaped and Z-shaped seismic reflection data to onshore duplex structures, and the geometry of hundreds of meters wide asymmetric (verging, recumbent, isoclinal) folds and mylonitic shear zones and thrusts. This research was commended by various scientists in the field and was recognized by an invitation as a Keynote speaker at the EGU 2020 (Koehl, 2020). As to whether 3D data can get us this far, the answer is yes, absolutely, but if and only if one has trained one's eyes to hunt for specific types of reflections and reflection patterns (e.g., Koehl et al., 2023b). Arguing that seismic data are of poor quality is no longer a valid excuse in the case of Figure 4a–b because we now have tools and potential explanations for most of the reflections and seismic facies displayed in the seismic line.

Changes: Added reference to Koehl et al. (2023) in the present manuscript.

Comment 13: I especially question 4C – why curve the upper white dotted line up rather than connect to the brown straight along trend. That would make the two white dotted lines parallel;

Response: Disagreed. This would be inconsistent with the negative amplitude reflection (blue) located just above the interpreted dotted white line, which clearly curves up. Therefore, it is more probable that the positive amplitude reflection (red) also does the same at this specific location.

Changes: None.

Comment 14: 4D – the grouping of three reverse faults could easily be interpreted as a small graben that offsets the strong reflections at the top of the image;

Response: Disagreed. By calling it a "graben" the reviewer is suggesting that there is a south-dipping normal fault disrupting the positive amplitude reflection (red) above the dotted black (negative amplitude) reflection. However, the reflection interpreted as a dotted black line and all underlying reflection are not disrupted, therefore invalidating the suggested interpretation of a graben. A much more likely alternative is that the disruption of the positive amplitude (red) reflection above the dotted black line is offset by a small north-dipping thrust, which accommodated top-south movement and is dying out above and below the offset reflection because no further offsets are observed. Note that this is typical in sedimentary successions with strong rheological contrasts between interbedded units such as rocks of the Carboniferous–Permian Gipsdalen Group in Billefjorden, which typically consists of weak evaporites and shales interbedded with strong sandstone–siltstone and carbonates. In the present case, the most likely candidate are carbonate- and evaporite-rich rocks of the Wordiekammen Formation and/or Gipshuken Formation (Gee et al., 1952; Cutbill & Challinor, 1965; Keilen, 1992; Ahlborn & Stemmerik, 2015).

Changes: Added small thrust mentioned here in Figure 4d.

Comment 15: 4E – how can you be certain that the dotted blue lines are all the same horizon?;

Response: Just like every single seismic interpreter, the authors of the present manuscript do not pretend to be sure of anything. However, the very similar seismic amplitude and geometry of the reflector throughout the area support the correlation presented. Note that the reviewer and any other geoscientist may very well come up with another interpretation of the presented data. Up to present, the interpretation proposed in the present manuscript is a first ever presented.

Changes: None.

Comment 16: 4G – I just don't see the faults you mark, why not interpret the beds as just following through?

Response: Partly agreed. The top red line interpreted by the reviewer may very well represent a continuous bed, although it is a strong oversimplification by the reviewer considering the undulating geometry of the reflection's northern half. The undulating geometry is not left our in the present interpretation and the authors of the present manuscript argue that it is related to top-south thrust faults arranged in imbricates. This interpretation gains weight when looking at the reflections below the top red line interpreted by the reviewer, which are more undulating and/or disrupted, thus forming packages of Z-shaped reflections (dotted white lines). Such reflections are typical in weak sedimentary successions deformed during contractional events, especially in the study area (e.g., Koehl, 2021). The alternate interpretation of the reviewer, though simplifying considerably the overall interpretation and geology of the area, undermines several key features and therefore misses the overall picture.

Changes: None.

Comment 17: Tie the seismic to surface geology more clearly, and explain how the stratigraphic picks are made. Is it by projecting surface geology down? Recognition of seismic facies? Wishful thinking?

Response: Again, from the reviewer's present comment, it is clear that he has not read/had access to the Supplementary data mentioned in the Extended data section in the present manuscript and available open access on DataverseNO (open access online data repository; https://doi.org/10.18710/1WTNQB). The reviewer is invited to review carefully Supplements S1 (named "Description of the late Paleozoic sedimentary successions in central Spitsbergen from the literature") and S5 (entitled "Description and interpretation of the upper Paleozoic sedimentary successions on seismic data in Billefjorden"). Among others, the stratigraphic pics on the seismic section were made considering the onshore geology of Dallmann et al. (2004) and many other studies in the study area (e.g., Harland et al., 1974; Cutbill et al., 1976; Ringset and Andresen, 1988; Smyrak-Sikora et al., 2018), as well as the known rock types in each stratigraphic units and their potential expression (seismic facies) on seismic data (see Supplements S1 and S5 in the Extended data section for an extended description of each relevant stratigraphic units and their correlation to seismic facies on the interpreted seismic data). The authors of the present manuscript regret that they did not make it clearer that the Extended data (Supplements S1 to S14; https://doi.org/10.18710/1WTNQB) and the Underlying data (i.e., high-resolution versions of the manuscript's figures and supplements; https://doi.org/10.18710/UCRW4L) were paramount in evaluating the quality of the work done. See also response to comment 2 for changes implemented to address this need.

Changes: See response to comment 2 and Supplements S1 and S5 for more information on the information required by the reviewer's comment.

Comment 18: It seems like the authors' tectonic model is driving the interpretation of the seismic to a very large degree. This leads to a house of cards effect, where the questionable interpretation is presented, which in turn is supported by reference to a lot of the author's own (often unpublished) work. Presenting citations to abstracts and unpublished work gives unjustified credence by making it look like a statement is supported by references, but those citations are not peer-reviewed.

Response: The reviewer is referred to Supplements S1 and S5 of the Extended data section (https://doi.org/10.18710/1WTNQB) for further information on how the interpretation of the stratigraphic units was done and on the arguments used to correlate onshore geology to seismic facies. The authors of the present manuscript would like to remind the reader that it is because of the strong resistance to change of many experienced/senior geologists, who generally get selected for peer-review work, that the work by young researchers gets published ever so slowly if it ever gets published. It is therefore necessary to take the appropriate steps so that the work by early-career researchers is not forgotten, which sometimes means publishing the work without it passing the peer-reviewing process. This happens regularly for small scientist communities such as the Geosciences, especially for areas with very few groups and individuals working in (e.g., Svalbard). In addition, most scientists having a different opinion than the main published models are generally in either one of the following two situations: (1) they do not have a permanent position and therefore would like to wait until they secure a permanent position before they share their new ideas with the rest of the world and irritate/anger experienced scientists who might not agree with them, or (2) they finally obtained a permanent position and wonder why they should bother "fighting" and trying to convince their peers and should not simply relax, focus on minor issues that are unlikely to arise emotion or anger anyone at all, and enjoy the ride instead of arguing and create tension with others who might very well be colleagues at the same institute or friends (or family). As human beings, we are naturally biased and unobjective, and oftentimes lack the courage to be disliked because of the need of the feeling that one belongs to a specific community and contributes to that community. The authors of the present manuscript argue that the present interpretation is the result of a large review of all the database of seismic data available in and around Svalbard and the northern Barents Sea, together with gravimetric and magnetic data, all the bathymetric data in and around Svalbard, field data and geochronological and microstructural data. The present interpretation is one of the only interpretations that reconcile all the datasets in the area. Note that a careful review and interpretation of all the datasets mentioned was done before any of the manuscripts written by the lead author of the present manuscript were written, i.e., the interpretation presented in the present manuscript is not driven by the model published in the other studies by the lead author of the present manuscript, but is rather part of a huge work, which would have never been possible to publish as a single manuscript (see also response to comment 50).

Changes: None. See also response to comment 50.

Comment 19: Reorganize discussion to focus only on the study area, cut out the regional implications that have been discussed in many of Koehl's other papers and need not be repeated here. The discussion is very jumpy between local and regional implications and may be better organized if it were shorter and more focused. The ratio of interpretation text to data text in this paper is lop-sided in favour of interpretation. Explain the implications within the study area first, then what any new interpretation can be used in regional interpretation. Don't just re-iterate what you've already published elsewhere. What is new from the study area, does it add to or support your published models? No need to spell out your previously published models in the discussion. If what you are discussing is not in the area of Figure 1, then seriously consider deleting it. The discussion could readily be cut in half.

Response: Partly agreed. This is exactly what the present discussion is trying to do: show that the findings in the present manuscript are in agreement with the interpretation of Timanian thrust systems throughout Svalbard (Koehl, 2020; Koehl et al., 2022a) and with the non-occurrence of the Svalbardian Orogeny in Svalbard (Koehl et al., 2022c). In addition, most of the areas discussed are in Svalbard or adjacent to Svalbard (e.g., Timanian thrust systems in Storfjorden). See response to comments 62, 63, 64, and 65.

Changes: See response to comments 62, 63, 64, and 65.

Comment 20: I have issue with citing your own unpublished work and abstracts as a back up for your interpretation. See detailed comments and editorial changes on the marked up pdf linked.

Response: Disagreed. The reviewer seems to have an issue with the non-peer-reviewed work of the lead author of the present manuscript rather than the "unpublished" work. Let it show for the record that all the work cited in the present manuscript is published, although not all works cited are peer-reviewed, and that absolutely all the studies (both peer-reviewed and non-peer-reviewed) by the lead author of the present manuscript are available online at open access repositories and/or on ResearchGate. Nevertheless, the cited work that is not yet peer-reviewed includes clear photographs of the described outcrops and interpreted structures in the field and are linked to Open Access datasets including extensive outcrop photographs and structural measurements (all available on DataverseNO). Comparing the studies done by the lead author of the present manuscript to the studies done by previous workers who established the occurrence of the Svalbardian Orogeny in Svalbard, a significant difference is the absence of any field photograph in the latter. The Svalbardian event was first proposed by T. Vogt, most of whose work is unavailable and possibly completely lost because never digitalized. The next group of workers to strongly argue in favor of and set the foundation of the Svalbardian Orogeny in Svalbard is the group of K. Piepjohn in the 90s. It is important to note that there rarely are any strata overlying tectonically deformed Devonian strata in Svalbard, thus rendering constraining the timing of the observed deformation in Devonian sedimentary rocks difficult. However, in the very few places that might provide crucial insights, e.g., Alvrekkdalen, Asvindalen, Tordalen, Munindalen, and Mimerdalen in central Spitsbergen near Billefjorden, none of the studies by the group of K. Piepjohn shows any field photograph (Piepjohn et al., 1997; Piepjohn, 2000; Dallmann and Piepjohn, 2020). Instead, these studies include exclusively idealized sketches drawn by the authors themselves on the basis of monodisciplinary scientific approach (structural geology) and monodisciplinary data (structural fieldwork), or sometimes on long-distance observation of large transects largely eroded and mostly covered by screes and/or inaccessible for detailed inspection because located on steep slopes and cliffs, which the authors of the present manuscript find astounding. The quality of the interdisciplinary research and the robustness of the conclusions drawn by the authors of the present manuscript can therefore not be compared with that of the group of Dr. K. Piepjohn. It is also worth noting that Dr. K. Piepjohn and his group tried pining the Svalbardian Orogeny in Svalbard based on highly questionable (and this is a massive understatement) paleontological evidence (Piepjohn et al., 2000), which included only one specimen of misidentified Retispora lepidophyta (see discussion in Koehl et al. 2022c and in Berry and Marshall, 2015 their supplement DR3), the sample of which can no longer be located (K. Hartkopf-Froeder pers. comm., 2020).

Changes: See “Other changes” section at the end of the present document.

Comment 21: deleted “The present contribution is part of a large study (Koehl et al., 2020) aiming at investigating cryptic WNW–ESE-striking structures and fabrics in the Norwegian Arctic.”

Response: Disagreed. This sentence was specifically requested by the journal’s editorial team.

Changes: None.

Comment 22: Maybe be clear that this paper presents an alternate view of the geological history that downplays the Svalbardian Orogeny and provides an interpretation where the structures can be explained by a combination of Proterozoic-Early Devonian-Cenozoic deformation and reactivation.

Response: See response to comment 9.

Changes: See response to comment 9.

Comment 23: Not sure truncated is clear in this context. Clarify what was truncated? Or cut by or was part of?

Response: Agreed.

Changes: Added “Precambrian rocks of” and changed “was” into “were”.

Comment 24: What is CC-BY4?

Response: CC-BY4 is an Open Access type of license. Please refer to the Creative Commons webpage for more information.

Changes: None requested.

Comment 25: Earyl.

Response: Agreed.

Changes: Updated to “Early”.

Comment 26: Nothing in the Mesozoic? There are Triassic-Jurassic strata on your map.

Response: That is correct. Not every strata is deposited during a period of active tectonism. The Mesozoic in Svalbard is generally thought to have been deposited during tectonic quiescence. Since these strata and geological periods are irrelevant to the present study, it is certainly best to leave them out of an already long manuscript.

Changes: None.

Comment 27: The.

Response: Agreed.

Changes: Added “at”.

Comment 28: Glacier. Might help for those of us who struggle with all these geographic names.

Response: Although adding “glacier” here would indeed help the reader grasp the nature of the locality described, it would also be redundant. In order to be consistent, one would need to change the name from “Nordenskiöldbreen” to “Nordenskiöld glacier”, which is not entirely optimal, especially if one is to search the Norwegian Polar Institute’s database of localities around the Svalbard Archipelago (toposvalbard.npolar.no): one would not find any entry under “Nordenskiöld glacier”. However, entering “Nordenskiöldbreen would immediately zoom in the specified area. In addition, the nature of the specified locality (glacial) is irrelevant to the present study, so it does not matter if the locality name is after a glacier, a valley or anything else. What matters is its actual location, which can be obtained in Figure 1 or from the toposvalbard.npolar.no database.

Changes: None.

Comment 29: Delete “gentle to moderate (typically” and “)”.

Response: Agreed.

Changes: Deleted “gentle to moderate (typically” and “)”.

Comment 30: Is the vertical scale time or thickness?

Response: None.

Changes: None.

Comment 31: Why do you only see jogs related to the strike slip in the offshore (where there is no hard data) but not onshore where the geology is exposed? Why not show the onshore geology on this map too?

Response: The geology is not exposed everywhere, especially in the investigated, deeply eroded Arctic areas where outcrops are typically of very poor quality with low vertical and lateral continuity, and/or located on steep cliffs and slopes and therefore inaccessible for detailed inspection. In addition, the investigated offshore area in southern Billefjorden (Figure 3d in the present manuscript) provides a laterally continuous horizontal/map view of the structures in the area. By contrast, outcrops in adjacent onshore areas are neither flat, nor vertical, but display outcrop curvature varying both in dip angle and orientation. Therefore, the jogs observed offshore would not be jogs onshore and might even be partly eroded. The along-strike variations in overall kinematics, geometry, and units it juxtaposes have been and continue to be a major issue when studying the onshore exposures of the Billefjorden Fault Zone as pointed out in Koehl (2021, 4th paragraph pp. 1041). It is time to stop considering onshore field data as “hard data” or so to say data that are more robust than offshore and/or subsurface data Onshore outcrops do indeed include their share of scientific uncertainty related to the interpretation scientists make of them. In addition, the hundreds to thousands of kilometers horizontal and several to tens of kilometers vertical continuity of, e.g., of good-quality seismic data is way higher than that of onshore outcrops, which generally show vertical continuity in the order of a few tens of meters and horizontal continuity in the order of a few hundreds of meters if lucky (which is rarely the case anywhere in the study area; see also the datasets of outcrop photographs published by the lead author of the present manuscript in the study area at DataverseNO: e.g., Koehl and Stokmo, 2021 https://doi.org/10.18710/BIJYVO; Koehl et al., 2022 https://doi.org/10.18710/NARMZS). Furthermore, offsets related to strike-slip (i.e., horizontal) movements are better observed in map view, i.e., in the setting observed in the offshore portion of the fjord in southern Billefjorden (Figure 3d in the present manuscript), whereas onshore outcrops would hardly show such well expressed offset due to extensive and differential fluvial and glacial erosion in the area. See also response to comments 3, 4, and 10

Changes: See response to comments 3, 4, and 10.

Comment 32: Hard to see what this fault is offsetting.

Response: If the reviewer is referring to the third southernmost WNW–ESE-striking fault in Figure 3d in the present manuscript: Not all the WNW–ESE-striking faults need to show some lateral offset. The fault pointed out by the reviewer may very well show little to no lateral offset, or that lateral offset may not be apparent possibly because of glacial erosion. If the reviewer is referring to the fourth southernmost WNW–ESE-striking fault in Figure 3d in the present manuscript: that fault offsets laterally the onshore Gipshuken Fault (Harland et al., 1974) from its offshore continuation (Balliolbreen Fault) in the fjord.

Changes: Added “and its southern continuation, the Gipshuken Fault” and “Harland et al., 1974”.

Comment 33: Hard to see a fault here too.

Response: Agreed, and this is why the associated line is stippled. However, the onshore geology suggests the presence of the northeast-dipping Cowantoppen Fault (Harland et al., 1974) at the present location, whose onshore expression correlates with the stippled, WNW–ESE-striking submarine escarpment.

Changes: Added “An example is the southernmost WNW–ESE-striking escarpment in Billefjorden (Figure 3D), which correlates with the onshore occurrence of the northeast-dipping Cowantoppen Fault (Harland et al., 1974)” to the interpretation section of the bathymetric data.

Comment 34: You can map these through the moraine?

Response: If there is a pronounced trend of WNW–ESE-striking faults in Billefjorden, it is possible that some of these are actually newly formed Cenozoic (Quaternary?) faults forming due to minor adjustments in the crust and therefore partly cut through the moraine. This would explain the slightly oblique character of smooth, glacial WNW–ESE-striking lineations and WNW–ESE-striking fault-related escarpments in Figure 3b in the present manuscript. This is supported by recent earthquakes and ongoing movement/activity along most of the major Timanian thrust systems mapped by Koehl et al. (2022a) in Storfjorden and southern Svalbard, which are responsible for ≥ 75% of all Mw ≥ 4.0 earthquakes in the past 100 years and controlled the formation of small, shallow, WNW–ESE-striking brittle faults, which crosscuts the seafloor in Storfjorden (Koehl and Rimando, 2023 submitted; see also Pirli et al., 2010, 2013). Analogously, N–S-striking faults such as the Billefjorden Fault Zone controlled the formation of recent landslides in Billefjorden (e.g., Munindalen, Odellfjellet, and Garmaksla; Dallmann et al., 2004; Koehl et al., 2022 submitted).

Changes: None.

Comment 35: Is the note about copyright needed? Is it separate from the copyright associated with this article?

Response: This was specifically requested by the journal.

Changes: None.

Comment 36: I would not be comfortable interpreting below 1.6 seconds.

Response: See response to comments 5, 6, 7, 11, and 12.

Changes: See response to comments 5, 6, 7, 11, and 12.

Comment 37: Just for fun – why not join these blue reflections up? It seems just as viable an interpretation, but cuts across most of your interpreted structures.

Response: Agreed, and this interpretation might very well be valid as a structure, e.g., as a top-south (mylonitic?) Eurekan thrust. However, it is not optimal if interpreted as a stratigraphic reflection from a seismic facies' perspective in that it would not fully separate reflections with large amounts of steep disruptions interpreted as Proterozoic basement rocks in the present manuscript. A potential interpretation other than a top-south Eurekan thrust might be an intra-basement lithological boundary. As it stands now, the northern half of the reflection is disrupted from the southern half, and it is possible that the northern half actually represents a multiple of the overlying reflection interpreted as a clear Top-basement erosional unconformity (pink line) with downlaps (white half arrows) in overlying (Lower Devonian) sedimentary strata. The two reflections show the exact same geometry and the time distance between them is comparable to that of sea level and the seafloor (Figure 4a–b in the present manuscript). The authors of the present manuscript are open to include the reflection highlighted by the reviewer in the present manuscript's interpretation provided that the reviewer provides further support as to why the highlighted northern half of the suggested reflection should not be a multiple.

Changes: None. Awaiting further arguments from the reviewer.

Comment 38: This is A LOT of interpretation considering the quality of the data an lack of drill control or cross lines. Most 3D cubes aren't getting this level of detail. This figure should be much larger and the insets much smaller.

Response: See response to comments 5, 6, 11, and 12.

Changes: See response to comments 5, 6, 11, and 12.

Comment 39: How does the compression get to these tiny reverse faults? Where is the decollement, why aren't the big red normal faults taking up the movement instead?

Response: The area consists of strong basement rocks tightly deformed during at least two major episodes of contraction orthogonal to one another: NNE–SSW-oriented Timanian contraction and E–W-oriented Caledonian contraction. Then, Devonian–Carboniferous collapse-related extension kicked in and resulted in the formation of moderate to high-angle normal faults (see also supplement S7 for depth-converted version of Figure 4a–b). Such high-angle normal faults were simply not suitable to accommodate more than minor reverse movement shown as gentle open folding. Instead, it was much easier to create new low-angle faults and deform the very weak, shale-rich Devonian succession, which acted as a buffer between very strong basement rocks and relatively strong sandstone–siltstone- and carbonate-rich Carboniferous–Permian sedimentary strata.

Changes: None.

Comment 40: Why not bring upper white dotted line here?

Response: See response to comment 13.

Changes: See response to comment 13.

Comment 41: I cant see this as a primary stratigraphic structure?

Response: Agreed. And it is not suggested by the present interpretation. The white half-arrow simply pointed at the termination of a seismic reflection, seemingly truncated upwards. The authors of the present manuscript would like to point out that many similar reflections are highlighted in Figure 4b in the present manuscript and that the upwards truncation of the highlighted seismic reflections are mostly tectonic in nature (e.g., due to arrangement into contractional duplexes or thrust imbrication). Please note that only some of the reflections highlighted by white half-arrows are interpreted as sedimentary onlaps, toplaps and downlaps (e.g., in Figure 4d).

Changes: None.

Comment 42: The offset on this structure don’t make a lot of sense.

Response: The offsets on the highlighted structure make perfect sense: (1) formation of a bedding-parallel décollement along the weak blue marker/bed, (2) offsetting of the décollement by low-angle thrusts and staking of the blue bed/marker, and (3) formation of high-angle reverse faults (or inversion of preexisting Devonian normal faults) crosscutting the low-angle thrusts and décollement, possibly because the thrust stack became locked due to tremendous amount of lateral movement.

Changes: Added “showing (1) a possible bedding-parallel décollement (dotted blue line), (2) low-angle thrusts offsetting and staking sheets of the décollement onto one another, and (3) high-angle reverse faults (or inverted preexisting Devonian normal faults) crosscutting the low-angle thrusts and décollement, possibly because the thrust stack became locked due to tremendous amount of lateral movement” in the caption of Figure 4e.

Comment 43: I cant see these faults on 4A – I suggest that the lines I ve draw in red would work better.

Response: Disagreed. See response to comment 16.

Changes: See response to comment 16.

Comment 44: This fault doesn’t seem to offset anything?

Response: Disagreed. If the reviewer’s comment is targeting one of the northern two early Cenozoic thrusts (yellow lines), these offset two levels of Z-shaped reflections/beds (dotted white lines). At both levels, the thrusts offset the Z-shaped reflections from one another. If the reviewer is targeting the inverted Devonian normal fault (red line), the fault appears to die out upwards, but it clearly offsets many reflections below the orange-marked reflection, where each reflection is juxtaposed against a reflection of opposite polarity.

Changes: None.

Comment 45: What is the evidence for these?

Response: The evidence for these is a continuous reflection (dotted dark green line) capping disrupted and upwards terminating reflections. Onshore, evidence for these are tightly folded and thrust, weak Lower Devonian rocks (mostly shales) of the Wood Bay Formation below thick, strong carbonate beds of the Wordiekammen Formation observed in many occurrences and localities in the study area, which decoupling at or near the stratigraphic unconformity between the two formations. This notably occurs in Asvindalen (just southwest of Brimerpynten), Brimerpynten, Narveneset (location in Figure 3 in the present manuscript), Garmdalen (just north of Narveneset), Yggdrasilkampen, and Reuterskiöldfjellet (in Mimerdalen; see location at toposvalbard.npolar.no). Importantly, and although the onshore geology part of the this work is not yet published, this claim is indeed possible to verify by checking the outcrop photographs of the lead author of the present manuscript by visiting the related dataset on DataverseNO (Koehl and Stokmo, 2021 https://doi.org/10.18710/BIJYVO, days 0, 2, 4, 5, and 8 in the dataset; note that overview photographs of the Reuterskiöldfjellet locality are also available from the other days of the field trip, specifically days 6 and 7). The reviewer is notably referred to photographs IMG_3779 to 3797 in the folder “Eirik”, which show the tectonized unconformity between the Devonian and Permian with bedding-parallel gouge (photo IMG_3797) and embrittled, sigma-clast-looking blocks in the Devonian indicating both top-west and top-east transport direction within tens of cm from one another (i.e., extremely limited movement, probably in the range of a few meters). The authors of the present manuscript are open to mentioning the onshore evidence in the Extended data supplement available on DataverseNO should this be judged necessary. However, they would prefer to do so in the upcoming manuscript.

Changes: None. Awaiting decision by the reviewer and the editors.

Comment 46: Not dashed on figure?

Response: Disagreed. This line is both dashed (in the hanging wall of the Garmaksla fault, just below the thick dashed red line) and not dashed (everywhere else) in Figure 4b in the present manuscript.

Changes: None.

Comment 47: It was submitted but never accepted? I wouldn’t cite something that is uploaded by yourself on ResearchGate as scientific literature. Peer review is here for a reason – it does prevent some crazy ideas from gaining traction.

Response: The authors of the present manuscript wonder what the more trustworthy is between (1) a peer-reviewed fieldwork-based study including zero outcrop photograph and no access to the structural data used (i.e., no access to any of the data used in the study to evaluate their claim; e.g., Piepjohn et al., 1997; Piepjohn, 2000), which was peer-reviewed by a couple of reviewers, and (2) a non-peer-reviewed manuscript published open access (e.g., Koehl et al., 2022 submitted; dx.doi.org/10.13140/RG.2.2.28031.33448) including actual outcrop photographs, which are linked to supplements including high-resolution versions of each photograph and figure as supplements (Supplements S1 to S11), and linked to datasets of structural data and numerous outcrop photographs in the study area all available open access on DataverseNO (doi.org/10.18710/BIJYVO and doi.org/10.18710/TIIIKX), so that everyone (i.e., not only a couple of favorable reviewers) may review and evaluate their claim?

According to the FAIR research principles, the latter is ethically correct and appropriate to be submitted for peer review, whereas the former is not. The manuscript in question here (Koehl et al., 2022 submitted) was submitted and rejected unfairly by unobjective reviews by a couple of disgruntled senior scientists. The lead author of the present manuscript and of the study in question has a clean conscience and all the evidence used in the rejected manuscript is fully presented and available to the reader in the manuscript, in the supplements attached to the manuscript (S1 to S11), and at the online open access data repository DataverseNO (doi.org/10.18710/BIJYVO and doi.org/10.18710/TIIIKX). The goal of the manuscript in question is to discredit old-fashioned, monodisciplinary work previously done in the study area (Billefjorden) by specific geologists who ended up being selected to review the manuscript.

The lead author of the present manuscript and of the study in question regrets that he had the naivety to believe that these two peer-reviewers would produce objective reviews and behave in a manner fit to a senior researcher. It is now obvious that these senior scientists did not want to let their models (which they seem to view as their legacy) go down without an unethical pushback, i.e., an unobjective review. Peer review is certainly here for many reasons, but sometimes used by senior scientists to retain control over what new ideas are being published, which is in a certain way unfair, because younger scientists with more updated/modern ways of proceeding (both ethically – cf. FAIR research principles, and scientifically – e.g., interdisciplinary approach) generally end up being rejected (and segregated when applying for positions in academia) if they disagree with models previously published by senior researchers. Unfortunately for these senior scientists and fortunately for early-career scientists, knowledge is like water. If there is a crack in the hull, the ship will inevitably capsize, i.e., erroneous geological models will eventually be abandoned, albeit much later than they could have, therefore significantly delaying scientific progress. Note that such a scenario is rendered unlikely by the open, author-driven peer-review system created by Open Access Research. The authors of the present manuscript would like to call the attention of the readers and reviewers of the present work to the fact that the present study is part of an earlier manuscript, which included the present manuscript and the following two (now published and peer-reviewed) articles:

Koehl et al. (2023a) and Koehl et al. (2023c). This earlier large manuscript was rejected by senior reviewers who lacked the skill (notably in interpreting bathymetric and seismic data) to appreciate the merit and impact of the work that had been done and/or lacked the courage to be disliked and allow new ideas opposing commonly accepted models (including their own models) to be published. Consequently, tremendous time, human, and financial resources have been wasted to divide the earlier large manuscript into three discrete manuscripts (this issue will be addressed by the lead author of the present manuscript in a manuscript about science ethics and the peer review process in the Geosciences). This pitfall occurs very commonly in the Geoscience community and appropriate steps should be taken to avoid this to continue to happen. In the end, is it not more important that a "crazy" idea goes through the peer review process and is available for the taking and for pursuing in the event it eventually turns out that it is the most realistic model (e.g., the idea of Continental Drift by Wegener and du Toit), or that a crazy idea is rejected and never published and therefore never pollutes the mind of new researchers nor becomes available to future researchers in dire need of new solutions to reconcile all the new data that become available with the dawn of the Open Access movement? Some "crazy" ideas far less realistic than the idea presented in the present manuscript because monodisciplinary and requiring a much more complicated model with more tectonic movements have previously been accepted by the peer review process (e.g., the 2000-km-sinistral-strike-slip-displacement model for the Great Glen Fault based exclusively on paleomagnetic data; van der Voo and Scotese, 1981), and these ideas have now been fairly abandoned. However, the fact that these ideas were allowed to be published in the first place allowed a broader community to further test them. If an idea/product is so crazy, e.g., destroying one's health with heavy drugs, has it evet helped that the local authorities in charge ban/veto the idea/product? Is it not when an idea or product is banned by the authorities in charge (in the present case, the more experienced scientists selected as peer reviewers) that it actually gains even more attention? In the end, each and every individual will be confronted with the choice to either give in the new idea or resist it.

Changes: None.

Comment 48: These are not helpful in the interpretation?

Response: Yes, the dashed white lines representing intra-basement reflections are indeed important for the present interpretation because they highlight the obliquity of potential stratigraphic intra-basement reflections and mylonitic surfaces within the main shear zone in the south. This relationship is highlighted in the first paragraph of the "Structures in Proterozoic basement rocks" section.

Changes: None.

Comment 49: Im thinking about the relative weights of evidence for glacial vs resistant bed as part of the stratigraphic package vs resistant unit brought up by faulting. It might be helpful to have the onshore geology shown next to the bathymetric maps? This would allow the reader to see how close the correspondence is between the submarine features and mapped onshore features.

Response: Agreed. See response to comment 10.

Changes: See response to comment 10.

Comment 50: There is far more interpretation on the seismic than I would be willing to make. There must be hundreds of ways to interpret this line! How much of the interpretation is being driven by the tectonic model that the authors wish to display? The lack of drill control for checks on age and velocity structure leads to a decrease in confidence. There is all sorts of noise that comes in from

Response: Some of the seismic artifacts mentioned by the reviewer were taken into account by the authors of the present manuscript (see response to comment 37). See also response to comment 4. The interpretation presented in the present manuscript is based on several field campaigns by the lead author in the Billefjorden area between 2015 and 2021, including visits of onshore areas directly adjacent to the seismic line in Narveneset and Brimerpynten (see also Extended data and Underlying data sections in the present manuscript and the attached datasets https://doi.org/10.18710/1WTNQB and https://doi.org/10.18710/UCRW4L). Although there must indeed be hundreds of ways to interpret every single seismic section ever acquired (including those with one or more well controls), the authors of the present manuscript have provided scientific arguments as to why they believe that the presented interpretation is likely the correct one (cf. description section of the stratigraphic units on seismic data and corresponding units in the Geological setting chapter and the extended description in supplement S1 in the Extended data, including notably detailed arguments on the correlation of rock types and rock type variation with seismic facies; https://doi.org/10.18710/1WTNQB). Despite the suggestion by the reviewer that the presented interpretation is driven by earlier interpretation by the lead author of the present manuscript published in previous articles (e.g., Koehl et al., 2022a, 2023b), the data presented herein were interpreted before the lead author came to the conclusion that the only way to reconcile all the data in the entire Barents Sea, northern Norway, Svalbard, and the Fram Strait was that of continuous Timanian thrust systems, which were repeatedly reactivated and overprinted during the Caledonian Orogeny, Devonian–Carboniferous extensional collapse, Eurekan contraction, and late Cenozoic rifting (which then led him to write several manuscripts on the matter, including Koehl et al., 2022a, 2023b). If it had been up to the lead author of the present manuscript, he would have happily submitted his ground-breaking discovery of continuous Timanian thrust systems as a large monograph or book including the entire database (including field data, seismic, bathymetric, magnetic, gravimetric, well bore, and geochronological data) he interpreted between 2016 and 2020 in the whole Barents Sea, northern Norway, Svalbard, and the Fram Strait. Unfortunately, because of the current peer-review system in place, if the lead author of the present manuscript had attempted to compile his whole work into a book/monograph, not only it would have taken him 2–3 years of focused work doing just that in a world driven by a “publish or perish” attitude (in which one has to find funding for research and for salary, teach, and keep developing one’s skills and CV to hopefully get a permanent position someday, and in which one also has to face constant nation-wide bullying because proposing a new idea diverging from previously published models), but in addition to this he would have had to deal with obtuse reviewers who may have abandoned their dignity and rejected flat out his work (which the lead author of the present manuscript has unfortunately witnessed already many times in his career although still an early-career scientist). Again, the present work and the two related manuscripts (Koehl et al., 2023a, 2023c) are a textbook illustration of this pitfall of the current peer-review system: the three manuscript were initially submitted as a whole (http://dx.doi.org/10.13140/RG.2.2.35857.97129), but the senior scientists tasked to evaluate the work failed to see its merit, and/or unobjectively disagreed with its conclusions, and/or did not have all the necessary skills to fully judge this interdisciplinary piece of work (especially when it comes down to seismic interpretation, which the lead author is an expert of with no less than 11 courses in seismic interpretation during his Masters Degree and two years in the hydrocarbon industry). The reviewers both agreed that in order to be published, this work (http://dx.doi.org/10.13140/RG.2.2.35857.97129) had to be split into 2 to 3 separate manuscripts (#forcedsalamislicing), which is now almost done and took over 3 years. The lead author of the present manuscript regrets that the current peer-reviewing system does not allow smoother publishing of ground-breaking discoveries because of the unreasonable amount of power given to senior researchers (by comparison to early-career researchers) who commonly keep doing research at the same level and using the same tools as at the time of their Ph.D. during their whole career because there is no time to learn new skills in our constantly busy modern work environments. The author of the present manuscript takes the opportunity to salute the new, author-driven, open peer-review system offered by the journal Open Research Europe, which is much fairer because a manuscript cannot be rejected because of one or two unobjective review. Instead, the manuscript will still be out there, published (though not yet passed peer-review) and the authors will be able to keep improving it and to keep suggesting more appropriate reviewers.

Changes: See response to comment 4.
Comment 51: Are they mylonitic onshore?

Response: Yes, some onshore faults in basement rocks are mylonitic (Koehl et al., 2023c their figure 4d and e).

Changes: None required.

Comment 52: As interpreted on.

Response: Agreed that the content of the parenthesis is confusing.

Changes: Deleted “and” and moved “Koehl *et al*., 2023b their figures 2–6” to a different parenthesis earlier in the same sentence.

Comment 53: Spelling.

Response: Agreed.

Changes: Updated “modetarely” into “moderately”.

Comment 54: The former are interpreted to have been deposited as an alluvial fan.

Response: Agreed.

Changes: Replaced “were” by “are interpreted to have been”.

Comment 55: Im having a hard time seeing these.

Response: See response to comments 5 and 6.

Changes: See response to comments 5 and 6.

Comment 56: I would have interpreted the folds at the top of 4D as a little graben created by normal faults rather than a compressional feature. This is an example of where the tectonic model drives the interpretation. Maybe Im not looking hard enough on 4B, but where is the folding in the top Billefjorden Grp?

Response: One thing is to have a model drive an interpretation and another is to produce an interpretation that reconciles all the datasets and observations (i.e., not only those presented in the present manuscript, but also all over Svalbard, the Barents Sea, northern Norway, and the Fram Strait). In the present case, the latter approach was used. The Top Billefjorden Group reflection (dotted green line) is indeed potentially mildly folded (see curving geometry of the reflection), but this reflection only appears on a small portion of the seismic line, so if the authors of the present manuscript had to consider only this reflection alone, their interpretation would be inconclusive. Nevertheless, this is what is argued for here: that the synclinal geometry of strata of the Ebbadalen (i.e., Lower Pennsylvanian) and Minkinfjellet formations although they are mildly folded partly reflects the syn-kinematic character of the Ebbadalen Formation, whereas the Minkinfjellet Formation is late-tectonic or postdates normal faulting. It is the interpretation of the character of all the reflections that determined the interpretation of the seismic line. See also response to comment 14.

Changes: See also response to comment 14.

Comment 57: Can be attributed to?

Response: Agreed.

Changes: Changed “are imputable” into “can be attributed”.

Comment 58: This whole paragraph seems peripheral to the current work. Haakon VII Land doesnt even show on the map, so the reader cant follow this thread easily.

Response: Agreed that the location of Haakon VII Land is missing in Figure 1a. However, the present paragraph is highly relevant to the present discussion because it is about analogous findings in an adjacent area of Spitsbergen, compares them to the study area, and provides perspective for recent studies of potential metamorphic core complex-related detachments (e.g., Braathen et al., 2018).

Changes: Added the location of Haakon VII Land in Figure 1a.

Comment 59: Deleted “the occurrence of”.

Response: Agreed.

Changes: Delete “the occurrence of”.

Comment 60: This text is unclear to me. The features that link hard and soft need to be pointed out.

Response: Agreed that the highlighted text may be confusing.

Changes: Added “(two thick, deep yellow lines in Figure 4B)” and “(two thick, shallow yellow lines in Figure 4B)”, and split the sentence into two and rewrote the second sentence into “The shallow and deep thrustsa re separated by aggregates of top-SSW contractional duplexes (Figure 4A–B), which may correspond to soft-linked portions of the thrusts”.

Comment 61: Is this sentence needed?

Response: Yes, it is. It refers the reader to an important piece of work that demonstrates that the Svalbardian Orogeny presents severe issues. The authors of the present manuscript firmly oppose the idea of the Svalbardian Orogeny in Svalbard, but the authors of the present manuscript do not oppose the publishing of this idea nor its discussion by its believers.

Changes: None.

Comment 62: A lot of this paragraph seems out of scope of the paper. This is general Svalbard, not just the study area. Haven't these ideas already been published in Koehl and Munoz-Barrera etc. Why do they need to be restated here?

Response: Disagreed. The present paragraph compares WNW–ESE-striking faults in western Spitsbergen to the identified WNW–ESE-striking faults in the study area. These ideas have not been published in Koehl and Muñoz-Barrera (2018). The authors of the present manuscript believe that it is important for the reader to note that the interpretation argued for in the present manuscript has very strong similarities with the WNW–ESE-trending segment of the West Spitsbergen Fold-and-Thrust belt in western Spitsbergen, and that similar Eurekan structures occur in the same stratigraphic units (e.g., Gipshuken and Wordiekammen formations), which show very comparable lithological variations as in Billefjorden both onshore and offshore. In addition, the present paragraph sets the stage for paragraphs 2 and 3 of the “Possible origin for WNW–ESE-striking faults and shear zones in Billefjorden” section, which suggest that the WNW–ESE-striking faults and shear zones in the study area are part of a major late Neoproterozoic Timanian thrust system, which controlled the formation of subsequent, early Cenozoic Eurekan thrusts both in Billefjorden (study area) and in western Spitsbergen.

Changes: None.

Comment 63: Again, this paragraph is expanding the results of this study to the broad region. Seems like an over-reach.

Response: Disagreed. The present paragraph is needed to highlight the high intensity of Eurekan deformation in central Spitsbergen (i.e., some distance away from the Eurekan front in western Spitsbergen) and show that the alternate interpretation proposed for the study area in central Spitsbergen is also highly relevant for areas in western Spitsbergen (i.e., near the Eurekan front or within the West Spitsbergen Fold-and-Thrust Belt), where previous studies postulated (i.e., no geochronological constraints) a Late Devonian age for numerous thrust structures in pre-Carboniferous rocks (e.g., Thiedig and Manby, 1992; Kempe et al., 1997). Nonetheless, the authors of the present manuscript concede that the present paragraph is poorly organized.

Changes: Reorganized and split the paragraph into two, and added "(especially in the west near the West Spisbergen Fold-and-Thrust Belt)" and "Therefore, differences in deformation type and intensity between basement, Devonian, and post-Devonian strata may be explained by Eurekan tectonism alone" to the newly created paragraph.

Comment 64: All this is in other publications?

Response: The present paragraph highlights the similarity of structures (e.g., bedding-parallel décollements) in a nearby area (Sassenfjorden) to those investigated in the study area (Billefjorden). It is therefore argued that the present paragraph is needed to give further weight to the presently proposed interpretation.

Changes: None.

Comment 65: Hard to follow without detailed maps. Again, this seems to be fighting a bigger battle than is warranted by the data and interpretation presented.

Response: Disagreed. If the reviewer's comment targets the upper paragraph, it is about the Billefjorden area (i.e., the study area of the present manuscript). If the reviewer's comment targets the lower paragraph, it is also about Billefjorden (i.e., the study area of the present manuscript). Regarding the reviewer's comment on the need for a detailed map, it is available in the Figure 1b. However, it is still not enough to fully appreciate the topography, which is available in the detailed map by Dallmann et al. (2004) and at svalbardkartet.npolar.no (see also response to comment 67). Note that the calculations, the topographic data needed, and the source of the data is available in Supplement S12 of the Extended data (available on DataverseNO at https://doi.org/10.18710/1WTNQB).

Changes: See also response to comment 67.

Comment 66: ??

Response: Specifically requested by the journal.

Changes: None.

Comment 67: No data presented to help the reader follow along.

Response: Disagreed. The data dealt with include topographic data (specifically the altitude at which rocks of certain stratigraphic units crop out onshore) available in Dallmann et al. (2004) and at svalbardkartet.npolar.no (including both topographic data and the geological map), and offshore depth conversion available on DataverseNO (Supplement S6 in Extended data available at https://doi.org/10.18710/1WTNQB and a high-resolution version of the table at https://doi.org/10.18710/UCRW4L). Note that the calculations, the topographic data needed, and the source of the data is available in Supplement S12 of the Extended data (available on DataverseNO at https://doi.org/10.18710/1WTNQB).

Changes: None.

Comment 68: Delete.

Response: Disagreed. This would undermine the impact of the presentation.

Changes: None.

Other changes: Updated Koehl et al. (2023), Koehl et al. (2023 submitted), Koehl et al. (2023b), and Koehl et al. (2023c) into Koehl et al. (2023a), Koehl et al. (2023b), Koehl et al. (2023c), and Koehl et al. (2023d) respectively due to the recent publishing of Koehl et al. (2023 submitted).

Competing Interests: None.

Reviewer Report 25 August 2023

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✓ **Liang Qiu**
State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences and Resources, China University of Geosciences, Beijing, China

The manuscript demonstrates a commendable overall organization and introduces a novel dataset of seismic reflection profiles. The figures are clear and the text is generally well-crafted. Herein, I bring to your attention a few minor points of consideration.

The article delves into the Cenozoic and the Devonian to Carboniferous periods; however, it also provides an introduction to the geological setting of the Neoproterozoic and early Paleozoic eras. Consequently, the initial two paragraphs could be omitted or simplified.

It seems that the research significance in the section of Introduction appears to be relatively straightforward and superficial, lacking sufficient depth.

Certain sentences within the main text could benefit from further refinement, such as the following examples: 'The present contribution is part of a large study (Koehl *et al.,* 2020) aiming at investigating cryptic WNW–ESE-striking structures and fabrics in the Norwegian Arctic. The present contribution focuses on the offshore portion (seismic and bathymetric data) of the Billefjorden area, whereas Koehl *et al.* (2023a) and Koehl *et al.* (2023b) focus on onshore outcrops respectively on the western shore and the eastern shore of the fjord.'

Fig.1 lacks latitude and longitude.

The figure panels referenced in the text are presented in uppercase, such as Figure 3A, while all figure numbers are rendered in lowercase.

The legend of Figure 4 is too tiny to see.

Koehl *et al.,* 2022a or Koehl *et al.,* 2022b?

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Structural geology and tectonics; geochronology

I confirm that I have read this submission and believe that I have an appropriate level of

expertise to confirm that it is of an acceptable scientific standard.

Author Response 14 Oct 2023

Jean-Baptiste Koehl

Reply to Liang Qiu Dear Prof. Qiu, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

Comments by the reviewer

Comment 1: The article delves into the Cenozoic and the Devonian to Carboniferous periods; however, it also provides an introduction to the geological setting of the Neoproterozoic and early Paleozoic eras. Consequently, the initial two paragraphs could be omitted or simplified.

Response: The first two paragraphs are rather simple and non-extensive and are absolutely needed to introduce the episodes of deformation that are discussed in the Discussion chapter. If any, the authors of the present manuscript are open to merging the two paragraphs or to expand them further, although more details are already given in the discussion.

Changes: None yet.

Comment 2: It seems that the research significance in the section of Introduction appears to be relatively straightforward and superficial, lacking sufficient depth.

Response: Agreed.

Changes: Add the following sentence at the end of the first paragraph of the Introduction chapter: “In addition, the N–S-striking structural trend does neither explain the provenance of Lower Devonian sediments of the Wood Bay Formation from the south-southwest in northern Spitsbergen (Friend and Moody-Stuart, 1972), nor the sourcing of the Central Tertiary Basin from the north-northeast in the Paleocene (Petersen et al., 2016).”. The authors of the present manuscript also recommend the addition of the following paragraph at the end of the Introduction chapter: “The present study has implications for the late Neoproterozoic–Phanerozoic tectonic evolution of the Svalbard Archipelago and for plate tectonics modelling, which typically place the accretion of Svalbard’s basement terrane in the mid-Paleozoic through large lateral tectonic movements along hundreds to thousands of kilometers long, N–S-striking fault zones (e.g., Billefjorden Fault Zone). The structures discussed in the present contribution provide new anchor points for the Svalbard Archipelago with the Barents Sea block and Baltica in the late Neoproterozoic and introduce new limitations on the possible amount of N–S-oriented lateral tectonic movements. The present work therefore calls for major revisions of current local plate tectonics models for Arctic regions and full-plate models, notably regarding large-scale lateral movements of blocks and terranes during short periods of time, which is not possible to reconcile with the longevity and continuous character of inherited Neoproterozoic structures. Furthermore, the present results show the influence of strain partitioning on deformation is discrete stratigraphic units, thus underlining the value of interdisciplinary studies over monodisciplinary (e.g., structural) approaches. Finally, the present study shows that the Billefjorden Trough is not a typical rift basin as generally suggested by previous studies in the area.”.

Comment 3: Certain sentences within the main text could benefit from further refinement, such as the following examples: ‘The present contribution is part of a large study (Koehl et al., 2020) aiming at investigating cryptic WNW–ESE-striking structures and fabrics in the Norwegian Arctic. The present contribution focuses on the offshore portion (seismic and bathymetric data) of the Billefjorden area, whereas Koehl et al. (2023a) and Koehl et al. (2023b) focus on onshore outcrops respectively on the western shore and the eastern shore of the fjord.’

Response: These sentences were included on specific request by the editorial team. They must therefore remain unchanged.

Changes: None.

Comment 4: Fig.1 lacks latitude and longitude.

Response: Agreed.

Changes: Added latitude and longitude to Figure 1a.

Comment 5: The figure panels referenced in the text are presented in uppercase, such as Figure 3A, while all figure numbers are rendered in lowercase.

Response: Agreed. The authors of the present manuscript are open to updating the figure numbers according to the reviewer’s suggestion pending that it is in line with the journal’s format.

Changes: Awaiting decision by the editorial team.

Comment 6: The legend of Figure 4 is too tiny to see.

Response: Agreed. The authors of the present manuscript recommend the journal to separate figure 4a–b from figure 4c–h and to expand figure 4a–b to an entire page to allow the readers to view the presented interpretation in detail, pending that it is alright with the journal.

Changes: Awaiting decision by the editorial team.

Comment 7: Koehl et al., 2022a or Koehl et al., 2022b?

Response: Both Koehl et al. (2022a) and Koehl et al. (2022b) are listed in the reference list.

Changes: None required.

Competing Interests: None.