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Devonian-Mississippian faulting controlled by WNW-ESE-striking structural grain in Proterozoic basement rocks in Billefjorden, central Spitsbergen

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ABSTRACT

In Billefjorden, central Spitsbergen, Devonian collapse and Carboniferous rift-related sedimentary strata were deposited unconformably over Proterozoic basement rocks displaying well developed N-S-trending Caledonian grain. Caledonian structures and fabrics are thought to have controlled the location and trend of subsequent Devonian and Carboniferous basin-bounding faults like the Billefjorden fault zone and Lemströmfjellet–Løvehovden fault. However, fieldwork and interpretation of aerial photographs in Proterozoic basement rocks reveal the existence of steep, abundant, WNW-ESE-striking brittle faults that are sub-orthogonal to known major Caledonian and post-Caledonian structures in Billefjorden, but that do not extend into adjacent-overlying, rift-related, Pennsylvanian rocks of the Gipsdalen Group. Structural analysis of field data and aerial photographs suggest that WNW-ESE-striking faults in basement rocks in Billefjorden formed as (sinistral) strike-slip and normal faults during Devonian-Mississippian extension in agreement with previously inferred models of sinistral transtension. The abundance of these faults suggests that their formation was controlled by analogously trending, preexisting structural grain (planar anisotropies) at depth, and their pronounced WNW-ESE strike suggests that the strike of preexisting anisotropies were comparable to recently identified, crustal-scale, WNW-ESE-striking Timanian thrust systems in Svalbard and the northern Barents Sea.

KEYWORDS **Faults. Svalbard. Devonian-Mississippian. Timanian.**

INTRODUCTION

Inheritance exerts a significant control on the strike and geometry of structures formed during subsequent events in various tectonic settings (Fazlikhani *et al.*, 2017; Koehl, 2020; Koehl *et al.*, 2018, 2019, 2022a; Lund, 2008; Moreno-Martin *et al.*, 2022; Molnar *et al.*, 2017; Osagiede *et al.*, 2020; Phillips *et al.*, 2016; Schiffer *et al.*, 2020; Thomas, 2005). It is therefore important to constrain the strike and architecture of preexisting structures and their influence on subsequent structures prior to investigating younger structures. In Svalbard for example, Eurekan structures extensively follow preexisting Caledonian grain (Dallmann *et al.*, 1993).

The Svalbard Archipelago in the Norwegian Arctic (Figure 1A) underwent a complex series of tectonic events in the Paleozoic, including E-W Caledonian contraction (Gee *et al.*, 1994; Harland *et al.*, 1992; Witt-Nilsson *et al.*, 1998) and related, latest Silurian-Devonian, late-post-orogenic collapse (Friend *et al.*, 1997; McCann, 2000), Late Devonian Svalbardian contraction (Dallmann and Piepjohn, 2020; Piepjohn *et al.*, 1997), and Carboniferous-Permian rifting (Braathen *et al.*, 2011; Cutbill and Challinor, 1965; Cutbill *et al.*, 1976). These events resulted in the development of a well defined N-S-trending structural grain and structures, both in Proterozoic basement and post-Caledonian sedimentary rocks, such as the Caledonian Atomfjella Antiform in northeastern Spitsbergen (Ny Friesland, see Figure 1B for location; Gee *et al.*, 1994; Witt-Nilsson *et al.*, 1998) and the Svalbardian and/or Carboniferous Billefjorden fault zone and related brittle faults in central Spitsbergen (Billefjorden, see Figure 1B for location; Harland *et al.*, 1974). These structures were reactivated and overprinted during subsequent events, such as the Eurekan tectonic event, when Greenland and Svalbard collided resulting in the formation of the West Spitsbergen Fold and Thrust Belt (Dallmann *et al.*, 1993; Harland, 1969; Harland and Horsfield, 1974; Maher Jr. *et al.*, 1986).

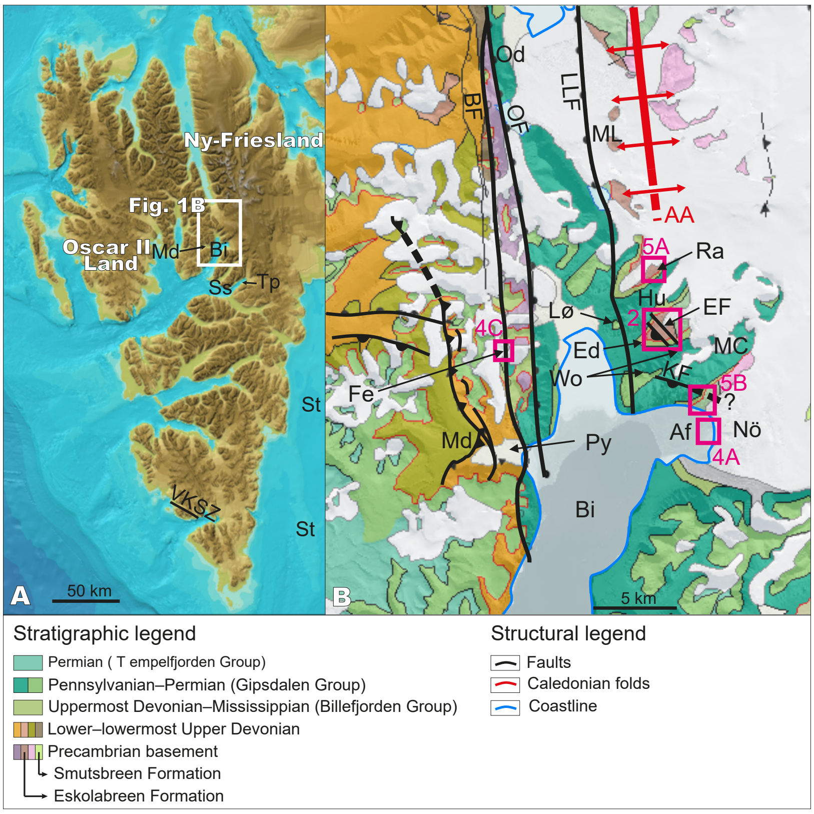

FIGURE 1. A) Topographic-bathymetric map around Spitsbergen, modified after Jakobsson *et al.* (2012). Abbreviations: Bi= Billefjorden; Md= Mimerdalen; Ss= Sassenfjorden; St= Storfjorden; Tp= Tempelfjorden; VKSZ= Vimsodden-Kosabapasset shear zone; B) Geological map modified from svalbardkartet.npolar.no showing the main tectono-stratigraphic units and structures in the study area in Billefjorden, central Spitsbergen. Pink frames show the location of aerial photographs in Figure 2A and Figure 5A-D. For details about the color scheme, the reader is referred to the interactive version of the map at svalbardkartet.npolar.no. Abbreviations: AA= Atomfjella Antiform; Af= Adolfbukta; BF= Balliolbreen Fault; Bi= Billefjorden; Ed= Ebbadalen; EF= Ebbabreen Faults; Fe= Ferdinandbreen; Hu= Hultberget; KF= Kampesteindalen Fault; LLF= Lemströmfjellet-Løvehovden Fault; Lø= Løvehovden; MC= McCabefjellet; Md= Mimerdalen; Nö= Nordenskiöldbreen; Od= Odellfjellet; OF= Odelfjellet Fault; Py= Pyramiden; Ra= Ragnardalen; Wo= Wordiekammen.

Despite the widespread, well developed, and long-lived character of N-S-trending structural grain throughout Spitsbergen, another trend seems to be increasingly recognized in recent years and includes WNW-ESE-striking structures and fabrics. Most importantly, recent field studies identified late Neoproterozoic Timanian (650-550Ma) thrusts and shear zones in southwestern Spitsbergen (*e.g.* Vimsodden-Kosibapasset shear zone; Faehnrich *et al.*, 2020; Majka *et al.*, 2008; Mazur *et al.*, 2009) and possibly in central Spitsbergen (Koehl and Muñoz-Barrera, 2018). In addition, structural analysis of regional seismic data showed the presence of several crustal-scale, WNW-ESE-striking, Timanian thrust systems in central Spitsbergen, Storfjorden and the northern Barents Sea (see Figure 1B for location; Koehl, 2019, 2020; Koehl *et al.*, 2022a).

The present contribution partly builds on previous works by Christophersen (2015) and reports, for the first time, descriptions and structural analysis of a set of abundant brittle faults showing a similar WNW-ESE strike in Proterozoic basement rocks in Billefjorden (see location in Figure 1B), an area that was previously thought to be completely and exclusively dominated by N–S-trending Caledonian grain (*e.g.* Braathen *et al.*, 2011; Harland *et al.*, 1974, 1992) apart from areas in northern Ny-Friesland (Witt-Nilsson *et al.*, 1998) and in Odellfjellet (Koehl and Muñoz-Barrera, 2018). The study discusses the potential timing of formation of these faults based on inferred kinematics and crosscutting relationships. Finally, the implications of these structures for the tectonic history of the region (*e.g.* presence of and relationship to preexisting structural grain and influence on subsequent tectonic events) are briefly reviewed.

GEOLOGICAL SETTING

Paleoproterozoic-Neoproterozoic metaigneous and metasedimentary rocks of the Eskolabreen, Smutsbreen and Bangenhuk units (Balashov *et al.*, 1993; Gayer *et al.*, 1966; Harland *et al.*, 1966; Figure 1B) in Billefjorden were involved in early-mid-Paleozoic E-W Caledonian contraction, during which they were metamorphosed to greenschist-amphibolite facies rocks. Caledonian deformation in Ny Friesland resulted in the formation of a pronounced N-S-trending, moderately East- and West-dipping foliation (Gee *et al.*, 1992) and regional gently north-plunging antiform, the Atomfjella Antiform (Gee *et al.*, 1994; Witt-Nilsson *et al.*, 1998; Figure 1B).

In the latest Silurian-Early Devonian, the onset of late- to post-orogenic extensional collapse resulted in the formation of the N-S-trending Devonian Graben in northern-central Spitsbergen (Figure 1B), which was filled with a several kilometers thick succession of reddish conglomerate, sandstone and shale (Friend and Moody-Stuart, 1972; Friend *et al.*, 1966; Gee and Moody-Stuart, 1966; Murascov and Mokin, 1979; Manby and Lyberis, 1992; Manby *et al.*, 1994). In places such as northwestern Spitsbergen and Andrée Land, Devonian sediments were deposited along high-angle, WNW–ESE-striking, normal to sinistral strike-slip faults (Dallmann and Piepjohn, 2018; Friend *et al.*, 1997; McCann, 2000) and in central Spitsbergen (Koehl *et al.*, in press) and bowed, low-angle, ductile extensional detachments (Braathen *et al.*, 2018, 2020; Chorowicz, 1992; Maher *et al.*, 2022; Roy, 2007, 2009).

In the Late Devonian, central Spitsbergen experienced short-lived Svalbardian contraction. This led to the formation of N-S-striking reverse faults such as the Balliolbreen fault segment of the Billefjorden fault zone, which juxtaposed Proterozoic basement rocks in the East against post-Caledonian Lower Devonian sedimentary rocks in the West (Dallmann and Piepjohn, 2020; Harland *et al.*, 1974; Piepjohn *et al.*, 1997; Vogt, 1938). However, recent studies of field and seismic data suggest that the Balliolbreen fault formed as a Carboniferous normal fault, which was inverted during Eurekan contraction, and that Svalbardian contraction did not occur in central Spitsbergen (*e.g.* Koehl, 2021 and references therein; Koehl *et al.*, 2022b).

Uppermost Devonian-Mississippian (Lindemann *et al.*, 2013; Marshall *et al.*, 2015; Playford, 1962, 1963; Scheibner *et al.*, 2012) fluvial, coal-rich sediments of the Billefjorden Group were deposited in multiple, widespread, fault-controlled mini (kilometer-wide and several to tens of kilometer-long) basins possibly trending N-S and WNW-ESE (Aakvik, 1981; Cutbill and Challinor, 1965; Cutbill *et al.*, 1976; Gjelberg, 1983, 1984; Koehl and Muñoz-Barrera, 2018). In latest Mississippian-Pennsylvanian times, (kilometer-scale) extensional faulting was localized along a few major high-angle faults, such as the East-dipping Billefjorden fault zone, West-dipping Lemströmfjellet-Løvehovden fault, SW-dipping Ebbabreen faults, and SSW-dipping Kampesteindalen fault (Figure 1B), led to the deposition of thick shallow marine sedimentary rocks of the Gipsdalen Group in the Billefjorden Trough (Braathen *et al.*, 2011; Maher and Braathen, 2011; McCann and Dallmann, 1996; Smyrak-Sikora *et al.*, 2018). These rocks include uppermost Mississippian-lower Permian sediments of the Hultberget, Ebbadalen, Minkinfjellet, Wordiekammen, and Gipshuken formations (Ahlborn and Stemmerik, 2015; Braathen *et al.*, 2011; Cutbill and Challinor, 1965; Cutbill *et al.*, 1976; Gee *et al.*, 1952; Gjelberg and Steel, 1981; Holliday and Cutbill, 1972; Johannessen, 1980; Johannessen and Steel, 1992; Keilen, 1992; Lønøy, 1995; McWhae, 1953; Playford, 1962, 1963; Smyrak-Sikora *et al.*, 2018).

In the early Cenozoic, Greenland and Svalbard collided during the Eurekan tectonic event, resulting in the formation of the West Spitsbergen Fold-and-Thrust Belt in western Spitsbergen (Dallmann *et al.*, 1993; Harland, 1969; Harland and Horsfield, 1974; Maher *et al.*, 1986) and mild reactivation of major high-angle and moderately-dipping faults and thin-skinned tectonics in the study area in central Spitsbergen (Koehl, 2021).

METHODS

The present study involves observations of and interpretation built from glacially eroded, three-dimensionally discontinuous, local (<a few hundreds of meters wide) field outcrops. The study reports structural field measurements and descriptions of brittle faults in Proterozoic basement rocks in Ebbadalen (Figures 2A-C; 3A-B) and in Adolfbukta–Nordenskiöldbreen (Figure 4A-E; 5A). Structural measurements of fracture surfaces are plotted in lower hemisphere, equal-area, Schmidt stereonets and characterized by fault strike and dip. Slickenside lineations are characterized by fault strike and dip (American right-hand rule), and lineation plunge. However, due to the poor quality of the few occurrences of slickensides in the field, fault kinematics were mostly studied using fault geometries in cross section and map view, and crosscutting relationships of brittle fault sets. The study also includes structural analysis of onshore escarpments and lineaments on aerial photographs of the Norwegian Polar

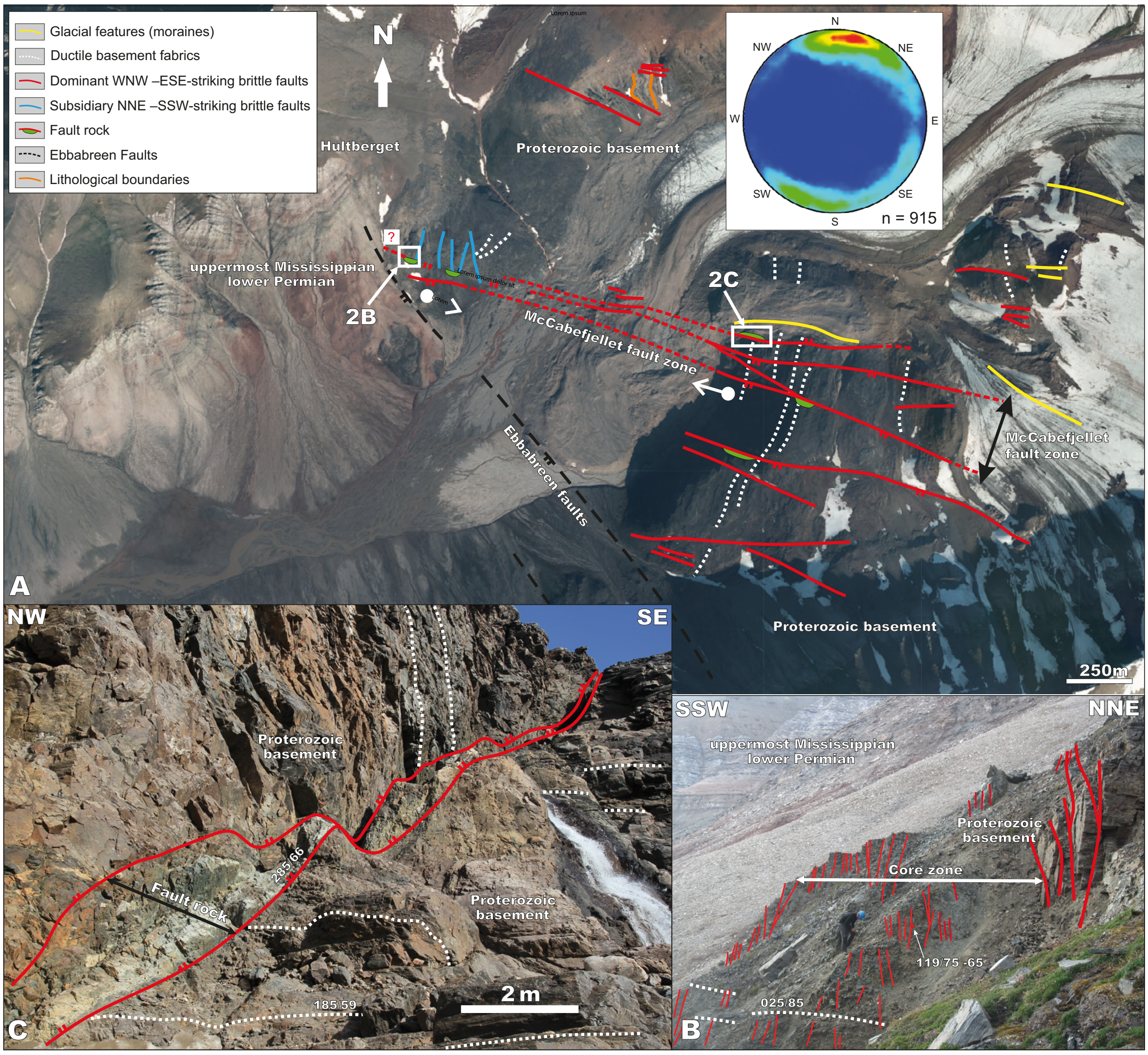

FIGURE 2. A) Aerial photograph showing field relationships between ductile basement fabrics (dotted white lines), brittle faults and related escarpements (red and blue lines), and glacial features (yellow lines) in Proterozoic basement rocks in Ebbadalen (see Figure 1B for location). The gradient-shading stereonet (red: high density; blue: low density) shows that brittle faults in basement rocks in Ebbadalen strike dominantly WNW-ESE and subsidiarily NNE-SSW. Note that WNW-ESE-striking faults in Proterozoic basement rocks, such as the McCabefjellet fault zone, show preserved lenses of fault rocks along strike (green) but do not extend into uppermost Mississippian–lower Permian sedimentary strata in Hultberget to the West-Northwest. The white dot and arrow symbols show from where and in which direction the photographs displayed in Figure 3A-B were taken. Notice the obliquity of WNW-ESE-striking faults with the Ebbabreen faults of McCann and Dallmann (1996). B) Field photograph of the (North-) western portion of the McCabefjellet fault zone showing the c. 10 meters wide, highly fractured, fault rock-bearing core zone of the fault. Notice the lone slickenside lineation (strike; dip; lineation plunge) with uncertain sense of shear along this part of the fault. C) Field photograph of a NNE-dipping fault antithetic to the McCabefjellet fault zone. The fault shows c. two meters wide zone with quartz-cemented brecciated/cataclastic fault rock.

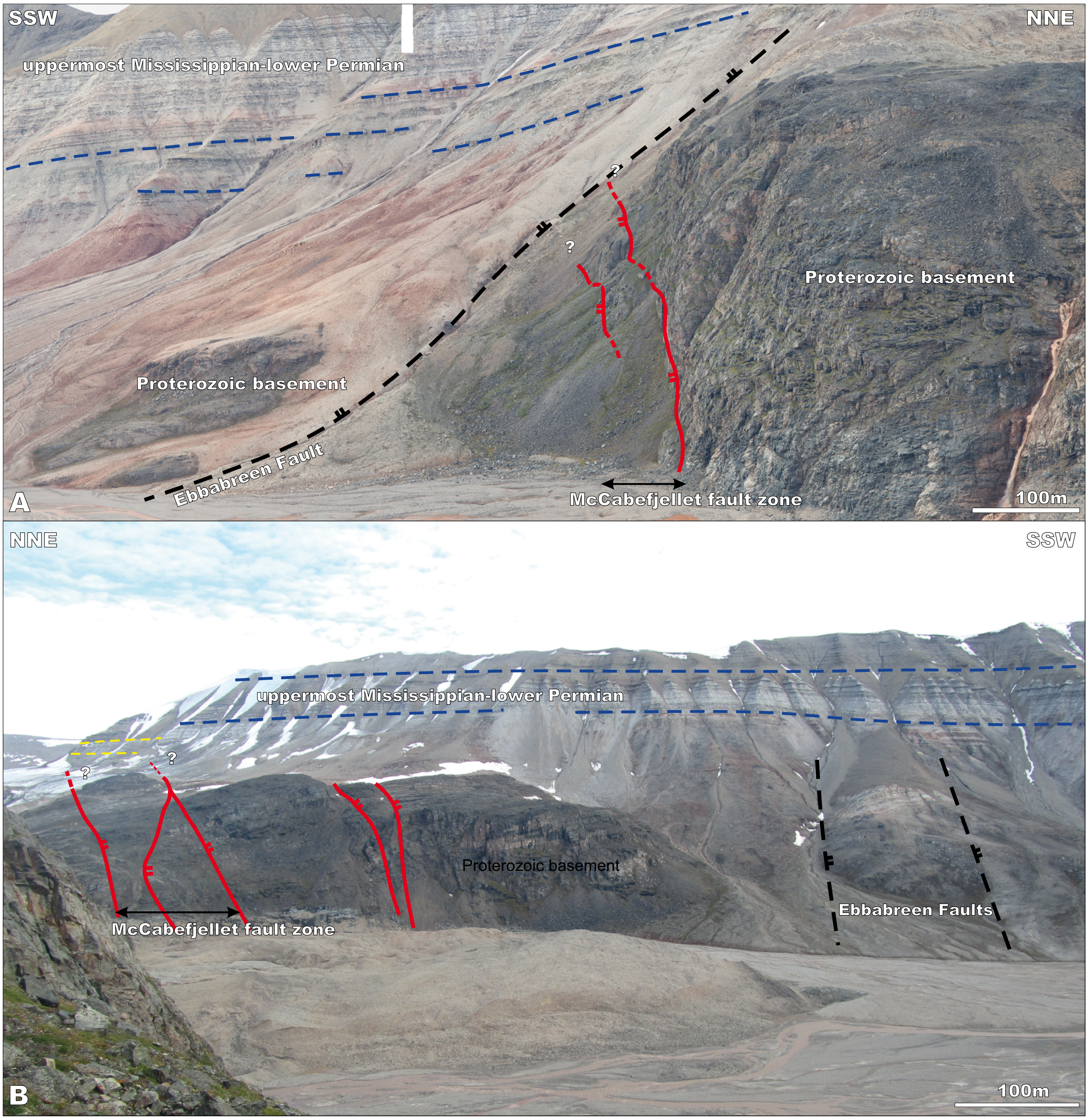

FIGURE 3. Photographs of the McCabefjellet fault zone (red line) and of the presumed trace of one of the Ebbadalen faults (dashed black line) in A) northern and B) southern Ebbadalen. Notice how the McCabefjellet fault zone seems to die out prior to reaching adjacent cliffs of sub-horizontal, relatively undeformed uppermost Mississippian-lower Permian sedimentary strata of the Gipsdalen Group (dashed dark blue lines) in Hultberget (A) and Wordiekammen (B). View is towards the West-Northwest in (A) and towards the East-Southeast in (B).

Institute (Figure 2A; 4A; 5A-C; toposvalbard.npolar.no). Field observations, existing literature and geological maps were used to distinguish between fault-related escarpments, ductile fabrics, and glacial features. The presented field data, uninterpreted field and aerial photographs, and high-resolution versions of the figures necessary to the reader to identify structures and stratigraphic units mentioned in the text can be found at doi.org/10.18710/MXEG3W and doi.org/10.18710/TIIIKX.

RESULTS AND INTERPRETATIONS

Structural field measurements in Proterozoic basement rocks

Observations in Ebbadalen

Brittle faults in Proterozoic basement rocks in Ebbadalen display two major strikes, including a dominant

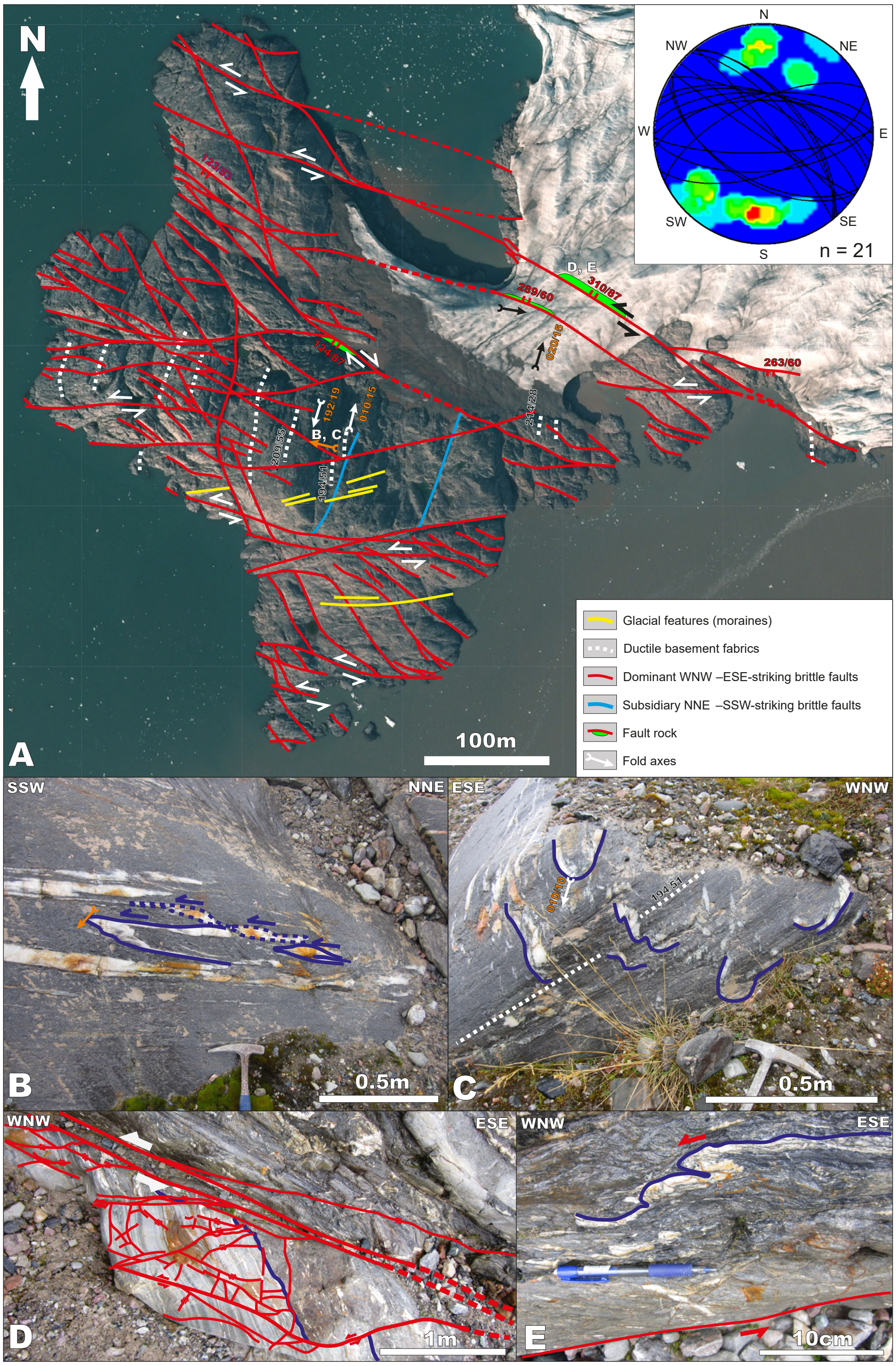

FIGURE 4. A) Aerial photograph of Adolfbukta-Nordenskiöldbreen (see Figure 1B for location) showing a dominant set of E-W- to NW-SE-striking fault-related escarpments arranged in Z- and S-shaped duplex-like structures (red lines). Possible subsidiary NNE-SSW-striking faults are shown as blue lines. Both fault sets truncate a set of high-frequency, gently curving, NNE-SSW- to N-S-trending lineaments (dotted white lines), which are correlated to Caledonian ductile fabrics. Glacial features are displayed as yellow lines. Note that the glacier has retreated from the peninsula after the aerial photograph was taken (*e.g.* location of D and E). The Schmid stereonet in the upper right hand-side shows fracture surfaces displayed as great circles (black lines) and as gradient to poles (red reflects high fracture density and blue low density). B) Asymmetric folds (dark blue lines; fold axis in orange) and sigma-clast structures (dotted dark blue lines) indicating top-SSW movement in Proterozoic basement rocks in the Adolfbukta-Nordenskiöldbreen area. See location in (A). C) Refolding of top-SSW structures in Adolfbukta-Nordenskiöldbreen into N-S-trending folds (dark blue lines; fold axis in white). N–S-trending Caledonian foliation is shown as dotted white lines. See location in (A). D) Subhorizontal outcrop showing a steep, WNW-ESE-striking, brittle-ductile fault zone in the northeastern part of the peninsula in Adolfbukta–Nordenskiöldbreen. Minor faults within the fault zone (red lines) show centimeter- to meter-scale, dominantly left-lateral and subsidiarily right-lateral brittle offsets of geological markers (dark blue lines). The photo was taken from above the outcrop (map view). See location in (A). E) Field photograph of sub-vertical asymmetric folds (dark blue line) suggesting sinistral strike-slip ductile movement along the steep WNW-ESE-striking fault in (D) (red line). See location in (A).

WNW-ESE-striking, both SSW- and NNE-dipping set, and a subsidiary set of East-dipping, NNE-SSW- to N-S-striking faults (see stereonet in Figure 2A). Subsidiary East-dipping faults are relatively sparse in basement rocks.

WNW-ESE-striking fracture surfaces are abundant in Proterozoic basement rocks in Ebbadalen (see stereonet in Figure 2A). These fractures display high-angle to sub-vertical and planar mesoscale geometries. In places, high fracture density (c. 5-10 fracture surfaces per meter) and the presence of up to one-meter-wide fault rock comprised of angular to sub-rounded clasts indicate the presence of major fault zones with highly fractured, c. 10 meters wide core zones (Figure 2B). Sparse slickenside lineations along major fault surfaces within fault cores suggest oblique- to dip-slip movement along these major faults. However, due to the poorly-preserved character of slickensides in basement rocks, the sense of shear along the main fault zones could not be consistently deduced. For further description of brittle faults in basement rocks in Ebbadalen, the reader is referred to Christophersen (2015).

Interpretations in Ebbadalen

Faults of the subsidiary set are parallel to major East-dipping post-Caledonian normal faults along the eastern boundary of the Billefjorden Trough (*e.g.* Lemströmfjellet-Løvehovden fault) and well studied N-S-trending Caledonian grain in Ny Friesland and Billefjorden (*e.g.* Atomfjella Antiform; Witt-Nilsson *et al.*, 1998). Thus, it is highly probable that East-dipping brittle faults are directly related to the formation of the Billefjorden Trough in the Carboniferous and that their formation may have been controlled by Caledonian grain. These faults will not be discussed further because they are well studied and described in other studies (*e.g.* Braathen *et al.*, 2011; Maher and Braathen, 2011).

WNW-ESE-striking faults recorded in Proterozoic basement rocks in Ebbadalen (Figure 2A-C) are sub-orthogonal to major N-S-striking faults (*e.g.* Lemströmfjellet–Løvehovden fault; Maher and Braathen, 2011) and oblique (forming a 30-40º angle) to NW-SE-striking faults bounding the Billefjorden Trough in the east (*e.g.* Ebbabreen faults; McCann and Dallmann, 1996; Smyrak-Sikora *et al.*, 2018). In addition, WNW-ESE-striking faults in Proterozoic basement rocks do not extend into adjacent cliffs of Hultberget in the west-northwest, which consist of Lower-Middle Pennsylvanian sedimentary strata of the Ebbadalen and Minkinfjellet formations (Figure 3A).

Observations in Adolfbukta–Nordenskiöldbreen

In Adolfbukta-Nordenskiöldbreen (Figure 4A, see Figure 1 for location), dominant ductile features in Proterozoic basement rocks of the Smutsbreen unit (Gayer *et al.*, 1966; Harland *et al.*, 1966) include i) centimeter- to meter-scale, gently ESE- and WNW-plunging, E-W- to WNW-ESE-trending fold structures with sub-horizontal axes and axial surfaces gently dipping to the north-northeast and south-southwest (Figure 4B); ii) centimeter- to meter-scale, sub-horizontal, NNE-SSW- to N-S-trending folds; and iii) NNE-SSW- to N-S-trending foliation (Figure 4C). In E-W to WNW-ESE cross section, the former appears refolded into sub-horizontal, NNE-SSW- to N-S-trending folds (Figure 4C).

Brittle-ductile faults in the Adolfbukta-Nordenskiöldbreen area strike dominantly WNW-ESE to E-W and subsidiarily ENE-WSW, and dip steeply to moderately (Figure 4A). These faults truncate the N-S- to NNE-SSW-trending Caledonian foliation at a high angle (Figure 4A) and are therefore unlikely related to this tectonic event. The faults are largely eroded by Nordenskiöldbreen (glacier), but, in places, fault rocks are preserved, and these occurrences include lens-shaped finely-crushed cataclasite and coarse clasts–blocks in breccia (Figure 4A, D). Kinematic indicators along WNW-ESE- to E-W-striking faults include centimeter- to meter-scale brittle, dominantly left- and subsidiary right-lateral offsets of geological markers such as lithological contacts (Figure 4D), sigma-clasts, and sub-vertical asymmetric folds (Figure 4E). Kinematic indicators suggest dominantly sinistral and subsidiary (conjugate?) dextral strike-slip movements along WNW-ESE- to E-W-striking faults in the Adolfbukta-Nordenskiöldbreen area (Figure 4D-E).

Interpretations in Adolfbukta-Nordenskiöldbreen

Since the NNE-SSW- to N-S-trending folds and foliation are parallel to the N–S-trending fabrics of the Caledonian Atomfjella Antiform (Gee *et al.*, 1992; Witt-Nilsson *et al.*, 1998) we interpret them as Caledonian features. However, older E-W- to WNW-ESE-trending fold structures are yet to be described in the area and their origin will therefore be addressed in the discussion. Nevertheless, their refolding into sub-horizontal, NNE-SSW- to N-S-trending folds in E-W to WNW-ESE cross section (Figure 4C) suggests that they formed during a discrete, pre-Caledonian tectonic event.

Aerial photographs in Billefjorden

Observations in Ebbadalen and Ragnardalen

Analysis of aerial photographs in basement rocks in Ebbadalen and Ragnardalen reveals the occurrence of two sets of escarpments. Among these, steep, WNW-ESE-trending escarpments dominate, whereas NNE-SSW- to N-S-trending escarpments are subsidiary (respectively

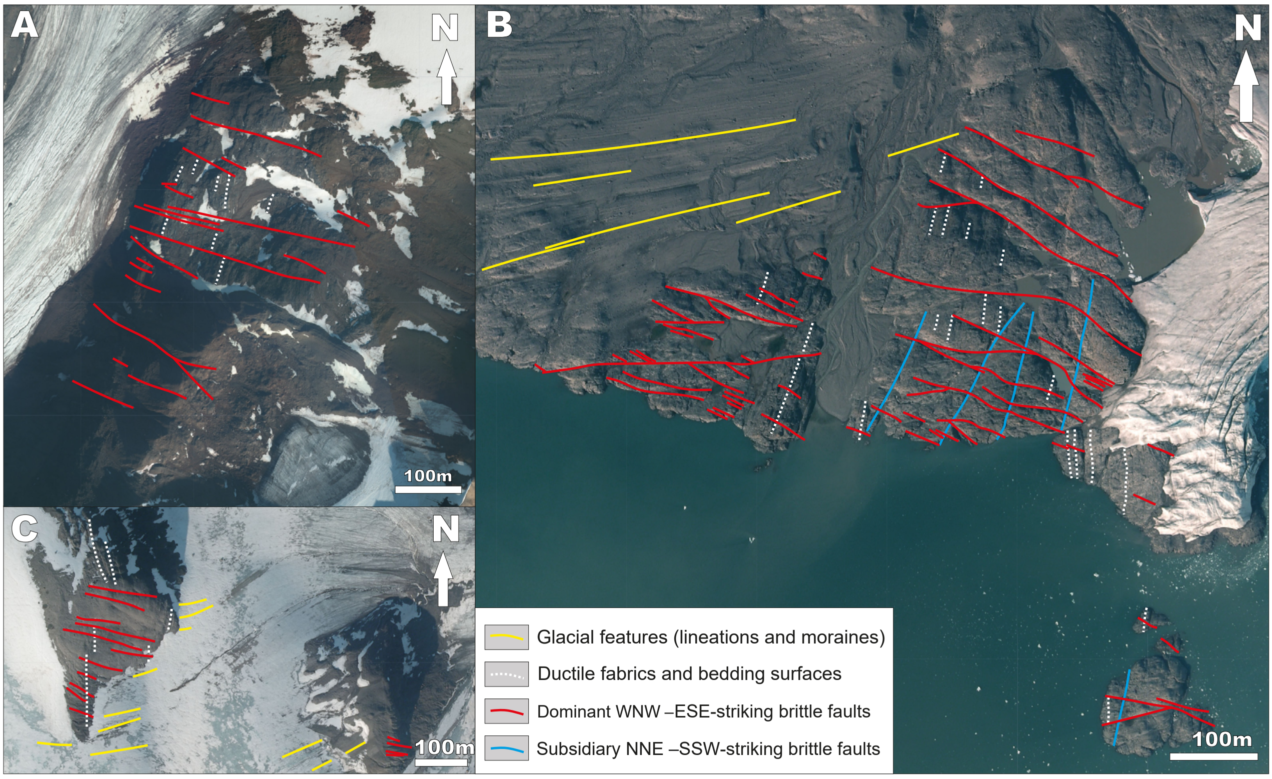

FIGURE 5. Aerial photographs of A) Ragnardalen, B) northern Adolfbukta-Nordenskiöldbreen and C) Ferdinandbreen (see Figure 1B for locations) showing smooth, high-frequency, gently curving, NNE-SSW- to N-S-trending lineaments (dotted white lines) representing sub-vertical ductile fabrics within Proterozoic basement rocks. These are crosscut by discrete, linear to undulating, dominantly WNW-ESE-trending (red lines) and subsidiarily NNE-SSW-trending (blue lines) fault-related escarpments. Glacial features are shown as yellow lines. The legend is common to A-C and is displayed in (B).

red and blue lines in Figures 2A; 5A). Aerial photographs also reveal a set of high-frequency, NNE-SSW-trending lineaments. In places, these high-frequency lineaments bend smoothly in map view and display arcuate geometries (dashed white lines in Figures 2A; 5A). Near snow patches in Ebbadalen, another set of smooth, high-frequency, WNW–ESE-trending lineations is observed locally (yellow lines in Figure 2A). These lineaments also show arcuate geometries in map view and trend slightly oblique to the dominant set of steep, WNW-ESE-striking escarpments (Figure 2A). These smooth, arcuate, WNW-ESE-trending lineations appear to merge with similarly trending, arcuate lineations forming a fan-shaped aggregate in snow patches.

Interpretations in Ebbadalen and Ragnardalen

The high-frequency, NNE-SSW-trending lineaments with arcuate geometries in Ebbadalen and Ragnardalen (dashed white lines in Figure 2A; 5A) appear to follow the dominant ductile bedrock fabrics of the Atomfjella Antiform (Gee *et al.*, 1992; Witt-Nilsson *et al.*, 1998). In addition, these lineaments are slightly oblique to and crosscut by steep, subsidiary, NNE-SSW to N-S-trending escarpments. They are therefore interpreted to represent ductile fabrics in basement rocks (Figure 2A-C).

The set of smooth, high-frequency, WNW-ESE-trending lineations (yellow lines in Figure 2A), which merge with similarly trending, arcuate lineations forming a fan-shaped aggregate in snow in Ebbadalen are interpreted as glacial landforms, such as medial and lateral moraines reflecting the glacier flow.

Furthermore, in Ebbadalen, the two sets of dominant WNW-ESE- and subsidiary NNE-SSW-trending escarpments trend oblique to both glacial features and ductile fabrics and are parallel to the two sets of high-angle brittle faults identified in the field (see stereonet in Figure 2A). Furthermore, several major WNW-ESE-trending escarpments coincide with analogously striking major fault zones and occurrences of fault rocks (green bodies in Figure 2A-C). Hence, we interpret WNW-ESE- and NNE-SSW- to N-S-trending escarpments as high-angle brittle faults in basement rocks. Noteworthy, occurrences of fault rocks and highly fractured fault cores seem to be localized along just a few major faults in the field, some of which align and are connected to each other by two-three major, interconnected, WNW-ESE-striking, SSW-dipping, fault-related escarpments (Figure 2A). It is suggested that this group of SSW-dipping fault-related escarpments, brittle faults, core zones, and associated fault rocks represent sub-parallel segments or splays (Biddle and Christie-Blick, 1985; Peacock *et al.*, 2000) of a major fault zone. This newly identified fault zone is hereby named the McCabefjellet fault zone (Figures 2A; 3A). Near Hultberget in the West, the McCabefjellet fault zone is c. 100 meters wide, but the fault widens eastwards to a width of 300 meters as its main segments-splays slightly diverge from each other (Figure 2A). The McCabefjellet fault zone does not continue into adjacent uppermost Mississippian-lower Permian sedimentary strata of the Gipsdalen Group in Hultberget in the (North-) West (Figure 2A) and Wordiekammen in the (South-) East (Figure 3B).

Observations in Adolfbukta–Nordenskiöldbreen and Ferdinandbreen

Aerial photographs of Adolfbukta, Nordenskiöldbreen, and Ferdinandbreen (see Figure 1B for location) show series of pronounced, linear to bending escarpments (Figures 4A; 5B-C) in Proterozoic garnet micaschists of the Smutsbreen unit and in granitic to granodioritic gneisses of the Bangenhuk unit. These escarpments can be divided into two major sets trending WNW-ESE (E-W to NW-SE) and NNE-SSW that both crosscut a set of poorly defined, high-frequency, N-S-trending, undulating escarpments. The E-W- to NW-SE-trending escarpments of the dominant WNW-ESE-trending set are arranged into rhomboid-shaped (duplex-like) patterns and commonly display dominantly anticlockwise-bending (Z-shaped) and subsidiarily clockwise-bending (S-shaped) geometries in map view near or at the intersection with slightly oblique escarpments of the same set (Figure 4A). All three sets are oblique to a subsidiary set of smooth, ENE-WSW- to E-W-trending lineaments (Figures 4A; 5B-C).

Interpretations in Adolfbukta–Nordenskiöldbreen and Ferdinandbreen

High-frequency undulating escarpments of the (NNW-SSE- to) N-S-trending set in Adolfbukta–Nordenskiöldbreen and Ferdinandbreen, parallel the main ductile foliation in the field (Figures 4A; 5A-B) and the main ductile basement fabrics in Ny Friesland (Gee *et al.*, 1992; Witt-Nilsson *et al.*, 1998). N-S-trending escarpments are therefore interpreted to correspond to ductile basement fabrics. In addition, the subsidiary set of smooth, ENE-WSW- to E-W-trending lineaments is well developed in adjacent till and moraine deposits (Allaart *et al.*, 2018) and snow patches. It is therefore believed to represent glacial lineations (possibly supraglacial and medial moraines; Figures 4A; 5B-C).

The two sets of steep, dominant WNW-ESE- and subsidiary NNE-SSE-trending escarpments crosscut ductile fabric-related escarpments but are crosscut by glacial lineations (Figures 4A; 5B-C). Their steep character and crosscutting relationships with ductile fabrics and glacial lineations, and the occurrence of major WNW-ESE-striking, brittle-ductile faults in the field (Figures 4A, D) suggest that WNW-ESE-trending escarpments correspond to brittle-ductile faults. NNE-SSW-trending escarpments are not well developed in the field, but their steep geometries and the fact that they truncate N-S-trending ductile fabrics suggest that they also correspond to brittle (-ductile) faults. Furthermore, the observed rhomboidal and Z-shaped (and subsidiary S-shaped) geometries in Adolfbukta-Nordenskiöldbreen suggest a component of brittle–ductile sinistral (and subsidiary-conjugate?-dextral) strike-slip movement along major E-W- to NW-SE-striking brittle faults (see white half-arrows in Figures 4A). This is consistent with the kinematic indicators found along WNW-ESE-striking faults in the field (Figures 4D-E). As mentioned earlier, NNE-SSW-striking faults are parallel to and most likely related to major post-Caledonian, basin-bounding brittle faults in the study area and will not be discussed further.

DISCUSSION

Proterozoic basement rocks in Billefjorden show abundant WNW-ESE-striking faults in the field and on aerial photographs in Billefjorden (Figures 2A-C; 4A, D-E; 5A-C). Our field observations and interpretation of aerial photographs show that WNW-ESE-striking faults in basement rocks, such as the McCabefjellet fault zone in Ebbadalen, do not extend into overlying-adjacent uppermost Mississippian-lower Permian sedimentary strata of the Gipsdalen Group in Hultberget and Wordiekammen (Figures 3A-B). Thus, the faults must have formed prior to the latest Mississippian. Possible timing of formation for WNW-ESE-striking faults in basement rocks in Ebbadalen include the Timanian orogeny, Caledonian orogeny, Devonian extensional collapse, Late Devonian Svalbardian orogeny, and latest Devonian-Mississippian extension.

WNW-ESE-striking faults in Proterozoic basement rocks are unlikely to have formed due to Svalbardian tectonism because dominant Svalbardian fabrics and structures trend N-S (Dallmann and Piepjohn, 2020). Noteworthy, in Ferdinandbreen, Proterozoic basement rocks of the Bangenhuk unit crop out West (*i.e.* in the footwall) of the Balliolbreen fault as observed on aerial photographs (Figures 5C) and as reported in previous field mapping by the Norwegian Polar Institute (Norwegian Polar Institute, 2016). In this area, the Balliolbreen fault was previously thought to juxtapose Proterozoic basement rocks in the East against Lower Devonian sedimentary strata in the West, both of which are unconformably overlain by uppermost Devonian-Mississippian sedimentary rocks of the Billefjorden Group (Dallmann, 2015; Harland *et al.*, 1974), thus justifying the need for a Late Devonian episode of reverse movement along the fault. This is no longer the case. In addition, recent studies in central Spitsbergen show that Svalbardian tectonism did not occur in central Spitsbergen (Koehl, 2021; Koehl *et al.*, 2022b).

The mapped structures are also unlikely to have formed during the Caledonian orogeny since they trend sub-orthogonal to and truncate the well documented, moderately-dipping, N–S-trending Caledonian grain (moderately East- and West-dipping foliation, thrusts and shear zones) of the Atomfjella Antiform in the study area (Gee *et al.*, 1992, 1994; Gee and Page, 1994; Harland *et al.*, 1992; Witt-Nilsson *et al.*, 1998).

The first Timanian structures and fabrics reported in Svalbard were only discovered in the past 20-25 years (*e.g.* Vimsodden–Kosibapasset shear zone in southwestern Spitsbergen; Faehnrich *et al.*, 2020; Majka *et al.*, 2008, 2012; Manecki *et al.*, 1998; Mazur *et al.*, 2009). Thus, much work remains in identifying and mapping these old structures. However, WNW-ESE-striking faults and sub-horizontal, E-W- to WNW-ESE-trending folds in Proterozoic basement rocks in Billefjorden (Figures 2A-C; 4A-E; 5A-C) trend parallel to the few potential Timanian structures reported in Svalbard (Faehnrich *et al.*, 2020; Koehl and Muñoz-Barrera, 2018; Mazur *et al.*, 2009) and to recently reported, deep, crustal-scale, Timanian thrust systems in central Spitsbergen, Storfjorden and the northern Barents Sea (*e.g.* Klitzke *et al.*, 2019; Koehl, 2019, 2020; Koehl *et al.*, 2022a; Figure 6A). It is possible that the E-W- to WNW-ESE-trending folds formed during late-

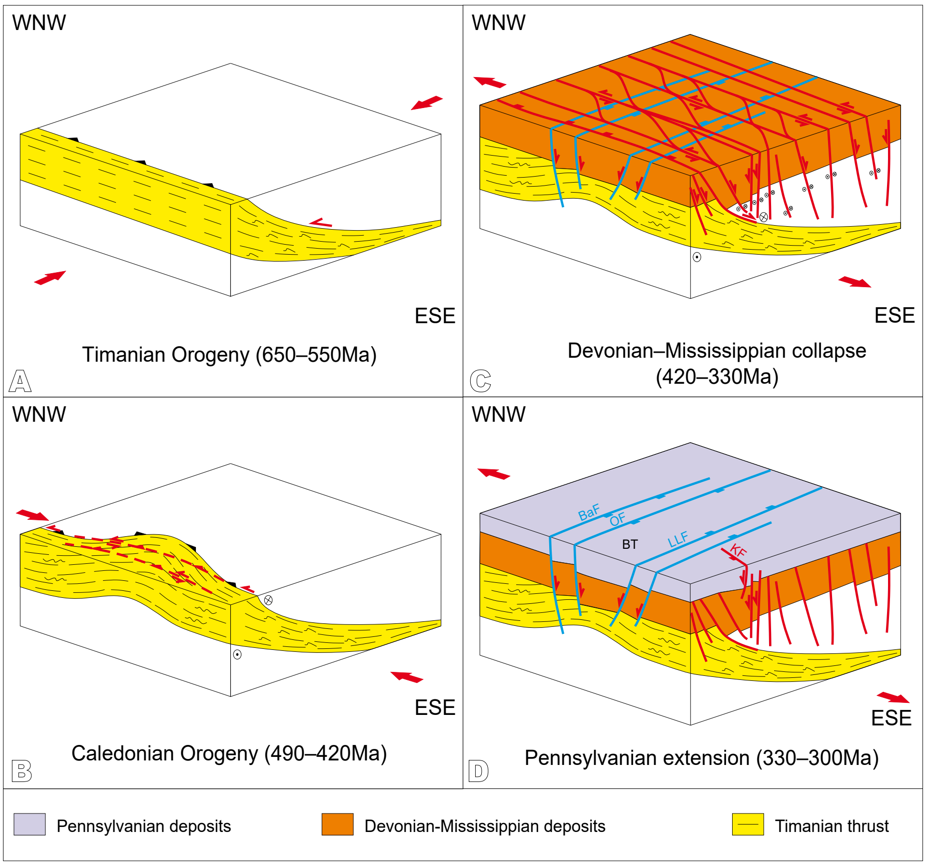

FIGURE 6. Tectonic evolution of the Billefjorden region showing A) the formation of dominantly top-SSW (notice also the SSW-verging asymmetric folds) and ductile Timanian thrusts in the late Neoproterozoic (*e.g.* Kongsfjorden-Cowanodden fault zone of Koeh), B) their folding into NNE-plunging anticlines (see also folding of SSW-verging folds into N-S-striking symmetrical folds) during E-W-oriented Caledonian contraction in the early Paleozoic with a probable sinistral component of reactivation and brittle overprinting (red lines and half-arrows), C) the formation of dominantly WNW-ESE-striking normal to sinistral (red lines; controlled by Timanian thrusts) and subsidiarily NNE-SSW-striking normal (blue lines; controlled by Caledonian fabrics) brittle overprints during late-post-Caledonian collapse in the Devonian-Mississippian and D) the continued normal movement along suitably oriented NNE-SSW-striking faults during continued, orogen-orthogonal, E-W-oriented extension in the Pennsylvanian, whereas most unsuitably oriented WNW-ESE-striking faults die out below Pennsylvanian sedimentary deposits of the Gipsdalen Group. Notice the rhomboidal shape and associated component of sinistral strike-slip movement along some of the WNW-ESE-striking faults in (C). Abbreviations: BaF= Balliolbreen Fault; BT= Billefjorden Trough; KF= Kampesteindalen Fault; LLF= Lemströmfjellet-Løvehovden Fault; OF= Odellfjellet Fault.

to post-Caledonian, top-North extensional faulting like in northwestern Spitsbergen (Braathen *et al.*, 2018; Maher *et al.*, 2022) as considered for folds in western Norway (*e.g.* Wiest *et al.*, 2020). However, the strike of both the faults and the folds is WNW-ESE in the present study, whereas they are orthogonal to each other in western Norway. In addition, the "hyperbolic" folds in Wiest *et al.* (2020) are symmetrical, whereas the folds in Billefjorden are SSW-verging and are therefore most likely of contractional origin. In addition, the refolding of E-W- to WNW-ESE-trending folds by N-S- to NNE-SSW-trending Caledonian fabrics in Billefjorden (Figure 6B) suggests that E-W- to WNW-ESE-trending folds in basement rocks in the Adolfbukta-Nordenskiöldbreen area formed prior to the Caledonian orogeny. It is therefore possible that the mapped WNW-ESE-striking faults and E-W- to WNW-ESE-trending folds in basement rocks in Billefjorden initiated during the Timanian orogeny in the latest Neoproterozoic (ca. 650–550Ma). However, unlike E-W- to WNW-ESE-trending folds, WNW-ESE-striking faults do not show any sign of top-SSW thrusting (Figure 4A, D-E), which is characteristic of the Timanian orogeny. Thus, it is more probable that the WNW-ESE-striking faults formed much after the WNW-ESE-striking folds, which is also supported by the truncation of Caledonian ductile fabrics by the WNW-ESE-striking faults (Figure 4A).

Another possibility is that the studied faults formed as normal to strike-slip faults during Devonian-Mississippian extension (Figure 6C). This is supported by i) kinematic indicators (drag-folding, sigma clasts, minor brittle offsets) and Z-shaped duplex-like geometries suggesting dominant sinistral strike-slip movements along WNW-ESE-striking faults in the Adolfbukta-Nordenskiöldbreen area (Figure 4A, D-E), ii) the presence in Devonian strata of analogously striking, syn-sedimentary, high-angle normal faults showing slickensides indicating top-NNE normal movements (Braathen *et al.*, 2018; Friend *et al.*, 1997; McCann, 2000) and iii) minor left-lateral offsets of basement rocks of the Bockfjorden Anticline in northwestern Spitsbergen (Dallmann and Piepjohn, 2018; Gee, 1972) and in sedimentary rocks of the Billefjorden Group and Hultberget Formation in central Spitsbergen (Koehl, 2021; Koehl and Muñoz-Barrera, 2018). Normal growth faults within strata of the Billefjorden Group in Odellfjellet (Koehl and Muñoz-Barrera, 2018) and Sassenfjorden-Tempelfjorden (Koehl, 2021) die out upwards at or below the base of latest Mississippian sedimentary strata of the Hultberget Formation, which is consistent with fault geometries observed in basement rocks in Billefjorden (Figures 2A-B; 3; 6C-D). A formation as steep, normal to (sinistral) strike-slip faults during Devonian-Mississippian extension is also supported by field data and observations in Ny Friesland where analogous WNW-ESE-striking faults showing both strike-slip and normal kinematics (slickenside lineations) offset Caledonian fabrics in Proterozoic basement rocks (Witt-Nilsson *et al.*, 1998). Furthermore, the brittle to brittle-ductile character of WNW-ESE-striking faults in Proterozoic basement rocks in Billefjorden differs from the dominantly ductile to brittle-ductile character of crustal-scale Timanian thrust systems in the Barents Sea, Storfjorden, central Spitsbergen (Klitzke *et al.*, 2019; Koehl, 2019, 2020; Koehl *et al.*, 2022a; Figure 6), and southwestern Spitsbergen (Majka *et al.*, 2008, 2012; Manecki *et al.*, 1998; Mazur *et al.*, 2009). This could be due to the burial of the deep ductile portions of Timanian thrusts in central Spitsbergen, where only the upper, overprinted-reactivated, brittle portion is visible in outcrops, and to their uplift and exhumation due to Caledonian and Eurekan tectonism and subsequent erosion in western-southwestern Spitsbergen (Koehl *et al.*, 2022a; Figure 6A-B). Nevertheless, the large dominance and abundance of WNW-ESE-striking faults (Figures 2A-C; 3A-B; 4A, D-E; 5A-B) and occurrence of top-SSW folds refolded by Caledonian fabrics (Figure 4B-C) in Proterozoic basement rocks in Ebbadalen, Adolfbukta-Nordenskiöldbreen, and Ragnardalen strongly suggest the presence of similarly trending fabrics and/or structures at depth. Thus, sub-vertical WNW-ESE-striking faults in basement rocks in Billefjorden are proposed to have formed as potential brittle (to brittle-ductile) overprints of deep, gently to moderately NNE-dipping Timanian structures and fabrics. Note that vertical drag folds might be Caledonian in age since Timanian thrust systems in Svalbard were reactivated as top-SSW, sinistral oblique-slip faults during the Caledonian orogeny (Faehnrich *et al.*, 2020; Koehl *et al.*, 2022a; Figure 6B).

WNW-ESE-striking faults in basement rocks in Adolfbukta-Nordenskiöldbreen parallel and align with the SSW-dipping Kampesteindalen fault (Figure 1B), which offsets uppermost Mississippian-lowermost Pennsylvanian sedimentary strata of the Hultberget Formation and Ebbaelva Member (*i.e.* lower part) of the Ebbadalen Formation showing normal movement of up to 50 meters and dying out upwards within the Ebbadalen Formation (Smyrak-Sikora *et al.*, 2018). It is possible that the Kampesteindalen fault represents the western continuation of major WNW-ESE-striking, fault-related escarpments mapped in basement rocks in Adolfbukta, i.e. that the latter acted as normal faults in the latest Mississippian-earliest Pennsylvanian (Figure 6D). However, the Kampesteindalen fault is believed to have accommodated exclusively normal movement (Smyrak-Sikora *et al.*, 2018), which contrasts with the (dominantly sinistral) strike-slip sense of shear inferred along WNW-ESE-striking faults in Proterozoic basement rocks in the Adolfbukta-Nordenskiöldbreen area (Figure 4A). Instead, it is more likely that WNW-ESE-striking basement-seated faults in Adolfbukta-Nordenskiöldbreen formed prior to and controlled the location and strike of subsequent Carboniferous faults like the Kampesteindalen fault (Figure 6D). This is consistent with the interpretation of Koehl and Muñoz-Barrera (2018) in Odellfjellet and Mittag-Lefflerbreen where basement-seated WNW-ESE-striking faults controlled the formation of parallel Carboniferous normal faults in the Billefjorden Group and Hultberget Formation in Odellfjellet.

The presence of Timanian grain in Billefjorden would reconcile observations and data of the present study with the model of sinistral transtension during Carboniferous rifting of McCann and Dallmann (1996). In their model, they propose that the obliquity of Carboniferous normal faults (*e.g.* Ebbabreen faults) to both preexisting (Timanian and Devonian-Mississippian) WNW-ESE-striking faults in Proterozoic basement rocks and major basin-bounding normal faults (*e.g.* Billefjorden fault zone and the Lemströmfjellet-Løvehovden fault) is directly related to sinistral movements along preexisting structures. Sinistral movement was recorded along inherited Timanian thrusts elsewhere in Spitsbergen (Koehl, 2020; Koehl *et al.*, 2022a; Mazur *et al.*, 2009). Most importantly, Early Devonian post-Caledonian sinistral strike-slip movement occurred at 410Ma along basement-seated mylonitic shear zones in Oscar II Land (western Spitsbergen; Figure 1A), which strike parallel to WNW-ESE-striking faults in basement rocks in Billefjorden (Ziemniak *et al.*, 2020, 2022). Devonian movement along WNW–ESE-striking faults in Billefjorden is further supported by field studies of Piepjohn *et al.* (1997) in Mimerdalen where parallel brittle faults offset (laterally?) Lower-Middle Devonian (Newman *et al.*, 2019) rocks of the Wood Bay Formation and Fiskekløfta Member of the Tordalen Formation but are unconformably overlain by lower Permian strata of the Wordiekammen Formation. However, ongoing work and recent datesets suggest that the presence of these faults is questionable (Koehl and Stokmo, 2021).

Nonetheless, the WNW-ESE strike, steeply dipping geometry, and normal to sinistral character of the studied faults is compatible with the most likely E-W extension direction during the collapse of the Caledonides in Svalbard (*i.e.* orthogonal to the N-S-trending orogen; Gee *et al.*, 1994; Harland *et al.*, 1992; Witt-Nilsson *et al.*, 1998) during the Devonian-Mississippian (*e.g.* McCann and Dallmann, 1996). The strike, geometry, and inferred kinematics of the faults also fit a formation due to locally orogen-parallel, N-S-oriented extension (*e.g.* in northwestern Spitsbergen; Braathen *et al.*, 2018; McCann, 2000).

CONCLUSION

The present study shows that, despite unsuitable strike and geometry with respect to the new tectonic stress direction, new brittle faults (*e.g.* the McCabefjellet fault zone) develop parallel to prominent preexisting structural trends in the crust. However, instead of reactivating preexisting structures, the new faults developed as overprints, which show the same strike as preexisting structures but developed with different geometry. By contrast, suitably oriented structures have higher chance to be reactivated (*e.g.* N-S-striking Balliolbreen fault of potential Carboniferous age inverted during the Eurekan event).

The studied, brittle to brittle-ductile, WNW-ESE-striking faults in Proterozoic basement rocks in Billefjorden initiated as sinistral strike-slip to normal faults during Devonian-Mississippian (collapse-rift-related) extension and overprinted similarly striking, pre-Caledonian (Timanian?) basement fabrics, as suggested by E-W- to WNW-ESE-trending, top-SSW fold structures in the field and crustal-scale Timanian thrust systems on seismic data in Svalbard and the northern Barents Sea. The occasional occurrence of WNW-ESE-striking normal faults within Pennsylvanian sedimentary successions (*e.g.* Kampesteindalen fault) and their alignment with parallel faults in adjacent Proterozoic basement rocks indicate that some of the studied Devonian-Mississippian faults were reactivated-overprinted during subsequent Pennsylvanian rifting and partly controlled the formation of new faults.

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