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RESEARCH ARTICLE

Recent earthquakes in Svalbard sourced from transform-parallel thrust systems: implications for linear earthquake swarms and earthquake risk

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Abstract

Background

Thus far, most earthquakes around the Svalbard Archipelago in the past 75 years, some reaching up to moment magnitude (M_W) 6.1, have been attributed to movements along N–S- to NE–SW-trending fault surfaces, possibly including inherited Caledonian (ca. 460–425 Ma) and late Paleozoic–Cenozoic structures. Recent geophysical studies in the Barents Sea and Svalbard have revealed that active transform faults in the Fram Strait parallel a newly identified structural trend comprising WNW–ESE-striking thrust systems of the Timanian Orogeny (ca. 650–550 Ma) thousands of km long.

Methods

We used seismicity data from the International Seismological Centre and seismic reflection data from the DISKOS database to correlate recent earthquakes and discrete slip surfaces in the sub-surface.

Results

Analysis of seismic reflection data in Storfjorden reveals a set of km-

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scale normal faults, which truncate the seafloor and are located above and parallel to a WNW–ESE-striking Timanian thrust system. Another Timanian thrust system, the Kinnhøgda–Daudbjørnpynten fault zone, coincides with the location of the 2008–2016 Storfjorden seismic sequence. The southwards migration and shallowing of the aftershocks over time is explained by rupture along a deep, gently NNE-dipping slip surface within the basal part of the thrust in the north and ensuing collapse of overlying rocks and thrust sheets along the shallow portion of nearby slip surfaces.

Conclusions

Seismicity and seismic reflection data in Svalbard indicate that most earthquakes in the last 75 years may be associated with movement along WNW–ESE-striking Timanian thrust systems. The regional stress field causing movement along the inherited Timanian thrusts is likely related to ongoing rifting and transform faulting in the Fram Strait. The present study suggests that linear earthquake swarms may be generated by and occur orthogonal to inherited brittle–ductile thrust systems. The structures responsible for the seismicity around Svalbard may generate earthquakes up to magnitude 8.9.

Plain language summary

We analyzed recent earthquakes around the Svalbard Archipelago and tied them to structures interpreted on seismic reflection data. Contrary to previous assumptions, the seismicity and seismic reflection data suggest that earthquakes around Svalbard are triggered by movements along WNW–ESE-oriented fault zones in the crust. These fault zones formed ca. 650–550 million years ago and are currently being reactivated due to ongoing tectonic extension (rifting) and transform faulting in the Fram Strait. In addition, the data shows linear, NNE–SSW-trending clusters of seismic events with a gradual shallowing and southwestwards migration of the seismic events over time from early, deep, high-magnitude events to younger shallower aftershocks. This relationship and correlation with faults interpreted on seismic reflection data suggest that the initial, deep, high-magnitude events destabilize the overlying rock column, which gradually collapses generating shallow aftershocks along the same fault or closely related faults. The absence of earthquakes in central Svalbard may be ascribed to the Central Tertiary Basin, a tectonic depression filled with weak sedimentary rocks, which may transfer tectonic movements from the Fram Strait to Storfjorden aseismically. The faults responsible for the earthquakes around Svalbard may generate earthquakes with magnitudes up to 8.9.

Keywords

Seismicity, Svalbard, linear earthquake swarms, structural inheritance, Timanian, earthquake risk

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Introduction

The latest studies of recent (< 75 years) earthquake sequences around the Svalbard Archipelago in the Norwegian Arctic (Figure 1a) have shown that seismic activity in this area is probably related to movement along faults with various orientations, including faults striking N–S, NE–SW (Junek *et al.*, 2014; Junek *et al.*, 2015; Pedrosa-Gonzalez *et al.*, 2024; Pirli *et al.,* 2010; Pirli *et al.,* 2013; Pirli *et al.,* 2021), and WNW–ESE (Mitchell *et al.*, 1990). These earthquakes (see Figure 1b for location of all recent earthquakes between 76–80° latitude and 10–30° longitude with $M_w \geq 4.0$; International Seismological Centre, 2024) are commonly ascribed to reactivation and/or overprinting of brittle faults inherited from Svalbard's complex tectonic history. Notable inherited structures are related to the Timanian Orogeny (top-SSW contraction at 650–550 Ma; Koehl, 2019; Koehl, 2020; Koehl *et al.*, 2022a; Koehl *et al.*, 2023a; Koehl & Mottram, 2024; Majka *et al.*, 2008), Caledonian Orogeny (closure of Iapetus Ocean and collision of Greenland and Svalbard at ca. 460–410 Ma; Dallmeyer *et al.*, 1990; Faehnrich *et al.*, 2020; Gee & Page, 1994; Horsfield, 1972; Ohta *et al.*, 1989), late Paleozoic collapse–rift-related extension (multi-kilometer-thick basins; Braathen *et al.*, 2011; Braathen *et al.*, 2018; Cutbill & Challinor, 1965; Manby & Lyberis, 1992; McCann & Dallmann, 1996), Eurekan tectonism (collision of Greenland and Svalbard at ca. 62 Ma; Bergh & Grogan, 2003; Dallmann *et al.*, 1993; Harland & Horsfield, 1974; Steel *et al.*, 1985), and late Cenozoic rifting (starting in the earliest Oligocene; Engen *et al.*, 2008; Lowell, 1972; Thiede *et al.*, 1990).

The Storfjorden sequence is a series of seismic events that took place from 2008 to 2016 in Storfjorden, east of Spitsbergen. The sequence began with a M_w 6.1 earthquake at a depth of 15.4 ± 5.1 km on February 21st 2008, which produced a series of aftershocks up to 2016 (Pirli *et al.*, 2013; Pirli *et al.*, 2021). It was initially proposed to have occurred along a preexisting NE–SW-trending brittle fault formed during late Paleozoic–Cenozoic rifting (Pirli *et al.*, 2013). Since crustal-scale, WNW–ESE-striking Timanian thrust systems in the northern Barents Sea and Svalbard were only discovered recently (Koehl, 2019; Koehl, 2020; Koehl *et al.*, 2022a), they were not considered in previous seismotectonic studies (e.g., Mitchell *et al.*, 1990; Pirli *et al.*, 2013). We review the evidence for current movement along deep Timanian thrust systems and related younger and shallower overprinting structures around Svalbard and discuss their implications for earthquake sequences in the Norwegian Arctic and linear earthquake swarms in general.

Geological setting

The Timanian structures discussed here are described in Koehl *et al.* (2022a) and include E–W- to NW–SE-striking, dominantly NNE-dipping brittle–ductile mylonitic thrust systems and shear zones (Figure 2 and Figure 3). These formed during NNE–SSW-oriented contraction in the latest Neoproterozoic and were later deformed into NNE–SSW-striking folds and reactivated as sinistral-reverse faults during E–W-oriented Caledonian contraction (Figure 1a–b; Koehl *et al.*, 2022a; Koehl *et al.*, 2023b; Koehl, 2024). Notably, the Kongsfjorden–Cowanodden, Bellsundbanken, and Kinnhøgda–Daudbjørnpynten fault zones intersect Storfjorden where multiple earthquakes were recorded in recent years (Figure 1b and Figure 2; Junek *et al.*, 2014; Junek *et al.*, 2015; Pirli *et al.*, 2010; Pirli *et al.*, 2013; Pirli *et al.*, 2021).

The Kongsfjorden–Cowanodden and Bellsundbanken fault zones propagate upwards as brittle overprints that possibly initiated as high-angle listric normal faults during late Paleozoic, late–post-Caledonian extension and were inverted during Eurekan contraction. Inversion resulted in local folding of shallow sedimentary rocks (Figure 2 and Figure 3a–c; Koehl *et al.*, 2022a).

The Kinnhøgda–Daudbjørnpynten fault zone is a c. 60 km wide zone involving km-scale thrust sheets and mylonitic shear zones (Figure 2; Koehl *et al.*, 2022a). This structure runs from the island of Hopen to west of Spitsbergen (Koehl, 2024; Koehl *et al.*, 2022a). It crops out onshore Wedel Jarlsberg Land in southern Spitsbergen, where a major deformation structure of this broad thrust system, the Vimsodden–Kosibapasset Shear Zone, is exposed (Figure 1b; Mazur *et al.*, 2009). The Vimsodden–Kosibapasset Shear Zone is a subvertical, WNW–ESE-striking shear zone associated with late Neoproterozoic amphibolite facies metamorphism (Timanian; Majka *et al.*, 2008; Manecki *et al.*, 1998) and Caledonian sinistral strike-slip reactivation (Faehnrich *et al.*, 2020; Mazur *et al.*, 2009).

The study area is also thought to be crosscut by N–S-striking fault zones, such as the Billefjorden Fault Zone (Haremo *et al.*, 1990; Harland, 1969; Harland *et al.*, 1974) and Lomfjorden Fault Zone (Andresen *et al.*, 1992; Haremo & Andresen, 1992; Piepjohn *et al.*, 2019; Figure 1b). These faults were previously thought to have formed during the early–mid Paleozoic and to have accommodated strike-slip movements of hundreds to thousands of kilometers (Harland, 1969; Harland *et al.*, 1974). Recent studies suggest that the amount of lateral displacement along these faults is challenging to estimate (Piepjohn *et al.*, 2019). In fact, strike-slip movements along these faults are unlikely because they do not show any lateral offset of late Neoproterozoic thrust systems (Koehl *et al.*, 2022a). Instead, the Lomfjorden Fault Zone and Billefjorden Fault Zone (apart from the Odellfjellet segment) are suggested to be Caledonian thrust (Koehl *et al.*, 2022a) and early Cenozoic Eurekan reverse faults respectively (Koehl, 2021a; Koehl *et al.*, 2024).

In the Fram Strait, rifting and breakup occurred later than in the Arctic and northeastern Atlantic oceans, possibly in the earliest Oligocene at ca. 24.8 Ma (Engen *et al.*, 2008). Little magmatism was involved (e.g., Amundsen *et al.*, 1987; Hansen *et al.*, 2003; Skjelkvåle *et al.*, 1989), and ongoing processes include transform faulting along the WNW–ESE-striking Molloy and Spitsbergen fault zones (Figure 1b).

Methods

We use interpretation of seismic reflection data from the Norwegian National Data Repository for Petroleum Data (DISKOS database) of the Norwegian Offshore Directorate using

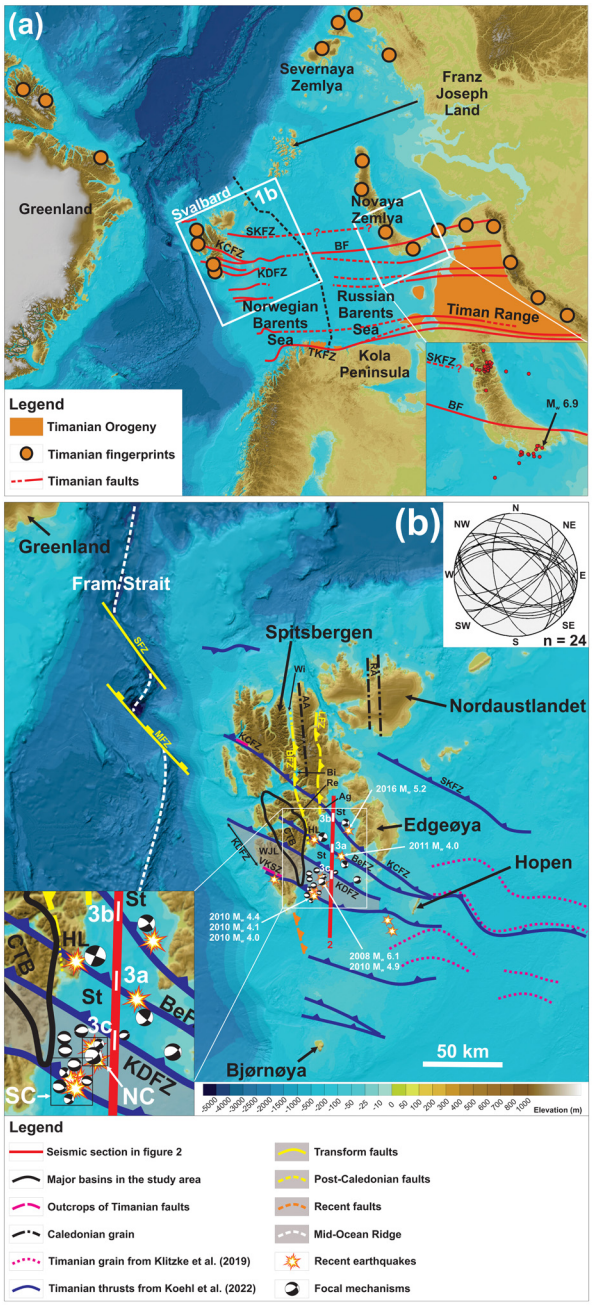

Figure 1. Overview map of the study area. (**a**) Overview map of the Barents Sea region showing Timanian thrust systems in Svalbard, the Barents Sea, and northwestern Russia and Novaya Zemlya. Basemap is from Jakobsson *et al.* (2012). Abbreviations: BF: Baidaratsky Fault Zone; KCFZ: Kongsfjorden–Cowanodden fault zone; KDFZ: Kinnhøgda–Daudbjørnpynten fault zone; SKFZ: Steiløya–Krylen fault zone; TKFZ: Trollfjorden–Komagelva Fault Zone. (**b**) Overview map showing Timanian thrust systems in the northern Norwegian Barents Sea and Svalbard. The location of recent earthquakes is based on data from the International Seismological Centre (2024). Focal mechanisms are from Pirli *et al.* (2010; 2013; 2021) and Junek *et al.* (2014; 2015) and are shown in detail in the lower left corner. The map includes all recent earthquakes between 76–80° latitude and 10–30° longitude with $M_w \geq 4.0$ (including the main shock and some aftershocks of the Storfjorden seismic sequence). The lower hemisphere Schmidt stereonet in the upper right corner displays the two fault surfaces extracted from the double-couple solution of each recent earthquakes around Svalbard, which are dominated by E–W- to NW–SE-striking faults (75%). Note that Timanian thrust systems are tens of kilometers wide and that their outline as thin dotted black lines only reflect their overall trend (not their width). Thus, earthquakes located a few kilometers away from dotted black lines still coincide with the location of major WNW–ESE-striking fault systems (e.g., Kinnhøgda–Daudbjørnpynten fault zone, which is 60 km wide along a NNE–SSW-trending axis in Storfjorden; see width of Timanian fault systems in Figure 2). The basemap is from Jakobsson *et al.* (2012). Abbreviations: AA: Atomfjella Antiform; Ag: Agardhfjellet; BeFZ: Bellsundbanken fault zone; BFZ: Billefjorden Fault Zone; Bi: Billefjorden; CTB: Central Tertiary Basin; HL: Heer Land; KCFZ: Kongsfjorden–Cowanodden fault zone; KDFZ: Kinnhøgda–Daudbjørnpynten fault zone; LFZ: Lomfjorden Fault Zone; NC: northeastern earthquake cluster; RA: Rijpdalen Anticline; Re: Reindalspasset; SC: southwestern earthquake cluster; SKFZ: Steiløya–Krylen fault zone; St: Storfjorden; VKSZ: Vimsodden–Kosibapasset Shear Zone; Wi: Wijdefjorden; WJL: Wedel Jarlsberg Land.

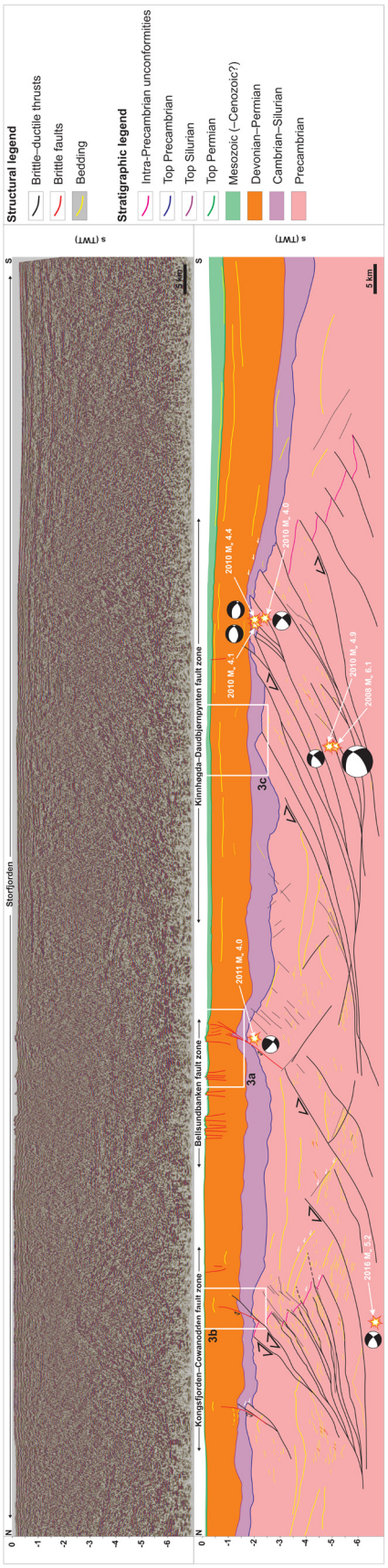

Figure 2. Seismic profile through Storfjorden. The data (in seconds Two Way-Time – TWT) shows three major, NNE-dipping Timanian thrust systems, including (from north to south) the Kongsfjorden–Cowanodden, Bellsundbanken, and Kinnhøgda–Daudbjørnpynten fault zones. White frames show the location of zoomed-in portion of the profile shown in Figure 3. The three earthquakes are projected along a WNW–ESE-trending axis (i.e., parallel to the Timanian thrust systems), and earthquake depths were time-converted using velocities from Gernigon *et al.* (2018) and seismic interpretation by Koehl *et al.* (2022a). A high-resolution version of the figure is available on DataverseNO (Koehl, 2021b). The time-conversion is included in supplement S1. The location of the profile is shown as a red line in Figure 1b.

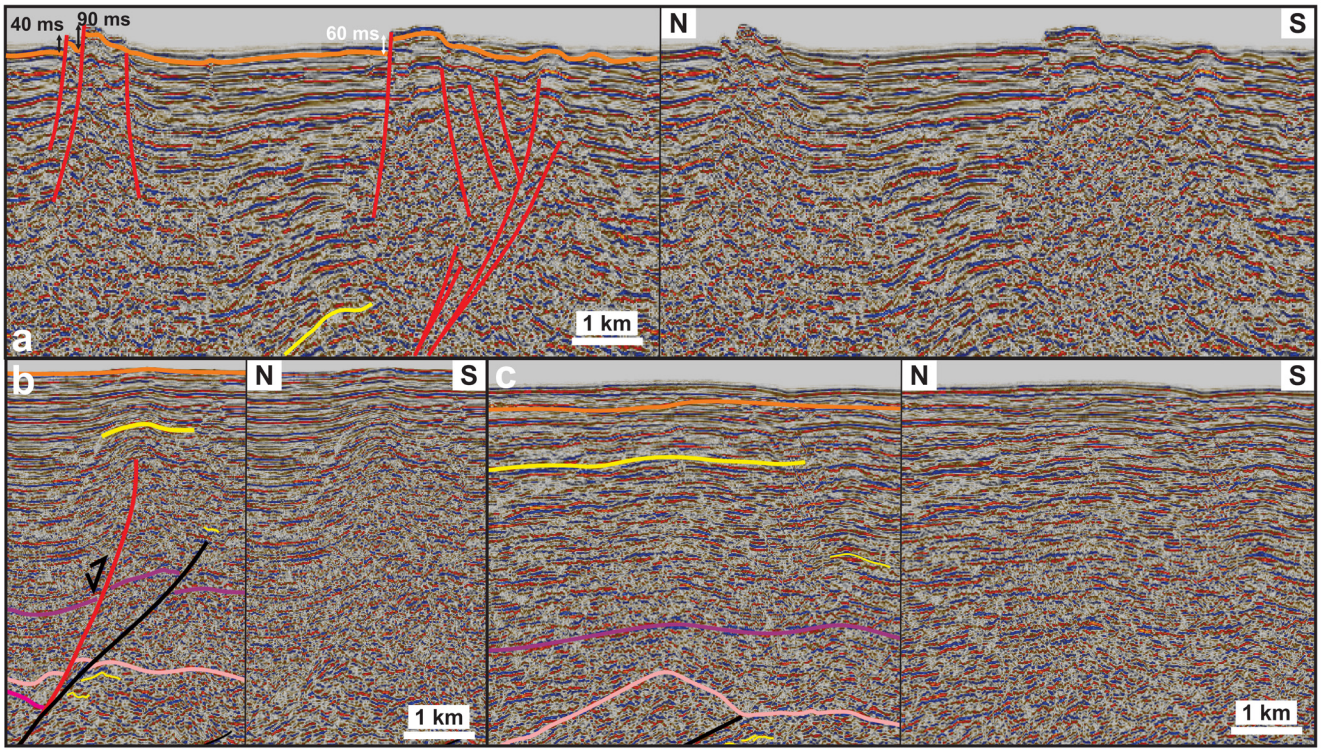

Figure 3. Interpreted and uninterpreted zoomed-in portions of the seismic profile (shown in Figure 2). (**a**) Series of normal offsets of the seafloor and sub-surface (offset orange line) along recent, high-angle, brittle overprints (red lines) of the Bellsundbanken fault zone. (**b**) Gentle, probably early Cenozoic folding of the seafloor and shallow sedimentary strata (yellow line) over and around a blind, high-angle, brittle, Devonian–Carboniferous (?) overprint (red line) of the Kongsfjorden–Cowanodden fault zone (black line). (**c**) Gentle early Cenozoic (?) folding of the seafloor and sub-surface (yellow, orange, and purple lines) above the northern portion of the Kinnhøgda–Daudbjørnpynten fault zone (black line). The yellow, orange, purple and pink lines in (**a**–**c**) respectively corresponds to bedding surfaces, the base of the Mesozoic sedimentary succession, the base of the Devonian–Permian sedimentary succession, and the top of the Proterozoic basement.

Petrel 2021.3. An open-access alternative to Petrel is OpendTect. We build on previous work by Koehl *et al.* (2022a). The seismic reflection database is shown in Koehl *et al.* (2022a their figure 1b). The figures were designed with CorelDraw 2017. An open-access alternative is GIMP.

To tie recent earthquakes to specific structures and slip surfaces on the interpreted regional seismic transects, we time-converted the earthquake hypocentral depths using seismic velocities from Gernigon *et al.* (2018). An uncertainty to the time conversion process is the possible spatial variation of the density of and, thus, seismic velocities in metamorphosed basement rocks. Previous studies have shown that the most impactful factor on seismic velocities is the composition of the metamorphosed rocks (mafic versus felsic; Gorbatsevich, 2014; Schön, 2011). Overall, seismic velocities in mafic metamorphic rocks are about 1 km.s^{-1} faster (c. 7 km.s^{-1}) than in felsic metamorphic rocks (c. 6 km.s^{-1}; e.g., Gorbatsevich, 2014). Using a 7.0 km.s^{-1} velocity for basement rocks (instead of 6.15 km.s^{-1} from Gernigon *et al.*, 2018) would result in slightly shallower hypocenters (c. 0.01–0.1 second TWT for the shallower hypocenters and up to 0.5 second TWT for the deepest M_w 5.2 2016 hypocenter in northernmost Storfjorden; Figure 1b). Nevertheless, the study area is well within continental crust, and since continental crust is dominated by felsic rocks, the potential variations generated by local occurrences of mafic rocks are believed to be negligible (< 0.1 second TWT) and would thus not impact the model proposed.

Another uncertainty is the earthquake hypocentral depths. Assuming a two sigma-one error, hypocenter depths may vary up to 1 km (in the case of the M_w 5.2 2016 earthquake in northernmost Storfjorden), i.e., ≤ 0.3 second (TWT), i.e., not significant enough to impact the model proposed.

Results

Seismic interpretation

Interpretation of seismic reflection data in Storfjorden shows multiple, ≤ 1 second (TWT) deep brittle faults bounding grabens and horsts on a NNE–SSW-trending seismic section. The faults offset the seafloor by 30–90 milliseconds (TWT), i.e., c. 22–66 meters (Table 1). The clear seismic imaging of these faults on the NNE–SSW-trending seismic section (Figure 2 and Figure 3a) suggests that they strike (sub-) orthogonal to the seismic section, i.e., approximately WNW–ESE.

Initially these faults were interpreted as reverse faults (Koehl *et al.*, 2022a). This error was due to the hard-linked connection of

Table 1. Depth conversion of seafloor offset across the small normal faults in Storfjorden. See Figure 1b for location of the faults.

	Length (in s TWT)	Length (in m)
Minimum offset	0.03	0
Maximum offset	0.09	0
Velocity from Gernigon *et al.*, 2018 (in m.s-1)	1470	

some of the faults with an underlying Devonian–Carboniferous high-angle normal fault, which overprints the Bellsundbanken fault zone. The Devonian–Carboniferous high-angle normal fault was inverted during early Cenozoic Eurekan contraction. Early Cenozoic contractional reactivation is suggested by folding of shallow late Paleozoic–Mesozoic strata there (Figure 3a) and above the tip of Devonian–Carboniferous overprints of other Timanian thrust systems (Figure 3b–c). This contractional episode is clearly distinct from the brittle normal faults truncating the seafloor.

Time-conversion of earthquake hypocentral depths

In order to display the recent earthquakes and correlate them with major structures on seismic reflection data in Storfjorden, we converted the depth obtained for these events into time depth (TWT) using seismic velocities from Gernigon *et al.* (2018) and seismic rock units from Koehl *et al.* (2022a). For more detail on the interpretation of the rock units and ties to nearby wellbores, see Koehl *et al.* (2022a) and related supplements.

To time-convert the hypocentral depths, we calculated the thickness and cumulated depth in meters of the water column and of the rock layers from Koehl *et al.* (2022a) with finite thickness, i.e., Mesozoic, upper Paleozoic, and lower Paleozoic rock successions (Figure 2; fifth and sixth columns in upper sub-tables in Table 2). We then calculated the thickness (in meters) of Precambrian basement rocks required to reach the depth of the hypocenters obtained from the International Seismological Centre database (second column in lower sub-tables in Table 2). We time-converted that thickness (third column in lower sub-tables in Table 2) and added it to the thickness of overlying rock units with finite thickness to obtain the time depth of the earthquake hypocenter on the seismic section (Figure 2). Finally, we projected the earthquake locations on the seismic section along a WNW–ESE-trending axis, i.e., parallel to major Timanian thrust systems in the area to see if these structures could be responsible for the studied earthquakes.

After time conversion and projection on the seismic reflection data, the main event (M_w 6.1) of the 2008–2016 Storfjorden seismic sequence and the 2010 aftershock with the highest magnitude (M_w 4.9) correlate with a major, c. 60 km wide, gently NNE-dipping, mylonitic thrust surface at a depth of 5.0–5.1 seconds TWT, i.e., in the deeper half of the Kinnhøgda–Daudbjørnpynten fault zone (Figure 2). There, the fault zone consists of folded (yellow lines) and imbricated, probably metamorphosed rock units and two major fault surfaces that die out below 4.0–4.5 seconds (TWT; Figure 2). Three 2010 aftershocks with M_w 4.0–4.4 of the Storfjorden seismic sequence occurred in the shallow portion of the fault zone, just below the boundary of Precambrian rocks with lower Paleozoic rocks at ca. 2.0–2.5 seconds (TWT; Figure 2). There, these events coincide with moderately NNE-dipping fault surfaces of more modest size (up to a few km). At depth, these fault surfaces merge with a major gently NNE-dipping fault surface, which nearly intersects with the 2008 M_w 6.1 main event and 2010 M_w 4.9 aftershock (Figure 2).

Farther north, the 2011 M_w 4.0 event occurred at a depth of 1.8–1.9 seconds (TWT) and correlates with a high-angle brittle overprint of the Bellsundbanken fault zone (red line in Figure 2), near the boundary with overlying lower Paleozoic rocks. The location of this event also corresponds with that of the interpreted small normal faults, which offset the seafloor (Figure 2 and Figure 3a).

Farther north, east of Edgeøya, the 2016 M_w 5.2 event occurred at a depth of 6.7–6.8 seconds (TWT) and correlates either with the lowermost portion of the Kongsfjorden–Cowanodden fault zone or the northward prolongation of a major, gently NNE-dipping fault surface of the Bellsundbanken fault zone (Figure 2). The truncation of the seafloor by small normal faults above the Bellsundbanken fault zone (Figure 3a) suggests the latter to be more likely.

Discussion

Potential source of the Storfjorden seismic sequence and other recent earthquakes in Svalbard

The 2008–2016 Storfjorden seismic sequence (Pirli *et al.*, 2013; Pirli *et al.*, 2021) could have been caused by movement along either a NW–SE-striking, northeast-dipping fault, or a NE–SW-striking, subvertical fault. Pirli *et al.* (2013) attributed the sequence to movements along a postulated NE–SW-striking fault at a depth of c. 15 km. Their interpretation is based on previous studies of mostly low-quality legacy seismic data in adjacent areas (Bergh & Grogan, 2003; Faleide *et al.*, 1984), on a potential "ridge-like" structure inferred from NE–SW-trending (i.e., sub-parallel to the stipulated fault) ocean-bottom-seismometer transects (Breivik *et al.*, 2005; Czuba *et al.*, 2008), and on a presumed gradual southwestwards migration of earthquakes over time (Pirli *et al.*, 2013 their figure 2e–f).

The "ridge-like" structure interpreted by Breivik *et al.* (2005) and Czuba *et al.* (2008) on an ocean-bottom-seismometer transect in Storfjorden is unlikely to be associated with movement along a NE–SW-striking fault. First, the "ridge-like" structure was interpreted on only one ocean-bottom-seismometer transect and, thus, its trend is uncertain. Second, the ocean-bottom-seismometer transect on which it was interpreted trends NE–SW, i.e., parallel to the presumed NE–SW-striking fault inferred by Faleide *et al.* (1984). Such a feature is therefore unlikely to show well on a sub-parallel transect. It is therefore more likely that the "ridge-like" feature instead reflects uplifted

Table 2. Time conversion of earthquake hypocentral depths in Storfjorden for projection on the interpreted seismic data. See Figure 2 for projection of the hypocenters after conversion of their hypocenter's depths into time depth.

Time conversion of the depth of earthquakes in Storfjorden for projection on interpreted seismic reflection data.					
Calculation Mw 6.1 2008 earthquake Storfjorden (main shock of the Storfjorden sequence along the Kinnhøgda-Daudbjørnpynten fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.1	1470	1470	73.5	73.5
Mesozoic (most likely Triassic)	0.25	3600–4550	4075	509.375	582.875
Upper Paleozoic	1.5	5000–5800	5400	4050	4632.875
Lower Paleozoic	0.3	5900–6300	6100	915	5547.875
Proterozoic basement rocks	?	6000–6300	6100		

Depth Mw 6.1 Storfjorden earthquake (m)	Missing thickness of Proterozoic basement rocks (m)	Missing thickness of Proterozoic basement rocks (s TWT)
15000	9452.125	**3.10**
9700	4152.125	**1.36**
20400	14852.125	**4.87**

Calculation Mw 4.0 2011 earthquake Storfjorden (aftershock of the Storfjorden sequence along brittle overprint of the Bellsundbanken fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.1	1470	1470	73.5	73.5
Mesozoic (most likely Triassic)	0.05	3600–4550	4075	101.875	175.375
Upper Paleozoic	1	5000–5800	5400	2700	2875.375
Lower Paleozoic	0.4	5900–6300	6100	1220	4095.375
Proterozoic basement rocks	?	6000–6300	6150		

Depth Mw 4.0 earthquake (m)	Missing thickness of Proterozoic basement rocks (m)	Missing thickness of Proterozoic basement rocks (s TWT)
5000	904.625	**0.29**
7500	3404.625	**1.11**

Calculation Mw 5.2 2016 earthquake Storfjorden (along the Kongsfjorden-Cowanodden fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.1	1470	1470	73.5	73.5
Mesozoic (most likely Triassic)	0	3600–4550	4075	0	73.5

Calculation Mw 5.2 2016 earthquake Storfjorden (along the Kongsfjorden-Cowanodden fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Upper Paleozoic	1.5	5000–5800	5400	4050	4123.5
Lower Paleozoic	0.4	5900–6300	6100	1220	5343.5
Proterozoic basement rocks	?	6000–6300	6150		

Depth Mw 5.2 earthquake (m)	Missing thickness of Proterozoic basement rocks (m)	Missing thickness of Proterozoic basement rocks (s TWT)
20000	14656.5	**4.77**

Calculation Mw 4.9 2010 earthquake Storfjorden (aftershock of the Storfjorden sequence along the Kinnhøgda-Daudbjørnpynten fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.1	1470	1470	73.5	73.5
Mesozoic (most likely Triassic)	0.25	3600–4550	4075	509.375	582.875
Upper Paleozoic	1.5	5000–5800	5400	4050	4632.875
Lower Paleozoic	0.3	5900–6300	6100	915	5547.875
Proterozoic basement rocks	?	6000–6300	6150		

Depth Mw 4.9 earthquake (m)	Missing thickness of Proterozoic basement rocks (m)	Missing thickness of Proterozoic basement rocks (s TWT)
14000	8452.125	**2.75**

Calculation Mw 4.1 & 4.4 2010 southern earthquakes Storfjorden (aftershocks of the Storfjorden sequence along the Kinnhøgda-Daudbjørnpynten fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.2	1470	1470	147	147
Mesozoic (most likely Triassic)	0.2	3600–4550	4075	407.5	554.5
Upper Paleozoic	1.5	5000–5800	5400	4050	4604.5
Lower Paleozoic	?	5900–6300	6100		
Proterozoic basement rocks	?	6000–6300	6150		

Depth Mw 4.1 & 4.4 earthquakes (m)	Missing thickness of lower Paleozoic rocks (m)	Missing thickness of lower Paleozoic rocks (s TWT)
5000	395.5	**0.13**

Calculation Mw 4.0 2010 southern earthquake Storfjorden (aftershock of the Storfjorden sequence along the Kinnhøgda-Daudbjørnpynten fault zone)					
Interval	**Thickness from Koehl *et al.* (in s TWT)**	**Velocity from Gernigon *et al.*, 2018 (in m.s-1)**	**Velocity used**	**Calculated thickness (m)**	**Calculated cumulated depth (m)**
Water	0.2	1470	1470	147	147
Mesozoic (most likely Triassic)	0.2	3600–4550	4075	407.5	554.5
Upper Paleozoic	1.5	5000–5800	5400	4050	4604.5
Lower Paleozoic	0.2	5900–6300	6100	610	5214.5
Proterozoic basement rocks	?	6000–6300	6150		

Depth Mw 4.0 earthquake (m)	**Missing thickness of Proterozoic basement rocks (m)**	**Missing thickness of Proterozoic basement rocks (s TWT)**
6000	785.5	**0.26**

basement rocks along a WNW–ESE-striking fault system. The NNE-dipping thrust systems interpreted by Koehl *et al.* (2022a) strike suborthogonal to the ocean-bottom-seismometer transect of Breivik *et al.* (2005) and Czuba *et al.* (2008). Moreover, the "ridge-like" structure coincides with the trace of the Bellsundbanken fault zone, which uplifted relatively dense Precambrian basement rocks at this location (Figure 2).

Based on structural interpretation of seismic and potential field data in the area, another possibility is that the "ridge-like" feature in Breivik *et al.* (2005) and Czuba *et al.* (2008) reflects N–S-trending structural fabric of the Caledonian Orogeny and/or of a N–S-striking fault zones, such as the Billefjorden and Lomfjorden fault zones (Figure 1b). This is supported by narrow, N–S- to NNE–SSW-trending positive magnetic anomalies in Storfjorden (see Koehl *et al.*, 2022a their fig. 5), which merge with anomalies related to Caledonian structural fabrics in northern Spitsbergen (e.g., Atomfjella Antiform; Witt-Nilsson *et al.*, 1998) and Nordaustlandet (e.g., Rijpdalen Anticline; Dumais & Brönner, 2020; Figure 1b). However, no focal mechanisms suggest any relationship to N–S-striking structures (Junek *et al.*, 2014; Junek *et al.*, 2015; Pirli *et al.*, 2010; Pirli *et al.*, 2013; Pirli *et al.*, 2021; Figure 1b).

In addition, the relatively shallow character of the Billefjorden and Lomfjorden fault zones, i.e., mostly surficial or near the surface down to c. 2.2–2.3 km depth at Reindalspasset (Bælum & Braathen, 2012; Koehl, 2021a; Koehl *et al.*, 2024) suggest that they cannot be responsible for the earthquakes, which all occurred at ≥ 5 km depth. Moreover, new constraints on their size from recent studies (hundreds of meters to a kilometer in width, tens of kilometers length) and timing of formation (respectively early Cenozoic and early–mid Paleozoic; Koehl & Allaart, 2021; Koehl *et al.*, 2024) suggest that the Billefjorden and Lomfjorden fault zones are significantly smaller (by one to two orders of magnitudes) and younger than the tens of km wide, hundreds-to-thousands of km long, crustal-scale, late Neoproterozoic Timanian thrust systems in Svalbard and the northern Barents Sea (Koehl *et al.*, 2022a; Figure 1a–b and Figure 2). Furthermore, new evidence suggest that the Agardhfjellet segment of the Lomfjorden Fault Zone was controlled by a Timanian thrust (Kongsfjorden–Cowanodden fault zone; Koehl *et al.*, 2022a). Thus, the Billefjorden and Lomfjorden fault zones are unlikely to be potential sources for the Storfjorden seismic sequence and other recent earthquakes in Svalbard.

The compilation of nodal planes extracted from the focal mechanisms associated with the earthquakes around Spitsbergen (International Seismological Centre, 2024 http://www.isc.ac.uk/iscbulletin/search/fmechanisms) shows that 75% (18 of 24) of all nodal planes strike NW–SE to E–W (see stereonet in Figure 1b) and that all the double-couple focal mechanisms involve at least one NW–SE to E–W nodal plane, i.e., parallel to Timanian thrust systems. This implies that all the earthquake focal mechanisms are consistent with movement along NW–SE- to E–W-striking Timanian faults. In contrast, only 50–60% involve a NE–SW-striking plane. In addition, interpretation of NW–SE-trending seismic reflection transects clearly indicates that there is no NE–SW-striking fault in the area. Note that the nodal planes plotted in the stereonet in Figure 1b do not include those of the Heer Land earthquake sequence, which is associated with a sub-vertical WNW–ESE-striking fault surface (c. 110°; see Mitchell *et al.*, 1979; Mitchell *et al.*, 1990). Therefore, at least half of all the recent $M_w \geq 4.0$ earthquakes around Svalbard between latitude 76–80° and longitude 10–30° are likely related to movement along WNW–ESE-striking faults.

Recent mapping of tectonic structures with high-resolution seismic data and potential field (magnetic and gravimetric) data by Koehl *et al.* (2022a) indicates that the main structures and fabrics at depth in Storfjorden strike WNW–ESE to NW–SE

(Figure 1a–b and Figure 2). These structures crosscut tightly folded and metamorphosed Precambrian basement rocks and form part of gently NNE-dipping, mylonitic thrust systems and related high-angle overprints (Koehl *et al.*, 2022a; Figure 2). While these thrust systems are located at great depth in Storfjorden (Figure 2), E–W-oriented Caledonian and Eurekan contraction contributed to exhume them in western Spitsbergen, where they yield late Neoproterozoic to earliest Cambrian U–Pb ages (Faehnrich *et al.*, 2020; Koehl & Mottram, 2024; Figure 1b), which indicate formation during the Timanian Orogeny. These thrust systems, especially the Kinnhøgda–Daudbjørnpynten, Bellsundbanken, and Kongsfjorden–Cowanodden fault zones, were then reactivated and/or overprinted during the Caledonian Orogeny, Devonian–Carboniferous extension, and early Cenozoic Eurekan event (e.g., Faehnrich *et al.*, 2020; Koehl *et al.*, 2022a; Ziemniak *et al.*, 2022). Notably, gentle folding of shallow late Paleozoic–Mesozoic rock successions in Storfjorden suggest that both the Kongsfjorden–Cowanodden, Bellsundbanken, and Kinnhøgda–Daudbjørnpynten fault zones were mildly reactivated during the early Cenozoic Eurekan event (Figure 2 and Figure 3a–c). This suggests that Timanian fault zones are prone to reactivation and are likely sources for recent earthquakes around Svalbard.

The present study shows several normal offsets of the seafloor reflection across WNW–ESE-striking brittle faults (Figure 2 and Figure 3a). Some of these small faults merge at depth with a gently NNE-dipping Timanian thrust system, the Bellsundbanken fault zone (black lines in Figure 2), and its high-angle overprints (red lines in Figure 2 and Figure 3a). This connection (in some cases hard linked) suggests ongoing inversion (i.e., with normal motion) of the Timanian thrust systems in Storfjorden. The time-conversion of the earthquake hypocentral depths in the present study (Table 2) shows that each of the major $M_w \geq 4.0$ events can be correlated to a discrete WNW–ESE-striking fault surface at depth (Figure 2). In addition, the 1977–1981, 3–5 km deep, Heer Land seismic sequence and the 2011, 5 km deep, M_w 4.0 event align along the trace of the Bellsundbanken fault zone and display consistent sinistral to normal-sinistral kinematics according to the focal mechanisms (Figure 1b; Mitchell *et al.*, 1979; Mitchell *et al.*, 1990; Pirli *et al.*, 2010; Pirli *et al.*, 2013). We therefore propose that the Storfjorden seismic sequence and most (if not all) the recent earthquakes around Svalbard were caused by reactivation of inherited NNE-dipping Timanian thrust systems and related overprints.

A feature of interest is the mild deviations from the main WNW–ESE Timanian trend of the strike of local fault surfaces suggested by the focal mechanisms (Figure 1b). The focal mechanisms suggest fault striking E–W to NW–SE (Junek *et al.*, 2014; Junek *et al.*, 2015; Pirli *et al.*, 2010; Pirli *et al.*, 2013; Pirli *et al.*, 2021; Figure 1b). Although Timanian thrust systems strike overall WNW–ESE, they are notably known to have been folded during subsequent oblique Caledonian and Eurekan contraction. Thus, they locally display NW–SE- and E–W-striking geometries (Koehl *et al.*, 2022a; Koehl *et al.*, 2023b; Koehl & Stokmo, 2024), which accounts for the observed mild fault strike variations obtained from the focal mechanisms.

The strong impact of Timanian structures on the structural development of Svalbard and on present-day tectonics is further illustrated by ongoing deformation and seismicity along the Timanian thrust front onshore northern Norway and the Kola Peninsula in northwestern Russia, the Trollfjorden–Komagelva Fault Zone (see location in Figure 1a; Gurevich *et al.*, 1972; Karpuz *et al.*, 1994; Roberts *et al.*, 1997).

Implications for linear earthquake swarms

Earthquakes of the Storfjorden seismic sequence migrated to the southwest between 2008 and 2012 (Pirli *et al.*, 2013). The migration was initially described as progressive and interpreted to indicate movement along a presumed NE–SW-striking fault (Pirli *et al.*, 2013). However, since the migration occurred exclusively between two and three years after the main event (Pirli *et al.*, 2013 their figure 2e–f), it is equally possible to describe it as abrupt and to separate the sequence into two clusters (northeastern and southwestern; see lower left inset in Figure 1b).

After time conversion (Table 2), the main events ($Mw \geq 4.0$) of the two clusters coincide with discrete fault surfaces of the 60 km wide, NNE-dipping Kinnhøgda–Daudbjørnpynten fault zone at depth (Figure 1b and Figure 2). The main 2008 event and the 2010 M_w 4.9 aftershock (northeastern cluster) occurred at a 15.1 ± 5.4 km depth in the direct vicinity of two fault surfaces tens of km wide, which die out upwards below depths of 4.0–4.5 seconds, i.e., blind faults (TWT; Figure 2 and Figure 4a–b). By contrast, the southwestern cluster of $M_w \geq 4.0$ aftershocks occurred at much shallower depth (5–6 km) near moderately to gently NNE-dipping, all of which merge with one another downwards and can be traced at depth as a major ≥ 30 km wide gently dipping fault surface that extends 0.2–0.5 second (TWT) away from the location of the main two events of the northeastern cluster (Figure 2 and Figure 4b).

Based on these spatiotemporal relationships, we propose that normal-sinistral movements related to regional tectonics occurred along a 14–15 km deep (i.e., ca. 5.0–5.5 seconds TWT), gently NNE-dipping, blind fault surface and triggered the main earthquake of the Storfjorden seismic sequence in 2008 (Figure 4a). These movements are believed to have created local instabilities along a nearby, NNE-dipping, shallower fault surface. Upwards propagation of the instabilities along the fault surface, i.e., towards the southwest, triggered the 2010 aftershocks of the southwestern cluster (Figure 4b). In this model, the migration of seismic events occurs abruptly when rupture occurs along a second nearby fault surface at shallower depth. This model is supported by the kinematics of the focal mechanisms of the aftershocks in the southwestern cluster, which suggest normal and normal-sinistral movements, i.e., in line with the regional kinematics along the main fault at depth (normal-sinistral) and with local shallow collapse processes in response to deep instabilities (normal; Figure 1b).

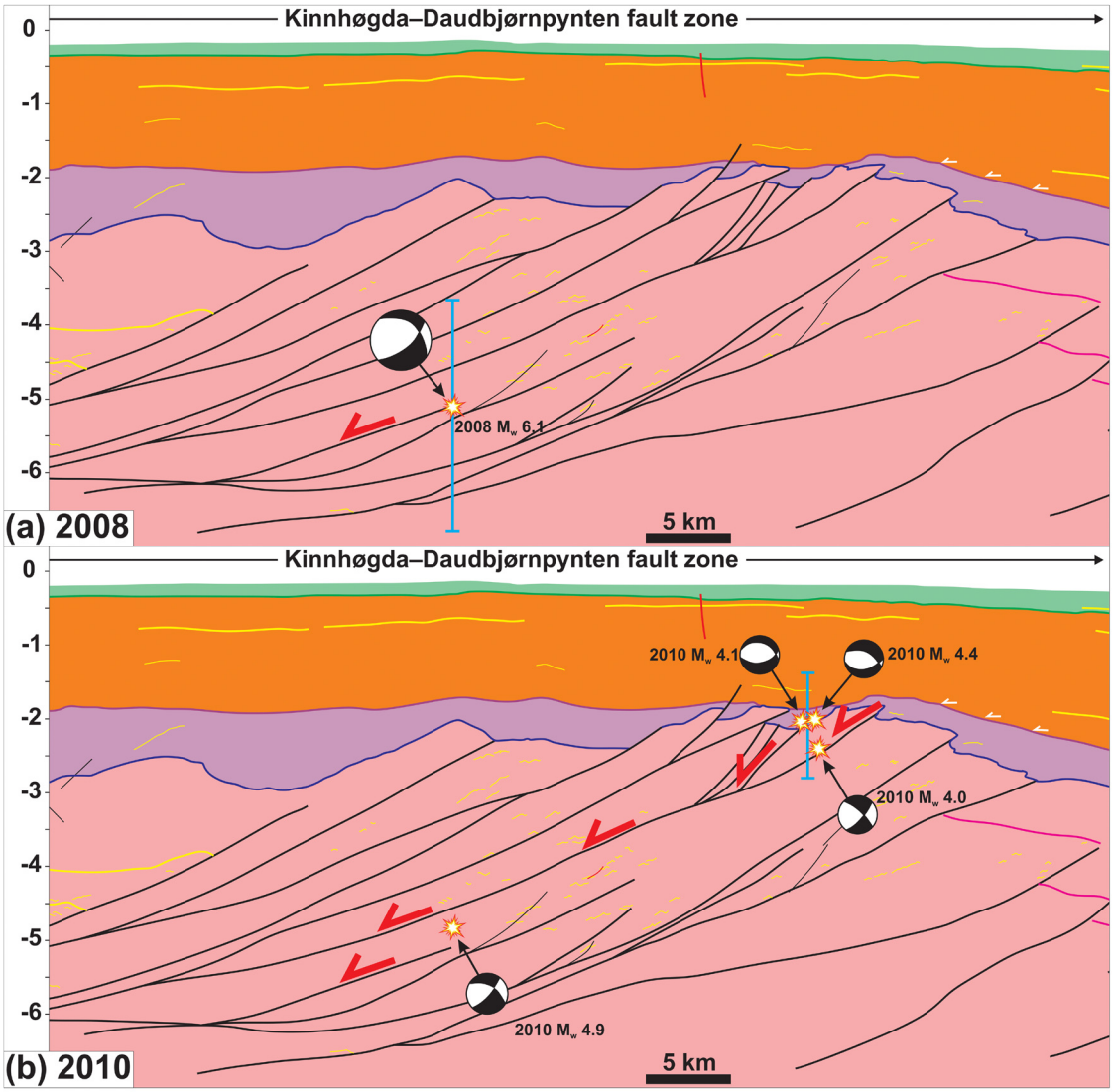

Figure 4. Zoom in the Kinnhøgda–Daudbjørnpynten fault zone. The figure shows a scenario that explains the abrupt southward migration of earthquakes of the Storfjorden sequence from 2008 to 2010 involving reactivation of two discrete thrust fault surfaces within the fault zone (see red half arrows). See Figure 2 for location of the profile. (**a**) In 2008, a deep, shallow dipping thrust surface was reactivated. (**b**) In 2010, a shallower thrust fault surface was reactivated, possibly due to continued movement along the deep thrust fault surface that triggered the 2008 earthquake. The blue error bars in (**a**–**b**) represent the uncertainty associated with hypocenter's depth.

Regardless of the associated error, the depth of the southwestern cluster is unlikely to be less than 5 km because no fault is seen in post-Caledonian sedimentary strata in the area (Figure 2 and Figure 4a–b). Even if a 50% error is assumed, the depth of the southwestern cluster (5–7.5 km) would still be significantly shallower than that of the northeastern cluster (9.7–20.4 km; blue error bars in Figure 4a–b). In addition, the southwestern cluster would still likely be triggered by the same fault surface due to the relatively low uncertainty and absence of faults in post-Caledonian sedimentary rocks (Figure 4b). Thus, the model proposed for the southwestward migration of earthquakes over time would still be consistent with the hypocenters being deeper.

The proposed model has implications for the source of linear earthquake swarms worldwide and suggests that these may be triggered by reactivation and/or overprinting of inherited, crustal-scale, brittle–ductile thrust systems. Other earthquake swarms with similar characteristics have been reported, for example, in northern Norway and along the San Andreas fault.

In northern Norway, Igland (2016) identified a NW–SE-striking linear earthquake swarm. Based on focal mechanisms indicating mostly normal movements, and gradual migration towards the southeast and the surface, he suggested that the earthquake swarm was generated by normal movements along a northwest-dipping fault. This fault geometry is typical of

Caledonian thrust systems and their extensional overprints in the area (Péron-Pinvidic & Osmundsen, 2020; Roberts, 2003). It is therefore possible that there too, deep thrust systems are responsible for recent seismicity.

In southern California, several such linear earthquake swarms have been recorded at the southern termination of the San Andreas fault (Hauksson *et al.*, 2017; Hauksson *et al.*, 2022). There, the San Andreas fault terminates and steps as the Imperial fault across the Brawley seismic zone. A notable feature of interest is the 2005 M_w 5.1 Obsidian Butte Sequence, which occurred as a NE–SW-striking swarm of earthquakes aligning along a gently northeast-dipping plane. Similarly to the Storfjorden seismic sequence, events of the Obsidian Butte Sequence occurred initially at deeper crustal level (i.e., to the northeast) and migrated upwards and to the southeast over time (Hauksson *et al.*, 2022 their figure 12a). Extensive studies of the San Andreas fault have suggested that it is related to gently northeast-dipping faults at a few km depth (e.g., Fuis *et al.*, 2017 their figure 6; Janecke *et al.*, 2018 their figure 15). Given the recently identified global correlation of major transform faults with preexisting orogens (Koehl & Foulger, 2024), the formation of the San Andreas fault and thus ongoing seismicity along this major transform plate boundary may be controlled by preexisting thrust systems in local orogens, e.g., Nevadan Orogen (Bateman, 1968; Garlick *et al.*, 2009; Schweickert *et al.*, 1984).

Driving mechanism of present-day tectonics

Recent studies have stressed the impact of unloading and ensuing isostatic rebound on recent tectonic movements along the western Svalbard–Barents Sea margin (Cooke *et al.*, 2023; Pedrosa-Gonzalez *et al.*, 2024; Plaza-Faverola & Keiding, 2019). Pedrosa-Gonzalez *et al.* (2024) notably suggested that recent reverse faulting south of Spitsbergen is related to postglacial rebound. While this is possible in their study area where Cenozoic brittle thrusts of the West Spitsbergen Fold-and-Thrust Belt occur at shallow levels (e.g., Bergh & Grogan, 2003), the structural setting in Storfjorden is different. There, all the recent earthquakes show focal mechanisms indicating normal, normal–sinistral, or sinistral strike-slip (Junek *et al.*, 2014; Junek *et al.*, 2015; Mitchell *et al.*, 1979; Mitchell *et al.*, 1990; Pirli *et al.*, 2010; Pirli *et al.*, 2013; Pirli *et al.*, 2021; Figure 1b). While the normal component (uplift of the horst blocks) may be (partly?) ascribed to postglacial rebound, the sinistral strike-slip component cannot (e.g., Wu *et al.*, 1999).

The sinistral strike-slip component of movement along WNW–ESE-striking faults (e.g., in Heer Land and west of Edgeøya; Mitchell *et al.*, 1979; Mitchell *et al.*, 1990; Pirli *et al.*, 2013; Figure 1b) matches the present-day kinematics at the southeastern tips of the Molloy and Spitsbergen fault zones in the Fram Strait (Figure 1b and Figure 5a–b). Recent studies indicate that the Kongsfjorden–Cowanodden and Kinnhøgda–Daudbjørnpynten fault zones extend past the De Geer Zone into the Fram Strait (Koehl, 2024; Koehl & Mottram, 2024). It is therefore plausible that they transfer sinistral transform movements in the Fram Strait as sinistral strike-slip movements in Storfjorden. Thus, a probable driving mechanism for most of the recent normal and sinistral strike-slip faulting and seismicity in Svalbard is transtension related to transform faulting (Figure 5a–b). This is supported by the 32.9 ± 9.9 Ma (earliest Oligocene) U–Pb age obtained for syn-kinematic carbonates along a reactivated Timanian thrust with sinistral–normal kinematics in western Spitsbergen (Koehl & Mottram, 2024; Figure 5a), i.e., well before post-glacial rebound. In this scenario, WNW–ESE-oriented extension in the Fram Strait is accommodated through sinistral–normal movements along inherited Timanian thrusts, which localized the formation of core complexes in the Fram Strait (Figure 5a) and, later on, of transform faults (Koehl *et al.*, 2021; Figure 5b). Thus, post-glacial rebound may have only minor influence on seismicity in Storfjorden.

Ridge push in the Fram Strait may have had a limited impact on seismicity in Svalbard. Ridge-push is thought to be responsible for recent earthquakes (1989–1996) on reverse faults in northern Norway (Bungum & Lindholm, 1997; Roberts *et al.*, 1997) and is also a potential driving mechanism for the observed seismicity around Spitsbergen (e.g., recent east-dipping thrust fault south of Spitsbergen; Pedrosa-Gonzalez *et al.*, 2024).

Since no recent earthquakes have been recorded in central and western Spitsbergen, strain along the western portion of Timanian thrust systems may be accommodated aseismically (e.g., via plastic deformation or lubricated fault surfaces). A possible hypothesis to be tested is lubrication of slip surfaces along Timanian thrust systems in western and central Spitsbergen facilitated by their proximity to surface water (Koehl, 2024; Koehl & Mottram, 2024; Koehl *et al.*, 2022a; Mazur *et al.*, 2009).

Another possibility is that the lack of earthquakes in central and western Spitsbergen is related to the presence of a thick sedimentary basin in this area in the form of a major Caledonian–Eurekan syncline. While competent metamorphosed Precambrian basement rocks are found at relatively shallow crustal levels in Storfjorden, the syncline in central Spitsbergen includes several kilometers of heterogeneous, relatively weak (compared to metamorphic basement rocks) upper Paleozoic, Mesozoic, and Cenozoic sedimentary successions (e.g., Central Tertiary Basin; Blinova *et al.*, 2013; Steel *et al.*, 1981; Figure 1b). The relatively weak character of these sedimentary successions is at least partly due to the dominance of weak rock types within the syncline. For example, the ≤ 8–10 km thick Lower Devonian to lowermost Upper Devonian succession is dominated by weak shales (Friend, 1961; Friend *et al.*, 1997; Murascov & Mokin, 1979), and uppermost Devonian–Mississippian (Aakvik, 1981; Cutbill & Challinor, 1965; Cutbill *et al.*, 1976; Gjelberg, 1984), Pennsylvanian–Permian (Harland *et al.*, 1988; Lønøy, 1995; Pickard *et al.*, 1996; Ringset & Andresen, 1988; Samuelsberg & Pickard, 1999), Triassic (Worsley & Mørk, 1978), and lower Cenozoic successions (Livshits, 1965; Livshits, 1974; Livshits, 1992; Steel *et al.*, 1981) in central and western Spitsbergen involve large amounts of coals, shales, and evaporites. Weak rock types are more prone to folding and (shale) smearing during deformation (i.e., plastic deformation), especially at shallow crustal levels. A key example is the San Andreas fault in California, along which strongly folded shale-rich sedimentary strata crop out (Bergh *et al.*, 2019; Janecke *et al.*, 2018; Koehl *et al.*, 2022b; Miller, 1998). The weakness of sedimentary strata permits them to accumulate significant amounts of shortening prior to rupture. Thus, the thick weak sedimentary deposits

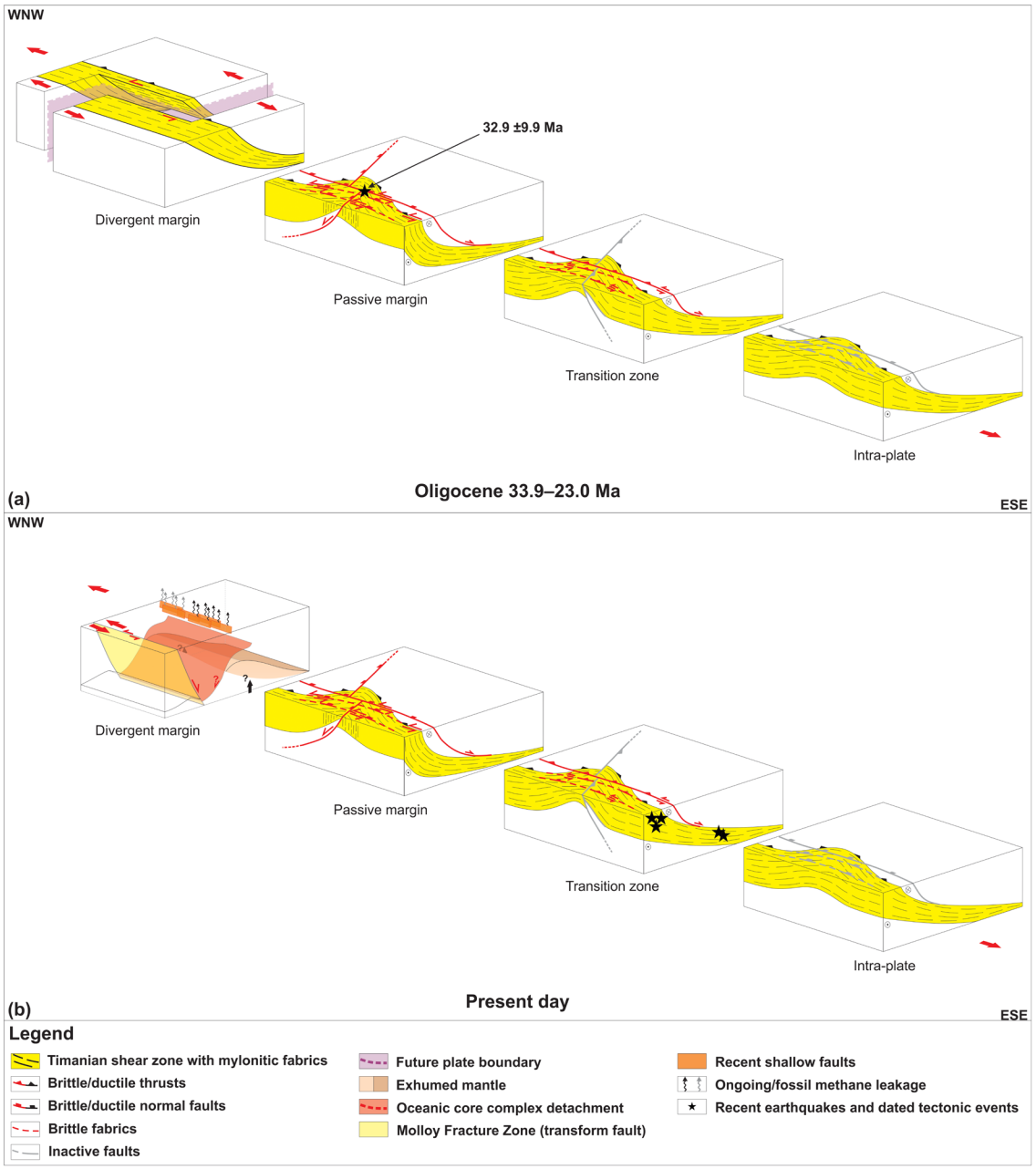

Figure 5. Schematic model of the breakup of the Fram Strait. (**a**) Breakup is hindered by the Timanian Orogen. Timanian thrust systems control the breakup and localize the formation of margin-oblique core complexes and related detachments near the future plate boundary and normal–sinistral strike-slip faulting occurs along Timanian thrusts in adjacent areas (e.g., 32.9 ±9.9 Ma U–Pb on synkinematic carbonate from Koehl & Mottram, 2024). (**b**) Transform faults form along major Timanian thrusts and take margin-oblique core complexes are only mildly active or inactive. Continued normal–sinistral strike-slip movements occur along inherited Timanian thrust systems in nearby areas (e.g., recent earthquakes in transition zone). Modified after Koehl *et al.* (2021; 2022a).

in the Central Tertiary Basin may partly explain the absence of recent earthquakes in central Spitsbergen.

Intra-plate seismicity occurring off the active transform fault segment also occurs in connection to other major transform faults. For example, the Davie fault zone, offshore the Mozambique Basin, is associated with many recent earthquakes with focal mechanisms suggesting normal and sinistral strike-slip movements along N–S-striking fault surfaces (Bertil *et al.*, 2021). These kinematics might be explained by residual extension at the Somali Basin fossil mid-ocean ridge. However, since rifting there ceased at ca. 121 Ma (Davis *et al.*, 2016), this is unlikely. A more probable driving mechanism is ongoing rifting and seafloor spreading at the South-West Indian Ridge and related sinistral transform faulting at the Andrew Bain Fault Zone (Peyve *et al.*, 2007; Sclater *et al.*, 2005). Similarly to the Storfjorden

area in Svalbard, the Davie fault zone parallels thrust structures of the East African Orogen (Armistead, 2019; Boger *et al.*, 2015; Collins *et al.*, 2000; Collins *et al.*, 2012; De Waele *et al.*, 2011; Key *et al.*, 1989; Mosley, 1993; Shackleton, 1996; Stern & Kröner, 1993), and possibly formed along such structures (Koehl & Foulger, 2024) as suggested from contractional structures parallel to the Davie fault zone on seismic reflection data (Klimke *et al.*, 2018 their figure 6). It is therefore possible that seismicity in the Mozambique Channel occurs along inherited late Neoproterozoic thrusts of the East African Orogen.

Earthquake risk of Timanian thrust systems

Should extension in the Fram Strait persist, it would be natural to expect further movement along inherited, crustal-scale Timanian structures and associated younger overprints in the near future. It is therefore paramount to carefully evaluate their geohazard potential for local communities.

Using the equation of Wells & Coppersmith (1994) for sub-surface rupture, the potential maximum magnitude of an earthquake generated by rupture along the entire length of the Kongsfjorden–Cowanodden fault zone and its Russian continuation, the Baidaratsky Fault Zone (Korago *et al.*, 2004; Lopatin *et al.*, 2001), i.e., total fault length of 2000 km, is c. 8.9 (Table 3). This is similar to major subduction-related fault zones at present, e.g., Sunda Trench, Cascadia subduction zone, Alaska–Aleutian Trench, and Japan Trench (e.g., Atwater *et al.*, 1991; Atwater *et al.*, 2015; Hubbard *et al.*, 2015). This a lower estimate considering that (1) the equation of Wells & Coppersmith (1994) generally yields lower magnitudes than modern datasets suggest (e.g., Stirling *et al.*, 1998) and (2) the Kongsfjorden–Cowanodden fault zone may extend farther southeast in Russia (Korago *et al.*, 2004; Lopatin *et al.*, 2001) and possibly farther offshore in the Fram Strait (e.g., Koehl *et al.*, 2021).

Similarly, rupture along the 430 km-long Kinnhøgda–Daudbjørnpynten fault zone may generate earthquakes with magnitudes up to 8.1 (Table 3). This is also a minimum magnitude estimate for the same reasons as the Kongsfjorden–Cowanodden fault zone. Further structural mapping on seismic reflection data is needed in the central Barents Sea to better constrain the length (especially southeastward extent) of this major thrust system.

Besides having been reactivated/overprinted in Svalbard recently, it is probable that movements along the Baidaratsky Fault Zone (continuation of Kongsfjorden–Cowanodden fault zone in Russia; Figure 1a) were responsible for aftershocks of earthquakes triggered by nuclear tests in southern Novaya Zemlya in 1973 (Khalturin *et al.*, 2005). In total, 47 events with $M_w \geq 2.0$ occurred as two WNW–ESE-trending clusters in southern and central Novaya Zemlya between 1970 and 2020 (see lower right inset in Figure 1a), most of them prior to 1990, some of which probably linked to nuclear explosions (Khalturin *et al.*, 2005). A potential hypothesis to be tested for the northern cluster is that they may be related to movements along the southeastward continuation of the Steiløya–Krylen fault zone of Koehl *et al.* (2022a; Figure 1a). Unfortunately, no focal mechanisms are available for these events, and a depth of c. 10 km was obtained for 14 of them (International Seismological Centre, 2024). Such a depth is compatible with an origin along Timanian thrust systems (Koehl *et al.*, 2022a). The event with the highest magnitude (M_w 6.9) records the underground nuclear explosion on October 27th 1973 (see lower right inset in Figure 1a). Using the empirical relationship of Wells & Coppersmith (1994), such a magnitude suggests that a c. 35–40 km long portion of the Baidaratsky Fault Zone could have ruptured (Table 4).

The current tectonic setting in Svalbard and Novaya Zemlya does not involve subduction or large-scale (San-Andreas type) transpression and is therefore not prone to generating large-magnitude earthquakes. Nevertheless, the occurrence of seismic events at both ends of the Timanian fault systems, especially the Kongsfjorden–Cowanodden fault zone and its continuation in Russia, the Baidaratsky Fault Zone, suggest that they are prone to reactivation and seismicity. Thus, future studies should focus on qualitatively assessing the risk these hundreds to thousands km long fault systems pose to local communities.

Table 3. Maximum earthquake magnitude along the studied faults using the equation of Wells and Coppersmith (1994). The faults include the Kongsfjorden–Cowanodden fault zone (KCFZ) and Kinnhøgda–Daudbjørnpynten fault zone (KDFZ). Abbreviations: KCFZ: Kongsfjorden–Cowanodden fault zone; KDFZ: Kinnhøgda–Daudbjørnpynten fault zone.

Maximum earthquake magnitude	
Fault length KCFZ (in km)	2000
Max Mw KCFZ (Wells & Coppersmith, 1994)	8.91
Fault length KCFZ (in km)	430
Max Mw KDFZ (Wells & Coppersmith, 1994)	8.13

Table 4. Minimum and maximum length of the subsurface rupture in southern Novaya Zemlya. Fault rupture followed the October 27th 1973 nuclear test. The subsurface rupture length was calculated using the equation of Wells and Coppersmith (1994). Abbreviations; BF. Baidaratsky Fault Zone.

Subsurface rupture length BF 27.10.1973	
Minimum subsurface rupture length BF	35
Minimum magnitude 27.10.1973 earthquake	6.87
Maximum subsurface rupture length BF	40
Maximum magnitude 27.10.1973 earthquake	6.94

Conclusions

1) Normal brittle offsets of the seafloor in Storfjorden suggest that most recent earthquakes in the Svalbard Archipelago and northern Barents Sea (e.g., Storfjorden seismic sequence) are related to inversion and overprinting of inherited, dominantly NNE-dipping Timanian thrust systems and related, shallow, Devonian–Carboniferous brittle overprints.

2) Correlation of discrete earthquakes of the Storfjorden with specific structures in the sub-surface on seismic reflection data shows that the migration in depth, time, and space of seismicity in linear earthquake swarms can be ascribed to reactivation of crustal-scale thrust systems through upwards propagation of instabilities along fault surfaces and ensuing collapse.

3) Recent–ongoing deformation in central and western Spitsbergen is likely accommodated aseismically by plastic deformation due to the abundance of weak rock types within the several kilometers thick sedimentary successions preserved in the Caledonian–Eurekan syncline (Central Tertiary Basin) and accommodated seismically in eastern Spitsbergen and Storfjorden where competent Proterozoic basement rocks are found at shallower levels.

4) A potential driver for recent earthquake sequences along inherited Timanian thrust systems and associated shallow brittle overprints is sinistral strike-slip transform faulting along the Molloy and Spitsbergen fracture zones in the Fram Strait and/or ridge-push along the mid-ocean ridge.

5) The thousands-of-km extent of Timanian thrust systems suggests that they may accommodate earthquakes with magnitudes up to 8.9 and their repeated reactivation/overprinting in the past 450 Myr and recent occurrences of seismic events at both ends and along discrete fault systems suggest that they are prone to reactivation and seismicity.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Underlying data

The Open Access seismicity data used in the present study are from the International Seismological Centre (2024; https://doi.org/10.31905/D808B830).

The seismic reflection data used in the present study are from the Norwegian National Data Repository for Petroleum Data (DISKOS database). The data can be accessed for research purpose by contacting the Norwegian Offshore Directorate at https://www.sodir.no/om-oss/kontakt-oss/.

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Rita de Nardis
University of Chieti-Pescara, Chieti, Italy

Review of the manuscript: *"Recent earthquakes in Svalbard sourced from transform-parallel thrust systems: implications for linear earthquake swarms and earthquake risk"*

Authors: Jean-Baptiste P. Koehl, Jesús Galindo-Zaldivar, María T. Pedrosa-González, Gemma Ercilla, Gillian R. Foulger

The manuscript provides a structural interpretation of seismic reflection data from the Svalbard region and attempts to correlate mapped faults and new interpreted seismic sections with recent seismic activity. The topic is of interest for both the structural geology and seismological communities, especially considering the growing concern regarding seismic hazard in Arctic regions. While the study has potential, it requires **major revisions** before it can be considered for indexing.

General and Technical Comments:

1. Seismicity is treated superficially throughout the manuscript. Although it is part of the title, the seismic swarm activity is only addressed briefly in the latter sections. The manuscript lacks a robust quantitative analysis of the earthquake dataset (e.g., number of events, magnitude range, depth distribution, temporal evolution). The 2008–2016 swarm is mentioned but not clearly localized or described in the figures. The authors should:
    - Specify how many earthquakes compose the swarm.
    - Clearly define the spatial extent and temporal pattern (e.g., recurrence intervals, clustering, possible triggering mechanisms).
    - Justify the use of the term "swarm", possibly using statistical or seismological criteria (e.g., absence of a mainshock, b-value, duration).
    - Discuss possible source processes, whether magmatic, tectonic, or hydrothermal.
2. The method used to convert earthquake depths into two-way travel time is critical for the correlation between structures and earthquake locations. The authors must:
    - Indicate whether this method has precedent in literature, and if not, offer a

transparent description, ideally in the Supplementary Materials.
    - Assess the validity of spatial correlations between seismicity and structures under this conversion using know example in the literature.
3. The association between earthquake hypocenters and mapped structures is not always compelling. A more detailed spatial analysis (e.g., cross-sections with depth, fault-plane solutions if available, clustering analysis) would strengthen the interpretation. A reference such as de Nardis et al., 2022 (Ref 1), where structure–seismicity association is supported by precise spatial and kinematic constraints, could serve as a methodological benchmark.
4. The figures require significant improvement. Fonts are often too small, symbols are unclear, and legends are not always sufficient to interpret the data. Each figure should stand alone in terms of clarity and readability.
5. The text would benefit from extensive revision for clarity. There are several redundant or overly detailed sections that do not contribute directly to the central message. A more concise and focused narrative, particularly in the Introduction and Discussion, would help readers follow the logic of the study. Some terminology should also be clarified, such as "linear swarm".
6. Tables are well-organized and informative.

In conclusion, while the manuscript addresses a topic of considerable interest, it requires substantial technical revisions. The integration between structural and seismic data must be more rigorously developed and supported by clearer illustrations and a more quantitative approach.
An annotated PDF is attached to this review with detailed suggestions throughout the manuscript and figures at the following link
https://openreseurope-files.f1000.com/linked/258846.dd36d566_e1ca_4f81_bc96_3bfcfba4ba37_19399___jean_baptiste_koehl_.pdf

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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?
Yes

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

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

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: Seismotectonics

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, however I have significant reservations, as outlined above.

Reviewer Report 19 June 2025

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Wolfram Geissler
Alfred Wegener Institute Helmholtz-Centre for Polar and Marine Research, Bremerhaven, Germany

The authors present a novel study by integrating seismicity data and seismic reflection data to challenge the present view on the causes of earthquake activity within and around the Svalbard archipelago and its hazard potential. For that, the authors build on recent studies lead by the first author that found evidence for Timanian structures within the crystalline basement underlying the platform sedimentary rocks of the Barents Sea shelf. In my opinion, the present study would have high potential to make a step forward in the understanding of tectonic processes at Svalbard and beyond. However, in its present form, the manuscript cannot be approved from my side. There are many more substantial flaws that should be addressed in a revised version of the manuscript.

1. First of all, the seismic data as presented does not allow to follow the line of argumentation of the authors, the resolution of the images is too low, and also the zoom ins do not show the full structures discussed. More seriously, the fault interpretations made by the authors does sometimes not really fit what I can see in the figures provided. It looks like the interpretations were not done very carefully. In principle I do not doubt the interpretations, but they should be clearly illustrated. For instance, only clear thrusts should be marked by solid lines. Extrapolations or interpolations should be indicated by dashed lines only.

2. Also, the seismicity data underlying the study is not fully documented. Tables with details about the earthquakes or at least supplementary materials are missing. The manuscript actually should focus on this very relevant part to integrate the seismicity data and the seismic reflection data (inherited structures) and discuss the results within the uncertainties of the different methods.

3. The discussion about the relation of earthquake activity to seafloor spreading and transform faulting in the NE Atlantic west of Svalbard is not yet convincing. Especially, it is not clear where there should be sinistral transform faults west of Svalbard. Furthermore, the discussion about the

hazard potential is just heavy arm waving at the moment, since no relevant information is given that the fault structures are really continues without major cross-cutting faults zones (that could be expected). Also, there should be evidence from postglacial tectonic activity within the Barents Sea (are there any expressions at the seafloor?) in that case. Overall, the discussion on the causes of seismicity needs to be more elaborated to convince the readers that not postglacial stresses are the relevant causes of seismic activity within Svalbard. The incorporations of observations from other parts of the world are ok, but you should not open aside discussions on these regions. Just take clear evidence from these regions to support your line of argumentation for the Svalbard case.

4. Overall, the structure of the manuscript is not yet well elaborated, results and discussions are partly mixed. The quality of figures is not yet adequate for indexing, e.g., too small font sizes and symbols are used, coordinates are missing, name and orientations of profiles are missing, labels of axes are missing, the yellow color is not visible.
I also miss a map showing the regional seismicity. Also, you argue about the causes of earthquake activity around Svalbard. What means "around Svalbard"? There are different causes, e.g., if you think about the seismicity along the spreading system or at the continental margins.

5. In principle it is a good idea to convert depth (focal depths of earthquakes) to two-way traveltime. It would be enough to provide an easy table with the velocity model/s used. Also, there is no need to provide a table to convert seafloor depth to time, just provide a sound velocity that you used, and maybe relevant references. Why actually the density should be relevant for the depth-time conversion? I do not get the point about the seismic velocities of mafic metamorphic rocks presented on page 7. Try to make clearer, what is important here. If it is just about uncertainties in the velocity model and therefore the interpretations, provide this in a separate paragraph on uncertainties of your methods. I suggest providing a clear Data section with uncertainties (seismicity, seismic reflection data, velocity models).

6. When you interpret the location of earthquakes along thrust, planes identified in seismic reflection data, also consider and discuss the role of crosscutting fault zones.
What means shallow character of the Billefjorden and Lomfjorden fault zones? There is evidence that there are deep structures underlying, e.g., from magnetic data. It is also not yet clear to me, why you can rule out an influence of these fault zones (or their southern extensions) on the seismicity discussed.

7. The Heer Land earthquake sequence should be introduced in more detail or at least give a reference. Discussions on past tectonic events on page 12 do not seem relevant for the line of argumentation. Maybe provide a sketch to better illustrate the mode of activation of discussed fault zones, e.g., on which faults you see inversion and where normal faulting.

8. I do not get the point about earthquake swarms. They were not introduced at all, and I do not get any idea of earthquake swarms from the presented material. Do you mean instead, earthquake sequences?

9. How the Oligocene fault activation relates to the recent activities? Where is the evidence for Oligocene activation located on map view? You discuss the De Geer Zone, is it relevant for your study?

10. The differences about seismicity or missing seismicity between western Svalbard and southeastern Svalbard should be better discussed. I get the main point, but do not yet feel convinced by your arguments.

11. Figure 5 needs major revision to make it clearer and more readable. I do not understand, why the Timanian Orogen hindered breakup.

12. Summarizing, the manuscript would need major revision before I would approve it. I hope my comments will help you to improve your manuscript and its impact.

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?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: seismology, seismic reflection, marine geophysics, Svalbard

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.

Reviewer Report 24 May 2025

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Yanghui Zhao
Second Institute of Oceanography, Hangzhou, China

This is a valuable study presenting a compelling new tectonic model for Storfjorden, Svalbard. The authors propose that recent seismicity is primarily driven by the reactivation of ancient WNW–ESE Timanian thrust systems with normal-sinistral motion, linked to regional transtension. A key part of this model is the re-interpretation of shallow, seafloor-offsetting faults (previously seen as reverse by Koehl et al., 2022a) as brittle normal faults connected to these deeper Timanian structures. The paper also thoughtfully discusses earthquake swarm migration and broader tectonic implications.
To further enhance its impact, the authors are encouraged to consider the following points, particularly concerning the foundational fault re-interpretations:

The manuscript's central argument regarding the re-interpretation of faults would be significantly strengthened by providing more detailed seismic evidence directly within this paper. Specifically, to clearly establish the Cenozoic inversion of the Devonian-Carboniferous normal fault (which explains the previous interpretation by Koehl et al., 2022a), showcasing seismic profiles with clear structural features (e.g., fault-propagation folds, specific fault geometries) would be highly beneficial. Similarly, a more detailed description or illustration of the seismic characteristics confirming the normal sense of slip for the shallow, seafloor-offsetting faults would further solidify this aspect of the new model.

To improve narrative clarity concerning the interplay between the different fault systems (Timanian, inverted Devonian-Carboniferous, and young shallow normal faults), the authors could guide the reader more explicitly. Perhaps a step-by-step explanation detailing: (1) the evidence for the Devonian-Carboniferous fault's Cenozoic inversion, (2) how these likely influenced previous interpretations of shallow faults, (3) the evidence for the new interpretation of shallow faults as normal, and (4) their link to the deeper Timanian system, would be helpful.

The authors are encouraged to more explicitly state the significance of re-interpreting the shallow faults from reverse to normal in the Discussion. Highlighting why this change is critical for the proposed regional tectonic model (e.g., better alignment with earthquake focal mechanisms or the transtensional regime) would underscore the impact of this finding. Leveraging supporting data more directly could also be beneficial. For instance, if focal mechanism data for the 2011 Mw 4.0 event (or similar events linked to these re-interpreted shallow faults) supports normal faulting, emphasizing this connection would further strengthen the re-interpretation.

Finally, a minor but important correction: Table 1 ('Length (in m)' column) appears to contain a typographical error, showing '0' for offsets. Please update this with the calculated metric values (c. 22–66 m).

This is a valuable study with strong potential. Addressing these points, particularly by enhancing the presentation of seismic evidence for the key fault re-interpretations, will undoubtedly strengthen the manuscript’s conclusions and overall impact.

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?
Partly

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, seismic interpretation, regional tectonics, fault analysis.

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, however I have significant reservations, as outlined above.