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Devonian–Mississippian collapse and core complex exhumation, and partial decoupling and partitioning of Eurekan deformation as alternatives to the Ellesmerian Orogeny in Spitsbergen

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Abstract

In the Late Devonian, Svalbard was affected by a short-lived episode of contraction called the Ellesmerian (Svalbardian) Orogeny, which resulted in top-west thrusting of Proterozoic basement rocks onto Devonian sedimentary strata along the Balliolbreen Fault, a major fault segment of the east-dipping Billefjorden Fault Zone, and juxtaposition of undeformed Mississippian–Permian strata against intensely folded Devonian rocks. The present study of field and seismic data shows that backward-dipping duplexes comprised of phyllitic coal and bedding-parallel décollements and thrusts localized along lithological transitions in thickened uppermost Devonian–Mississippian coals and coaly shales of the Billefjorden Group partially decoupled uppermost Devonian–Permian sedimentary rocks of the Billefjorden and Gipsdalen groups from Devonian rocks during Cenozoic contraction–transpression. In addition, Devonian strata probably experienced syn-depositional, post-Caledonian, extensional, detachment-related folding. Seismic data in Sassenfjorden and Reindalspasset show the presence of Cenozoic duplexes and bedding-parallel décollements within Lower–Middle Devonian, uppermost Devonian–Mississippian and uppermost Pennsylvanian–lowermost Permian sedimentary strata of the Wood Bay and/or Widje Bay and/or Grey Hoek formations, of the Billefjorden Group and of the Wördiekammen Formation respectively, which further decoupled stratigraphic units during Eurekan deformation. Bedding-parallel décollements and thrusts are possibly related to shortcut faulting, a roof décollement of a

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fault-bend hanging wall (or ramp) anticline, an imbricate fan, antiformal thrust stacks and/or fault-propagation folds over reactivated/overprinted basement-seated faults. Seismic data in Reindalspasset also indicate that Devonian sedimentary rocks might have deposited east of the Billefjorden Fault Zone, thus ruling out Late Devonian reverse movement along the Billefjorden Fault Zone in this area. Based on the present findings, juxtaposition of Proterozoic basement rocks against Lower Devonian sedimentary rocks along the Balliolbreen Fault in central Spitsbergen (e.g., Pyramiden–Odellfjellet) may be explained by down-east Carboniferous normal faulting with associated footwall rotation and exhumation and subsequent top-west Cenozoic thrusting along the Billefjorden Fault Zone. The uncertain relationship of the Balliolbreen Fault with uppermost Devonian–Mississippian sedimentary strata, the poorly constrained nature of the contact (unconformity or bedding-parallel décollements and thrusts?) between Lower Devonian and uppermost Devonian–Mississippian sedimentary strata, and along strike variations in cross-section geometry, offset stratigraphy, and inferred timing and kinematics along the Balliolbreen Fault suggest that this fault consists of several, discrete, unconnected (soft-linked and/or stepping) or, most probably, offset fault segments that were reactivated/overprinted with varying degree during Eurekan deformation due to strain partitioning. Finally, recent evidence for Devonian core complex exhumation and reinterpretation of presumed Ellesmerian structures and of Late Devonian amphibolite facies metamorphism suggest that Ellesmerian contraction is not necessary to explain fault geometries and (differential) deformation within Devonian–Permian sedimentary strata in Spitsbergen.

1. Introduction

The Ellesmerian Orogeny, also known as the Innuitian or Svalbardian Orogeny, refers to a short-lived episode of contraction–transpression that occurred in the Late Devonian–earliest Mississippian, when parts of the tectonic plates now constituting most of the Arctic (Laurentia and Baltica) collided with each other and deformed Franklinian basement in northerneastern Russia (Malyshev et al., 2011; Luchitskaya et al., 2015), Canada (Trettin, 1973, 1991; Embry and Klovan, 1976; Embry, 1991; Harisson, 1995; Harisson and Brent, 2005; Piepjohn et al., 2008, 2013; Piepjohn and van Gosen, 2017) and Alaska (Grantz and May, 1984; Kumar et al., 2011), Precambrian basement units in northeastern Greenland (Higgins et al., 2000; Piepjohn et al., 2015), and Devonian collapse basins and Precambrian–early Paleozoic basement in Norway (Roberts,

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1983; Osmundsen et al., 1998) and Svalbard (McCann, 2000; Piepjohn, 2000; Piepjohn et al., 2000; Figure 1a). The best example of Ellesmerian tectonism is observed in central Spitsbergen, in the Svalbard Archipelago, where folded Devonian sedimentary rocks are unconformably overlain by undeformed Mississippian sedimentary strata of the Billefjorden Group (Piepjohn, 2000; Piepjohn et al., 2000).

However, despite the numerous works showing evidence in favor of such contractional–transpressional tectonic event, a few studies highlight evident shortcomings of this tectonic model. Notably, Rippington et al. (2010) noticed that this contractional episode, though well-studied through the Arctic (e.g., in Arctic Canada, northern Greenland, and central Spitsbergen) currently lacks time constraints and, in places, structures ascribed to this event might partly belong to the early Paleozoic Caledonian Orogeny and/or to the Cenozoic Eurekan deformation event. Furthermore, in western Norway, east- to northeast-plunging folds trending parallel to the late–post-orogenic extension direction in Middle Devonian collapse basins initially interpreted as contractional–transpressional structures formed during an episode of (Ellesmerian) Late Devonian–Mississippian contraction (Roberts, 1983) were reinterpreted as transtensional folds formed during a late phase of the extensional collapse of the Caledonides (Chauvet and Séranne, 1994; Osmundsen and Andersen, 1994; Fossen et al., 2013).

The present contribution proposes an alternative tectonic model to the Ellesmerian Orogeny in Spitsbergen. Field data from Pyramiden (Figure 1b**Error! Reference source not found.**), a key locality used to establish the occurrence of the Ellesmerian Orogeny in central Spitsbergen (Piepjohn, 2000; Piepjohn et al., 2000; Rippington et al., 2010), challenge the commonly accepted Ellesmerian contractional–transpressional tectonic event in central Spitsbergen. Contractional structures in uppermost Devonian–Mississippian coal seams and shales of the Billefjorden Group are compared to undeformed overlying Mississippian clastic sedimentary deposits in Pyramiden (present study) and Odellfjellet (Koehl and Muñoz–Barrera, 2018; Figure 1b). The study discusses the roles and formation mechanisms of bedding-parallel décollements (i.e., parallel to initially undeformed bedding surfaces) and imbricate link thrusts (McClay and Insay, 1986) arranged into gently dipping duplexes in partial decoupling of Cenozoic contraction–transpression, and uses these structures to explain the significant differences in deformation state observed between folded Devonian sedimentary rocks and adjacent–overlying, undeformed, post-Devonian sedimentary deposits of the Billefjorden and Gipsdalen groups. The study also discusses the geometry, extent,

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kinematics and timing of formation and reactivation/overprint of the Balliolbreen Fault, a major segment of the east-dipping Billefjorden Fault Zone, and reinterprets Ellesmerian structures throughout Spitsbergen based on the presence of bedding-parallel thrusts and décollements in the Billefjorden Group in Pyramiden, Sassenfjorden and Reindalspasset (Figure 1a–b). The present findings and proposed tectonic model are briefly compared to recent studies in the SW Barents Sea (Koehl et al., 2018), northern (Steltenpohl et al., 2004, 2011) mid- (Eide et al., 2002; Braathen et al., 2002; Kendrik et al., 2004; Osmundsen et al., 2005) and western Norway (Chauvet and Séranne, 1994; Dunlap and Fossen, 1998; Eide et al., 1999; Braathen et al., 2000), and Northeast Greenland (Sartini-Rideout, 2006; Hallett et al., 2014; McClelland et al., 2016).

The presented evidences question the occurrence of the Ellesmerian Orogeny in Svalbard, and broader implications of the proposed tectonic model include the occurrence of the Ellesmerian Orogeny in other Arctic regions like northeastern Greenland, northern Canada, northern Alaska, and northeastern Russia, and the actual timing of formation of fold and thrust structures ascribed to this tectonic event, which might have formed (and were reactivated/overprinted) during Caledonian or Eurekan tectonism and/or during Devonian extensional collapse of the Caledonides. The present study simplifies the tectonic history of Spitsbergen, arguing for a continuous episode of late–post-Caledonian extensional collapse–rifting throughout the Devonian–Carboniferous. However, future work is required to further test the proposed tectonic model and constrain the tectonic setting during the deposition of Devonian–Mississippian sedimentary rocks throughout the Arctic, notably off the coasts of Alaska and northeastern Russia (Endicott Group), and of northern Canada (Emma Fiord Formation).

2. Geological setting

2.1. Caledonian Orogeny

The Svalbard Archipelago is composed of three terranes (excluding Bjørnøya) with significantly different geological histories. These terranes are thought to have started to assemble during Caledonian contraction–transpression and were juxtaposed against one another by N–S-striking crustal faults like the Billefjorden Fault Zone (Harland and Wright, 1979; Ohta et al., 1989, 1995; Gee and Page, 1994). Caledonian deformation was accompanied by tectonothermal events with high-grade (eclogite and blueschist) metamorphism from mid-Cambrian to late Silurian times

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that occurred during subduction and closure of the Iapetus Ocean and that are partly preserved in northwestern (Ohta et al., 1989) and western Spitsbergen (Horsfield, 1972; Kośmińska et al., 2014).

Caledonian grain in western, northwestern, central and eastern Spitsbergen forms major, gently plunging, N–S-trending folds and thrust stacks with well-developed foliation, e.g., the Atomfjella Antiform in Ny-Friesland (Figure 1b), an antiformal thrust stack that consists of a succession of nappes composed of Proterozoic granite and metasedimentary rocks separated by west-verging (Flood et al., 1969; Balashov et al., 1993; Witt-Nilsson et al., 1998; Johansson and Gee, 1999; Johansson et al., 2004, 2005) and/or top-east thrusts (Manby and Michalski, 2014).

2.2. Devonian post–late orogenic collapse

In the Early Devonian, late–post-Caledonian gravitational collapse initiated (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished) leading to the deposition of several km-thick (Old Red Sandstone) basins throughout Spitsbergen (Birkenmajer and Turnau, 1962; Harland et al., 1974; Manby and Lyberis, 1992; Manby et al., 1994; Dallmann and Piepjohn, submitted) and emplacement of late-orogenic plutons in northwestern, central and eastern Spitsbergen (Hamilton et al., 1962; Gayer et al., 1966; Ohta et al., 2002; Myhre et al, 2008).

In northern Spitsbergen, Devonian sedimentary rocks of the Red Bay and Andrée Land groups deposited during extension and subsidence along N–S-striking normal faults, forming west-tilted (half-) grabens, e.g., in Raudfjorden, Bockfjorden (Manby and Lyberis, 1992; Manby et al., 1994), Andrée Land and Kota (Roy, 2007, 2009; Roy et al., unpublished; Figure 1a). However, other works argue that Devonian sedimentary deposits in Svalbard deposited along low-angle, post-Caledonian detachments that accommodated large amounts of top-east, normal movement (e.g., the Woodfjorden detachment) and are associated with syn-kinematic east-verging folds (Roy, 2007, 2009; Roy et al., unpublished). In addition, recent studies show that basement ridges, e.g., the Bockfjorden Anticline in northwestern Spitsbergen, may have exhumed as core complexes along low-angle extensional detachments (e.g., the Keisarhjelmen detachment), and K–Ar geochronology suggests that exhumation occurred in late Silurian to Late Devonian times (Braathen et al., 2018).

In southern Spitsbergen, Devonian sedimentary rocks of the Marietoppen Formation (time equivalent to the Pragian–Eifelian Wood Bay–Grey Hoek formations at the base of the Andrée Land Group) unconformably overlie Precambrian–early Paleozoic basement rocks and are overlain

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by tightly folded sedimentary strata of the Late Devonian (–Mississippian?) Adriabukta Formation (time equivalent of the upper Andrée Land Group; Birkenmajer and Turnau, 1962; Birkenmajer, 1964; Cutbill and Challinor, 1965; Dallmann et al., 1993a; Bergh et al., 2011).

2.3. Ellesmerian contraction

Ellesmerian contraction is thought to have initiated in the Late Devonian, possibly in the Late Frasnian–Famenian (Vigran, 1964; Allen, 1965, 1973; Pcelina et al., 1986; Brinkmann, 1997; Schweitzer, 1999; Piepjohn et al., 2000) and was presumably recorded by the deposition of coarse-grained sedimentary rocks of the Planteryggen and Plantekløfta formations (Piepjohn and Dallmann, 2014). However, recent fossil and spore analysis suggest an early Frasnian (ca. 380 Ma) age for these stratigraphic units (Berry and Marshall, 2015). Contraction is believed to have stopped prior to the deposition of middle–late Famenian–Mississippian (Scheibner et al., 2012; Lindemann et al., 2013; Marshall et al., 2015; Würtzen et al., 2019; Lopes, pers. comm. 2019) sedimentary rocks of the Billefjorden Group (Piepjohn, 2000). Previous works also suggested that hundreds–thousands of kilometer scale strike-slip movement along N–S-striking faults, e.g., Billefjorden Fault Zone, finalized the accretion of basement terranes constituting the Svalbard Archipelago (Harland et al., 1974; Harland and Wright, 1979; Ohta et al., 1989), while more recent studies argue for limited amounts of strike-slip movement (McCann, 2000; Piepjohn, 2000).

In Pyramiden, in Dickson Land (northern–central Spitsbergen; Figure 1b), Proterozoic basement rocks were thrusted top-west onto Lower Devonian sedimentary rocks of the Wood Bay Formation along the Balliolbreen Fault (Piepjohn, 2000; Bergh et al., 2011; Braathen et al., 2011) in Late Devonian times, and presumably undeformed Mississippian clastic and coal-bearing sedimentary deposits of the Billefjorden Group overlie folded Lower Devonian metasedimentary rocks that were involved in Ellesmerian contraction (Piepjohn, 2000). West of Pyramiden, the lower Munindalen thrust transported Lower Devonian sedimentary rocks of the Wood Bay Formation over lower Frasnian (Berry and Marshall, 2015; Newman et al., 2019) sedimentary strata of the Plantekløfta Formation and is presumably unconformably overlain by flat-lying, undeformed, uppermost Pennsylvanian–lower Permian strata of the Wördiekammen Formation (McCann and Dallmann, 1996; MIchaelsen et al., 1997; Michaelsen, 1998; Piepjohn, 2000; Bergh et al., 2011). In Triungen (Figure 1a–b), folded Lower Devonian rocks of the Wood Bay Formation are juxtaposed against flat-lying, undeformed, Carboniferous–Permian strata of the Billefjorden

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Group and Wördiekammen Formation along the Triungen–Grønhorgdalen Fault Zone (McCann and Dallmann, 1996). In Sentinelfjellet and Odellfjellet (Figure 1b), the Balliolbreen Fault juxtaposes Proterozoic basement rocks in the hanging wall against Devonian sedimentary rocks in the footwall and is thought to be unconformably overlain by undeformed, uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group, thus suggesting Late Devonian contraction (Friend and Moody-Stuart, 1972; Harland et al., 1974; Lamar et al., 1986). Farther north, in Andrée Land (Figure 1a), west-verging (i.e., opposite to Cenozoic folds in western and southern Spitsbergen) folds are believed to represent evidence of Ellesmerian tectonic movements, although timing remains speculative because most post-Devonian sedimentary rocks in the area were eroded (Piepjohn, 2000).

In southern Spitsbergen, in Hornsund (Figure 1a), Ellesmerian folds and thrusts trend parallel to Cenozoic structures and verge towards the east, i.e., opposite to Ellesmerian folds in Andrée Land (Bergh et al., 2011; Dallmann and Piepjohn, submitted). The main argument for Ellesmerian tectonism in southern Spitsbergen is the occurrence of a ca. 250–300 m-thick shear zone, the Mariekammen Shear Zone (Bergh et al., 2011), within tightly folded, steeply dipping–subvertical, Upper Devonian–Mississippian, shaly sedimentary beds of the Adriabukta Formation (Birkenmajer and Turnau, 1962; Birkenmajer, 1964; Cutbill and Challinor, 1965; Dallmann et al., 1993a; Dallmann, 1999). The shear zone comprises hundreds of meter-long lenses of Cambrian metasedimentary basement rocks showing foliation/bedding surfaces (sub) parallel to the shear zone and to bedding surfaces within the Adriabukta Formation (Birkenmajer and Turnau, 1962; Birkenmajer, 1964; Bergh et al., 2011). These lenses are offset along the shear zone with dominant top-east, reverse dip-slip kinematic indicators (Bergh et al., 2011). Upwards, the Mariekammen Shear Zone is truncated by a moderately dipping erosional unconformity above which Pennsylvanian sedimentary rocks of the Hyrnefjellet Formation were deposited (Birkenmajer, 1959, 1964; Dallmann, 1999).

Recent Th–U–Pb geochronology on monazite yielded 371–355 Ma (latest Devonian–earliest Mississippian) ages for amphibolite facies metamorphism (Kośmińska et al., 2017; Majka and Kośmińska, 2017) along a gently west-dipping shear zone in Prins Karls Forland (Figure 1a), the Bouréefjellet fault zone, which crosscuts basement rocks of the Pinkie Unit (Faehnrich et al., 2017; Schneider et al., 2018), suggesting Ellesmerian deformation also affected western Spitsbergen.

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2.4. Carboniferous basins

In Carboniferous times, ENE–WSW extension formed narrow, km- to tens of km-wide, N–S- to NW–SE-trending troughs, e.g., Billefjorden Trough (Maher Jr., 1996; McCann and Dallmann, 1996; Braathen et al., 2011), bounded by major faults such as the Billefjorden Fault Zone (Harland et al., 1974), which was reactivated as a normal fault from Austfjorden in the north to Reindalspasset in the south (Bælum and Braathen, 2012; Figure 1a–b).

Shortly after the end of Ellesmerian contraction, partly eroded Devonian sedimentary rocks were covered by uppermost Devonian–Mississippian (Marshall et al., 2015), fluvial, coal- and clastic-rich deposits of the Billefjorden Group (Cutbill and Challinor, 1965; Cutbill et al., 1976; Gjelberg, 1981, 1984). These are divided into the Hørbyebreen and Mumien formations, which are composed of the Triungen and Hoelbreen, and Sporehøgda and Birger Johnsonfjellet members respectively. The Triungen and Sporehøgda members dominantly consist of clastics whereas the Hoelbreen and Birger Johnsonfjellet members are composed of coal seams and coaly shales (Cutbill and Challinor, 1965; Cutbill et al., 1976; Gjelberg and Steeel, 1981; Gjelberg, 1984).

These deposits are found in Arctic areas stretching from the Barents Sea (Bugge et al., 1995; Larssen et al., 2002) to Arctic Canada (Emma Fiord Formation; Davies and Nassichuck, 1988) and were presumably deposited during a period of tectonic quiescence (Johannessen and Steel, 1992; Braathen et al., 2011; Smyrak-Sikora et al., 2018), though a syn-tectonic deposition was also proposed for these rocks in Arctic Canada (Beauchamp et al., 2019), the Barents Sea (Koehl et al., 2018), Bjørnøya (Gjelberg, 1981), and in Spitsbergen in the northern part of the Billefjorden Trough (Koehl and Muñoz-Barrera, 2018).

In the Pennsylvanian, fluvial to shallow marine sedimentary strata of the Gipsdalen Group were deposited in subsiding basins. These are divided into the Hultberget, Ebbadalen, Minkinfjellet, Wördiekammen and Gipshuken formations in central Spitsbergen (Cutbill and Challinor, 1965; Johannessen, 1980; Gjelberg and Steel, 1981; Johannessen and Steel, 1992; Braathen et al., 2011; Smyrak-Sikora et al., 2018) and into the Hyrnefjellet and Treskelodden formations in southern Spitsbergen (Cutbill and Challinor, 1965), all of which range from late Serpukhovian to earliest Permian in age.

Sedimentary strata of the Gipsdalen Group are mostly composed of clastic, carbonate and evaporitic deposits and karst breccia, and represent the thickest sedimentary succession in the

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Billefjorden Trough (McWhae, 1953; Cutbill and Challinor, 1965; Holliday and Cutbill, 1972; Johannessen, 1980; Lønøy, 1995). The deposition of sedimentary strata of the Hultberget, Ebbadalen, Minkinfjellet, and Hyrnefjellet formations was accompanied by kilometer scale displacement along N–S-striking faults like the Billefjorden Fault Zone, whereas the Wördiekammen, Gipshuken and Treskelodden formations were deposited during minor tectonic activity (Gjelberg and Steel, 1981; Fedorowski, 1982; Braathen et al., 2011; Smyrak-Sikora et al., 2018).

2.5. Eurekan deformation event

In the Paleocene (ca. 62 Ma), Eurekan transpression initiated in western Spitsbergen due to the opening of the Labrador Sea and Baffin Bay between Canada and Greenland (Chalmers and Pulvertaft, 2001; Oakey and Chalmers, 2012) and resulted in the formation of the West Spitsbergen Fold-and-Thrust Belt between Kongsfjorden and Sørkapp (Harland, 1969; Lowell, 1972; Harland and Horsfield, 1974; Maher et al., 1986; Dallmann et al., 1988; Dallmann et al., 1993b; Andresen et al., 1994; Bergh and Grogan, 2003) and formation of a foreland basin, the Tertiary Central Basin in central Spitsbergen (Larsen, 1988; Petersen et al., 2016). Eurekan thrusts and folds in Spitsbergen dominantly strike and trend NNW–SSE (Harland and Horsfield, 1974; Bergh and Andresen, 1990; Dallmann et al., 1993b; Bergh et al., 2011; Blinova et al., 2012) except in Kongsfjorden (Figure 1a) where they strike and trend WNW–ESE (Bergh and Andresen, 1990; Bergh et al., 2000; Saalmann and Thiedig, 2000; Piepjohn et al., 2001). Cenozoic thrusts in western Spitsbergen commonly form décollements in shaly beds, e.g., in Triassic shales in Midterhuken (Maher, 1984; Maher et al., 1986; Figure 1a). In central–eastern Spitsbergen, major N–S-striking brittle faults like the Billefjorden Fault Zone were partly reactivated by Eurekan contraction in Flowerdalen (Harland et al., 1974; Haremo et al., 1990; Haremo and Andresen, 1992; Figure 1b) and Reindalspasset (Bælum and Braathen, 2012) in the south, but were apparently unaffected in nothern areas like Sentinelfjellet (Figure 1b) where uppermost Devonian–Mississippian strata seem to unconformably lie over the fault (Harland et al., 1974).

3. Methods

3.1. Seismic, field and petrological data, and satellite images

The present contribution uses satellite images (from toposvalbard.npolar.no) and structural measurements of bedding and fracture surfaces in Devonian–Mississippian sedimentary strata collected in summer 2016 in Pyramiden (Figure 1b). The study also uses microscopic analysis of fault rocks and sedimentary rocks adjacent to brittle faults as a confirmation tool (included in supplement 1).

Seismic data in nearshore fjords in central Spitsbergen are from the Norwegian Petroleum Directorate and uninterpreted seismic lines are provided in supplement 2. Seismic interpretation was tied to data from exploration well 7816/12-1 in Reindalspasset (Figure 1a–b; Eide et al., 1991) and time conversion of well data is based on checkshots from Equinor and Store Norske Spitsbergen Kulkompani. The well penetrated late Paleozoic–Mesozoic sedimentary rocks and ends at a depth of 2261 m with 54 m of Mississippian strata of the Billefjorden Group.

3.2. Restoration of the Adriabukta cross-section in southern Spitsbergen

The Adriabukta section (see figures 4 and 5 in Bergh et al., 2011) is a c. 5 km-wide, E–W transect in southern Spitsbergen where erosion exposed Precambrian basement and Devonian–Cretaceous sedimentary rocks (Bergh et al., 2011). In order to investigate the initial geometry of Devonian–Mississippian sedimentary rocks and faults prior to Cenozoic transpression, the unconformity surface between the Hyrnefjellet and Adriabukta formations was restored to a horizontal geometry. In addition, Triassic–Cretaceous sedimentary rocks were removed together with the effect of Mesozoic–Cenozoic normal faulting. A major change applied to the section was the rotation of the Mariekammen Shear Zone (Bergh et al., 2011), which crosscuts the Adriabukta Formation, by an angle equal to the rotation applied to the unconformity at the contact between the Adriabukta and Hyrnefjellet formations (c. 50° counterclockwise).

4. Results

4.1. Field and petrological data, and satellite images

4.1.1. Pyramiden

In Pyramiden, a steeply east-dipping, N–S-striking brittle fault crops out in a gully below the entrance of the Russian coal mine (Figure 2). This fault is located half-way to the mine in the gully and crosscuts steeply east-dipping Lower Devonian sedimentary rocks of the Wood Bay Formation, which are involved into an east-verging fold with locally overturned eastern limb

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(Figure 2 and Figure 3a, and supplement 3). The fault shows meter-thick lenses of cataclastic fault rock (supplement 1). Devonian sedimentary rocks are dominated by poorly deformed quartz crystals showing undulose extinction and limited recrystallization (supplement 1), whereas cataclastic fault rock shows distributed fractures with little (centimeter-scale) to no displacement.

There is no trace of Hecla Hoek basement in this area although field studies and geological maps suggest that Proterozoic basement were thrusted over Lower Devonian strata along the Balliolbreen Fault (McCann and Dallmann, 1996; Piepjohn et al., 1997; Dallmann, 1999; Dallmann et al., 2004; Bergh et al., 2011; Braathen et al., 2011; svalbardkartet.npolar.no). Sample preparation for thin sectioning actually proved problematic for Devonian sedimentary rocks located in the hanging wall of the presumed fault, which resulted in a misleading thick section (supplement 1). Thus, it is more likely that earlier maps showing exclusively Devonian–Mississippian sedimentary rocks of the Wood Bay Formation and Billefjorden Group below the mine entrance by Harland et al. (1974), Lamar et al. (1986), and Arktikugol (1988; Sirotkin, pers. comm. 2019) are correct.

Farther up the gully, a one–two meter-thick succession of interbedded sandstone and coal is juxtaposed against steeply east-dipping Devonian strata to the west and overlain by a (at least three meter) thick layer of uppermost Devonian–Mississippian coals of the Billefjorden Group that shows phyllitic shear fabrics (Figure 2 and Figure 3b). Bedding surfaces within the one–two meter-thick succession dip gently–steeply to the east (Fig. Figure 3a), display sigmoidal geometries with Z-like shapes, and terminate abruptly against the three meter-thick layer of uppermost Devonian–Mississippian phyllitic coal upwards and against Devonian rocks downwards (dashed yellow lines in Fig. Figure 3b). In addition, coaly shales within this succession display phyllitic fabrics similar to those observed within overlying coals, and seem to form repeated successions of alternating beds of sandstone and coaly shale truncated by steeply east-dipping sigmoidal fault surfaces (thin dashed red lines in Fig. Figure 3b). The Z-like sigmoidal shape of bedding surfaces, phyllitic shear fabrics of the coaly shales, and possible repetitions of the succession suggest that the steeply east-dipping, sigmoidal faults crosscutting the succession are imbricate thrust faults (stereonet 3 in Figure 2), i.e., possible link thrusts (McClay and Insley, 1986), which accommodated top-west to top-WNW movements. The truncation of sandstone–coaly shale beds upwards and downwards, the abrupt transition with underlying Devonian rocks and overlying uppermost Devonian–Mississippian coals, and Z-shaped phyllitic shear fabrics within overlying coals suggest that the sandstone–coaly shale succession is bounded by moderate–low-angle, east-dipping floor- and roof-thrusts (McClay,

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1992) with top-west to top-WNW sense of shear. In cross-section, the interaction of intra-succession, steeply east-dipping link thrusts and inter-succession, moderate–low-angle floor- and roof-thrusts defines an east-dipping duplex structure (Boyer and Elliott, 1982) of imbricate thrusts bounded upwards and downwards by potential décollements and/or detachments parallel to original (i.e., prior to deformation) bedding surfaces (e.g., transition from interbedded coaly shales and sandstone to coal, and from coal to sandstone; Figure 3b). The nomenclature of hindward/forward-dipping duplexes of Boyer and Elliott (1982) does not apply here since the foreland of the West Spitsbergen Fold-and-Thrust Belt (Tertiary Central Basin) is located southeast of Pyramiden. Thus, the term "backward" is used to describe the east-dipping character of the duplexes, i.e., opposite to the inferred transport direction.

Above the mine entrance, sedimentary rocks of the Billefjorden Group are dominated by yellow sandstone that are crosscut by dominant WNW–ESE-striking fractures and subsidiary N–S- and ENE–WSW-striking fractures (stereonets 1 and 2 in Figure 2) showing oblique-slip kinematics. Poorly preserved slickenside lineations did not yield any information on relative displacement between footwall and hanging wall. In the west, dark sandstone and quartzite crop out and contain wood fossils, which are probably Devonian in age. The contact between the Devonian dark sandstone and uppermost Devonian–Mississippian yellow sandstone of the Billefjorden Group, and intra-Devonian lithological contacts (e.g., between Devonian quartzite and dark sandstone; Fig. Figure ***3***a), although partly covered by screes and/or mostly made of loose blocks, do not appear to be faulted and trend c. WNW–ESE to NW–SE as bedding surfaces appear to change from moderately–steeply east-dipping below the mine entrance to gently NNE-dipping above the mine entrance (Figure 2 and Figure ***3***a), i.e., parallel to the dominant fault trend in both uppermost Devonian–Mississippian (stereonet 1 in Figure 2) and Devonian rocks (stereonet 4 in Figure 2).

Noteworthy, most outcrops of uppermost Devonian–Mississippian strata in this part of the study area trend E–W to WNW–ESE. Thus, the dominance of WNW–ESE-striking faults is unlikely the result of measurements flawed by a preferential outcrop trend, since E–W- to WNW–ESE-trending outcrops would rather favor identification and measurement of N–S-striking faults.

A possible interpretation of outcrops and structures in Pyramiden (Figure 1b) is that subvertical, N–S-striking brittle faults within steeply east-dipping Lower Devonian strata in the gully below the coal mine entrance (Figure 2 and Figure ***3***a) represent the Balliolbreen Fault

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segment of the Billefjorden Fault Zone, and that low-angle roof/floor thrusts between Lower Devonian rocks and the overlying succession of uppermost Devonian–Mississippian sandstone, coaly shale and coal (Fig. Figure 3b) correspond to the upward-flattening continuation of this fault. However, no fault was observed between Devonian rocks and sandstones of the Billefjorden Group above the mine, and lithogical and stratigraphic contacts there display significantly different trends (WNW–ESE to NW–SE; Fig. Figure 3a).

4.1.2. Triungen

Satellite images in Triungen (Figure 1a–b) show that the Triungen–Grønhorgdalen Fault Zone (McCann and Dallmann, 1996) and the contact between Lower Devonian of the Wood Bay Formation and overlying uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group in the hanging wall are largely covered by dark screes (Fig. Figure 3c). Based on the presence of thick, flat-lying, coal-rich strata in the lower part of the Billefjorden Group overlying Lower Devonian sedimentary strata in the hanging wall of the fault, the dark screes along the fault trace (right hand-side inset in Fig. Figure 3c) are believed to represent uppermost Devonian–Mississippian coals–coaly shales that might have been dragged along the Triungen–Grønhorgdalen Fault Zone during tectonic movements.

4.2. Seismic data

4.2.1. Seismic units and stratigraphy

In seismic sections, Precambrian–Caledonian basement rocks commonly show chaotic reflections, most likely arising from their complex tectonic history (e.g., Caledonian folding, shearing, thrusting and post-Caledonian extensional and contractional overprints), and subparallel reflections, possibly corresponding to seismic artifacts (e.g., multiples; Figure 4a–g).

In Reindalspasset (Figure 1a–b), potential Devonian rocks display partly disrupted, semi-continuous, sub-parallel to chaotic, moderate- to low-amplitude seismic reflections (Figure 4g). Devonian rocks in Reindalspasset are likely composed thick successions of medium- to fine-grained sedimentary rocks such as siltstone and shales, possibly of the Lower–Middle Devonian Wood Bay and/or Grey Hoek and/or Wijde Bay formations, or their time-equivalent in southern Spitsbergen, the Marietoppen Formation.

Uppermost Devonian–Mississippian sedimentary rocks are characterized by high-amplitude seismic reflections that are most likely the product of acoustic impedance contrast between low density coal seams interbedded with clastic deposits. Such seismic facies is relatively common for uppermost Devonian–Mississippian sedimentary rocks in the Norwegian Barents Sea (Koehl et al., 2018; Tonstad, 2018). In Reindalspasset, uppermost Devonian–Mississippian, phyllitic, coal-rich deposits of the Billefjorden Group were penetrated by exploration well 7816/12-1 at a depth of 2261 m (Eide et al., 1991), which corresponds to a time of 0.96 s (TWT) when time-converted (Figure 4g).

Pennsylvanian–Permian sedimentary strata of the Gipsdalen Group are mostly composed of packages of subparallel low- to moderate-amplitude seismic reflections separated by discrete, moderate- to high-amplitude reflections. The Hultberget and Ebbadalen formations dominantly show partly disrupted, subparallel reflections possibly representing medium- to fine-grained sedimentary strata (e.g., of the Trikolorfjellet Member) that, in places, alternate with chaotic seismic facies probably characterizing coarse-grained sedimentary deposits (e.g., of the Odellfjellet and/or Ebbaelva members; Johannessen, 1980; Johannessen and Steel, 1992; Braathen et al., 2011; Smyrak-Sikora et al., 2018). The Minkinfjellet and Wördiekammen formations are dominated by a thick package of sub-parallel, moderate- to low-amplitude seismic reflections mostly representing carbonate and gypsum deposits (Figure 4). The top reflection of the Wördiekammen Formation is characterized by high amplitude and is relatively easy to trace throughout the study area (Figure 4). Finally, the Gipshuken Formation displays chaotic to subhorizontal and subparallel low-amplitude seismic reflections (Figure 4). The Wördiekammen and Gipshuken formations are easily identified on seismic data because they crop out at sea level along the northern shore of Sassenfjorden and Tempelfjorden and, hence, can be directly tied to onshore geology (Dallmann et al., 2004, 2009; Dallmann, 2015). Mesozoic sedimentary rocks are not the focus of the present study and were therefore not described.

4.2.2. Structures in Sassenfjorden–Tempelfjorden

Seismic data in Sassenfjorden–Tempelfjorden (Figure 1a–b) show that basement rocks and overlying, uppermost Devonian–Permian sedimentary rocks of the Billefjorden and Gipsdalen groups are folded into two open, upright, NW–SE- to WNW–ESE-trending fold structures that coincide with similarly trending, several kilometer-wide, elongated ridges representing uplifted

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portion of the seafloor in Sassenfjorden and Billefjorden (Koehl, 2019; Koehl et al., in prep.), and with steeply NNE-dipping, basement-seated faults mostly confined to basement (–Devonian?) rocks and uppermost Devonian–Mississippian, coal-rich deposits of the Billefjorden Group, or that die out upwards in the lower part of the Gipsdalen Group (Figure 4a). Based on the minor reverse, top-SSW offset of thickened uppermost Devonian–Mississippian sedimentary strata, it is probable that the two gentle fold structures formed in the early Cenozoic as fault-propagation folds due to upward propagation and reverse reactivation/overprinting of NNE-dipping basement-seated faults.

Seismic data in Sassenfjorden and Tempelfjorden (Figure 1a–b) also show that high-amplitude seismic reflections characterizing uppermost Devonian–Mississippian sedimentary rocks significantly thicken (approximately twice thicker) towards the south-southwest, near the intersection of the east-dipping Billefjorden Fault Zone with NNE-dipping basement-seated faults, potentially suggesting that uppermost Devonian–Mississippian rocks represent early syn-rift sedimentary deposits (Prosser, 1993) and are part of the initiation stage (Gawthorpe and Leeder, 2003) of the Billefjorden Trough (Figure 4a–b). There, high-amplitude seismic reflections representing coal-rich uppermost Devonian–Mississippian strata display laterally disrupted, (SSW-) tilted, Z-shaped geometries (Figure 4b and e) that contrast with continuous, subparallel geometries of the reflections in the northeast (Figure 4a, c, d and e). Since similar Z-shaped geometries interpreted as duplex structures comprised of bedding-parallel décollements (floor- and roof-thrusts) connected by bedding-oblique link-thrusts were encountered in locally thickened, coal-rich, uppermost Devonian–Mississippian sedimentary deposits in Pyramiden (Figure 3b), it is conceivable that, in Sassenfjorden–Tempelfjorden too, significant rheological contrasts between uppermost Devonian–Mississippian coal–coaly shale and sandstone of the Billefjorden Group localized the formation of duplex-related décollements and thrust faults during Cenozoic contraction–transpression.

Locally, moderate- to low-amplitude, subparallel seismic reflections of the Hultberget, Ebbadalen, Minkinfjellet and Wördiekammen formations are disrupted by and slightly bending along moderate to shallow dipping, bedding-oblique reflections, which are interpreted as minor Cenozoic thrust faults (Figure 4a, c, d and f). These minor thrusts appear to flatten downwards and die out within high-amplitude seismic reflections of the Billefjorden Group, thus supporting the presence of bedding-parallel décollements in uppermost Devonian–Mississippian sedimentary rocks (Figure 4c).

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Seismic reflections within the overlying Gipshuken Formation dip gently to moderately and display continuous to partly chaotic facies (Figure 4f). These are disrupted by possible gently NE- to east- and SW- to west-dipping thrusts that seem to flatten downwards into the Top Wördiekammen Formation reflection, forming part of possible imbricate thrust systems (Figure 4a, c, d and f) resembling thrusts within coals and coaly shales of the Billefjorden Group (Fig. Figure ***3***b). This suggests the presence of (a) décollement level(s) within the Wördiekammen Formation and/or at the boundary between the Wördiekammen and Gipshuken formations. Internal seismic packages display significant thickness variations, pinching out laterally and, in places, becoming as thick as the whole Gipshuken Formation (Figure 4a, c, d and f). These thickness variations are tentatively related to tectonic thickening due to Cenozoic thrusting and, potentially, to the presence of partially mobile evaporite within the Gipshuken Formation (Dallmann, 1999).

4.2.3. Structures in Reindalspasset

Seismic data in Reindalspasset (Figure 1a–b) show a N–S-trending open fold structure (Figure 4g). In Devonian rocks, the lowermost part of the fold shows semi-continuous to chaotic, moderate- to low-amplitude, locally undulating seismic reflections that display intensive disruption and wedge-shaped geometries (Figure 4g). Moderate- to low-amplitude reflections within wedge-shaped seismic packages display S- and Z-shaped geometries that are disrupted respectively by moderately west- and east-dipping reflections that appear to be responsible for the thickening of internal units and that flatten and die out upwards prior to or at the boundary with overlying uppermost Devonian–Mississippian rocks (Figure 4g). These wedge-shaped seismic packages are interpreted as thickened sheets crosscut by Cenozoic thrust faults that, in places, form duplex structures comprised of floor- and roof-thrusts connected by link thrusts. Associated undulating reflection geometries are thought to represent folding. Based on the sub-continuous, low- to moderate-amplitude seismic facies and on the presence of folds and bedding-subparallel thrusts, it is probable that (at least the upper part of) this seismic unit is composed of shale-rich, Lower–Middle Devonian sedimentary strata of the Wood Bay and/or Grey Hoek and/or Wijde formations.

The core of the fold is partly composed of gently west-dipping to flat-lying, high-amplitude seismic reflections representing coal-rich sedimentary strata of the Billefjorden Group, which were penetrated by exploration well 7816/12-1 at a depth of 2261 m (Eide et al., 1991), i.e., 0.96 s (TWT; Figure 4g). In the east, sedimentary strata of the Billefjorden Group can be traced as continuous,

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gently west-dipping, sub-parallel reflections that thicken westwards against the eastern limb of the fold and that are locally folded and disrupted by a few gently west-dipping, bedding-subparallel reflections that accommodate local thickening of the Billefjorden Group and, hence, may represent minor Cenozoic thrust faults (Figure 4g). High-amplitude reflections of the Billefjorden Group are thickest within the fold hinge, where they show undulating geometries and are intensively disrupted. These disruptions may be the result of Cenozoic thrusting along low-angle, bedding-subparallel faults, which are probably responsible for the thickening of uppermost Devonian–Mississippian strata within the fold hinge and are possibly forming part of an antiformal stack or ramp anticline (Figure 4g). The largest of these potential Cenozoic thrusts localized along the boundary between uppermost Devonian–Mississippian and Pennsylvanian sedimentary strata, i.e., parallel to the eastern limb of the fold, and splays upwards into four fault splays. This fault and associated splays quickly die out upwards within the fold hinge in the upper part of the uppermost Devonian–Mississippian and in the lower part of the Pennsylvanian sedimentary succession, offset sediments of the Billefjorden and Gipsdalen groups in a reverse manner (possible repeated portion of the Billefjorden Group), and flatten into the base of the Billefjorden Group or uppermost part of the Devonian succession (Figure 4g). The lowermost splay of this thrust was most likely penetrated by exploration well 7816/12-1 and consists of phyllitic coal and sheared coaly shales of the Billefjorden Group (Eide et al., 1991; Figure 4g). Bedding-parallel thrusts in uppermost Devonian–Mississippian strata are further supported by the presence of an analogous, sub-horizontal, bedding-parallel fault within the overlying Middle–Upper Triassic sedimentary rocks of the Barentsøya Formation, which was also penetrated by well 7816/12-1 and represents a possible Cenozoic décollement (Eide et al., 1991; see uppermost sub-horizontal fault in Figure 4g).

Continuous to semi-continuous, parallel, dominantly moderate- to high-amplitude seismic reflections representing Pennsylvanian–lower Permian sedimentary strata of the Hultberget, Ebbadalen, Minkinfjellet and Wördiekammen formations thicken eastwards and westwards away from the fold hinge, i.e., opposite to sedimentary rocks of the Billefjorden Group, and appear to be affected by much fewer disruptions and, therefore, to be only mildly deformed (Figure 4g). Pennsylvanian–lower Permian strata are thickest along the eastern fold limb where they are crosscut by three splays of the Cenozoic thrust localized along the boundary between the Billefjorden and Gipsdalen groups and by a steeply east-dipping brittle fault. This steeply east-dipping fault shows a planar geometry in cross-section, thickening of the Hultberget, Ebbadalen,

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Minkinfjellet and Wördiekammen formations in the hanging wall, minor normal offsets of seismic reflections within these stratigraphic units, and dies out within the lower part of the Wördiekammen Formation and the upper part of the Devonian succession. Based on cross-section geometries, offset kinematics, and thickening of stratigraphic units, this steeply dipping normal fault is tentatively interpreted as the potential continuation of the Billefjorden Fault Zone.

4.3. Adriabukta

The results of the restoration of the western portion of the Adriabukta section of Bergh et al. (2011) are displayed in Figure 5a–b. The restored section shows minor, meter- to tens of meter-scale normal displacement along a possibly Pennsylvanian–Permian fault offsetting the Pennsylvanian–Permian Hyrnefjellet and Treskelodden formations and terminating into the Upper Devonian (–Mississippian?) Adriabukta Formation. In addition, the erosional unconformity between the Adriabukta Formation and the overlying Hyrnefjellet Formation was restored to a flat-lying position by applying a 50° counterclockwise rotation. As a result, the Mariekammen Shear Zone (Bergh et al., 2011), bedding surfaces within the Adriabukta Formation, and the stratigraphic boundaries between the Adriabukta Formation and Middle Devonian Marietoppen Formation and between the Marietoppen Formation and basement rocks in the west now dip steeply (ca. 65–70°) to the east, seemingly forming the eastern flank of a kilometer-scale anticline (Figure 5b). In addition, the Mariekammen Shear Zone now displays apparent down-east normal kinematics (Figure 5b).

5. Discussion

5.1. Deformation structures within Devonian and uppermost Devonian–Mississippian sedimentary deposits in central Spitsbergen

5.1.1. Implications of contractional duplexes and décollements in Devonian–Mississippian sedimentary rocks for Ellesmerian and Cenozoic contraction

Uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group in Pyramiden (Fig. Figure ***3***b) and Sassenfjorden–Tempelfjorden (Figure 4a, b, d and e) are arranged in gently dipping duplexes comprised of interbedded coal–coaly shale and sandstone deposits with sigmoidal shear fabrics and (imbricate) link thrusts (McClay and Insay, 1986) connecting bedding-

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parallel décollements (roof and floor thrusts/detachments; McClay, 1992) localized along lithological boundaries (Phillipson, 2003, 2005; Molinda, 2003; Elizalde et al., 2016). This interpretation is supported by minor Cenozoic thrusts crosscutting the Hultberget, Ebbadalen, Minkinfjellet and Wördiekammen formations in Sassenfjorden–Tempelfjorden (Figure 1a–b) that flatten downwards and die out within sedimentary strata of the Billefjorden Group (Figure 4c), and by the presence of analogous shallow-dipping, bedding-parallel, duplex-shaped décollements in uppermost Devonian–Mississippian coals and coaly shales sedimentary strata of the Billefjorden Group in Odellfjellet (Koehl and Muñoz-Barrera, 2018), in Robertsonbreen (between the uppermost Devonian–Mississippian Hørbyebreen Formation and Pennsylvanian–Permian Wördiekammen Formation; Diβmann and Grewing, 1997), in northeastern Bjørnøya (Koehl, in prep.), at Midterhuken and in St-Jonsfjorden (where the unconformity between uppermost Devonian–Mississippian and Pennsylvanian sedimentary rocks possibly acted as a décollement; Maher and Welbon, 1992; Figure 1a), in Nordenskiöld Land (Braathen and Bergh, 1995), and, potentially, in Oscar II Land (Bergh and Andresen, 1990) and Wedel Jarlsberg Land–Torell Land (Dallmann and Maher, 1989; Figure 1a). Imbrication within the duplexes indicates top-west thrusting, and most likely reflects early Cenozoic contraction–transpression since it is the only post-Mississippian episode of contraction recorded in Spitsbergen. Similar Cenozoic duplex geometries with sigmoidal bedding surfaces and link thrusts were also observed in Triassic strata in Spitsbergen (Andresen et al., 1992; Haremo and Andresen, 1992; Andresen, 2009), thus supporting our interpretation of Cenozoic thrusting in Pyramiden.

In Reindalspasset, potential décollements and low-angle thrusts folded into a gentle upright anticline and possibly forming an antiformal thrust stack were identified on seismic data within Lower–Middle Devonian strata of the Wood Bay and/or Grey Hoek and/or Wijde Bay formations and uppermost Devonian–Mississippian rocks of the Billefjorden Group (Figure 4g). In tectonically thickened and mildly folded uppermost Devonian–Mississippian rocks, low-angle brittle–ductile thrust faults are comprised of phyllitic (i.e., sheared) and brittle coals (penetrated by well 7816/12-1 at a depth of 2261–2280 meters; Eide et al., 1991) that are similar to sheared uppermost Devonian–Mississippian coals in Pyramiden, and are arranged into potential duplexes that are comparable to duplexes and thrust systems in uppermost Devonian–Mississippian sedimentary rocks in Pyramiden (Figure 1 and Figure ***3***b) and Sassenfjorden–Tempelfjorden (Figure 1, and Figure ***4***b and e) and to analogous structures worldwide, e.g., in the Hikurangi

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subduction margin in New Zealand (Morley et al., 2017, their figure 8). Potential Devonian rocks show wedge-shaped duplex structures, décollements, folding and thrusting comparable to deformation structures in analog rocks in Andrée Land, e.g., Bråvallafjella Fold Zone (Piepjohn, 2000; Dallmann and Piepjohn, submitted) and southern Spitsbergen (e.g., Røkensåta; Figure 1a; Dallmann, 1992), thus supporting the presence of Devonian sedimentary rocks east of the Billefjorden Fault Zone in Reindalspasset, pending that the observed normal fault does actually represent the southern continuation of the Billefjorden Fault Zone (Fig. Figure **4**g; see section 5.1.3). The presence of décollements within Lower–Middle Devonian rocks is further supported by the observation of similar structures between shale and sandstone units of the Wood Bay and Grey Hoek formations in Andrée Land (Roy, 2007, 2009; Roy et al., unpublished).

Based on the significant differences in deformation styles, it is probable that the décollements and backward-dipping duplexes in sheared uppermost Devonian–Mississippian coals–coaly shales decoupled Cenozoic deformation between tightly folded, shale-rich, Lower Devonian rocks and undeformed to poorly-deformed (uppermost Devonian–) Mississippian clastic and Pennsylvanian–Permian sedimentary strata in Pyramiden (Figure 2 and Figure **3**b). Seismic data in Sassenfjorden–Tempelfjorden also show potential duplexes and décollements within uppermost Devonian–Mississippian coal-rich deposits (Figure 4a, b, d and e). In these fjords, steeply dipping, basement-seated brittle faults seem to have propagated upwards during Cenozoic transpression, resulting in fault-propagation folding and reverse offsets in uppermost Devonian–Permian sedimentary strata (Figure 4a and c). These faults die out upwards within uppermost Devonian–Pennsylvanian sedimentary rocks, while minor Cenozoic thrusts crosscutting Pennsylvanian–Permian sedimentary strata appear to flatten downwards and die out into high-amplitude seismic reflections interpreted as uppermost Devonian–Mississippian coals, thus, also suggesting decoupling of Cenozoic deformation by Cenozoic décollements in uppermost Devonian–Mississippian coals of the Billefjorden Group.

In Reindalspasset, Cenozoic duplexes and thrusts within potential Lower–Middle Devonian strata of the Wood Bay and/or Grey Hoek and/or Widje Bay formations die out upwards and minor thrusts within Carboniferous–Permian rocks die out downwards prior to or at the boundary with coal-rich sedimentary rocks of the Billefjorden Group (Figure 4g), thus also supporting the presence of Cenozoic décollements within uppermost Devonian–Mississippian coaly shales and coals and (partial) decoupling of Cenozoic deformation. Thickened coal-rich deposits are long

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known to be able to decouple deformation both in contractional (Frodsham and Gayer, 1999, their figures 1b, 2, 7 and 9) and extensional settings (Wilson and Wojtal, 1986, their figures 7 and 10). In Svalbard, recent field studies by Koehl and Muñoz (2018) in the northern part of the Billefjorden Trough in Odellfjellet (Figure 1b) showed that bedding-parallel duplex-shaped décollements in uppermost Devonian–Mississippian coaly shales may have partly inhibited Cenozoic contraction–transpression in overlying Pennsylvanian strata, thus supporting the presence of such décollements in Pyramiden (Fig. Figure ***3***b), Sassenfjorden–Tempelfjorden (Fig. Figure ***4***a–f) and Reindalspasset (Fig. Figure ***4***g).

Uppermost Devonian–Mississippian coal-rich strata are locally thicker in Pyramiden, thus resulting in their exploitation by the Russian until the early 90s (Livshitz, 1966; Cutbill et al., 1976), in Sassenfjorden in the hanging wall of the east-dipping Billefjorden Fault Zone near the intersection with a NNE-dipping basement-seated fault (Figure 1, and Figure ***4***a and d), and within the hinge zone of the anticline adjacent to the possible southward continuation of the Billefjorden Fault Zone in Reindalspasset (Figure 4g). Recent studies of sedimentary rocks of the Billefjorden Group in the Ottar Basin (Tonstad, 2018), the Finnmark Platform (Koehl et al., 2018) and the northern part of the Billefjorden Trough (Koehl and Muñoz-Barrera, 2018) show that uppermost Devonian–Mississippian sedimentary strata were deposited into subsiding basins bounded by normal faults. In addition, high-amplitude seismic reflections in the Ottar Basin representing thickened, coal-rich, uppermost Devonian–Mississippian sedimentary strata analog to those observed in Sassenfjorden–Tempelfjorden are thickest on basin edges where fluvial systems dominated in latest Devonian–Mississippian times (Tonstad, 2018). It is possible that, in Spitsbergen too, thick uppermost Devonian–Mississippian coal seams are restricted to the basin edges along boundary faults, thus explaining the localization of contractional duplexes and décollements in areas such as Pyramiden, Sassenfjorden, Reindalspasset and potentially Triungen during Cenozoic transpression, partially decoupling deformation between Devonian sedimentary rocks and thick Pennsylvanian–Permian deposits and locally shielding the latter from Cenozoic deformation, while in basinal areas in the hanging wall of the Odellfjellet Fault, Pennsylvanian sedimentary rocks were involved in Cenozoic deformation and Carboniferous normal faults were inverted, e.g., in Odellfjellet (Koehl and Muñoz-Barrera, 2018), Løvehovden–Hultberget (Dallmann, 1993; Maher and Braathen, 2011), Pyramiden (Figure 3b), Adolfbukta (Harland et al., 1988), Anservika (Ringset and Andresen, 1988), and Sassenfjorden (Figure 4a–f).

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Based on field and seismic data in central Spitsbergen (present study; Koehl and Muñoz-Barrera, 2018) and on analog modelling (Bonini, 2001), it is probable that Devonian sedimentary deposits were folded in Cenozoic times since the differences in deformation style and intensity between Devonian and Carboniferous–Permian deposits can be explained simply by decoupling of Cenozoic transpression by soft, uppermost Devonian–Mississippian, coal- and shale-rich sedimentary deposits of the Billefjorden Group (Figs. Figure 3b, and Figure 4a–e and g; Koehl and Muñoz-Barrera, 2018). Hence, a short-lived episode of Late Devonian (Ellesmerian) contraction might not be required to explain differential deformation between late Paleozoic sedimentary successions in central Spitsbergen, thus potentially simplifying the late Paleozoic tectonic history of the area by reducing it to Caledonian contraction and late–post-Caledonian extensional collapse–rifting. This is further supported by a field study in Robertsonbreen (central Spitsbergen; Figure 1b), where Dißmann and Grewing (1997) noticed that sedimentary strata of the Upper Devonian Plantekløfta Formation and uppermost Devonian–Mississippian Hørbyebreen Formation are both similarly folded, i.e., suggesting that Cenozoic transpression may be (at least partially) responsible for folding of Devonian rocks in central Spitsbergen.

Strain decoupling, décollements and contractional duplexes are common features in the Cenozoic West Spitsbergen Fold-and-Thrust Belt and were described at various locations and within varied rock types. Notably, Ringset and Andresen (1988) and Harland et al. (1988) discussed the presence of subhorizontal, bedding-parallel décollements within Pennsylvanian evaporites of the Ebbadalen and Minkinfjellet formations in eastern Billefjorden, from which Cenozoic thrusts may have ramped upwards into trailing imbricate fans (Boyer and Elliott, 1982) due to lateral lithological variations within Pennsylvanian formations (Ringset and Andresen, 1988). In addition, in western Spitsbergen, Maher (1988), Saalmann and Thiedig (2000) and Bergh and Andresen (1990) described Cenozoic décollements and gently hinterland-dipping duplexes in uppermost Pennsylvanian–Permian sedimentary deposits of the Wördiekammen, Gipshuken and Kapp Starostin formations, which may represent analogs to duplex structures and associated bedding-parallel décollements and low-angle thrusts within uppermost Devonian–Mississippian coals and coaly shales in Pyramiden, Sassenfjorden–Tempelfjorden and Reindalspasset (Figure 3b and Figure 4).

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5.1.2. Formation mechanism for duplexes and décollements in uppermost Devonian–Mississippian rocks in Pyramiden

Backward-dipping duplexes in Pyramiden are located along the eastern limb of a major N–S-trending fold in Devonian sedimentary rocks (Figure 2), thus far ascribed to the Ellesmerian Orogeny (Piepjohn, 2000; Bergh et al., 2011). It is possible that, during Cenozoic folding, Devonian rocks in the west may have acted as a rigid buttress that localized the formation of duplexes and décollements within relatively soft, uppermost Devonian–Mississippian coals and coaly shales of the Billefjorden Group and allowed these structures to ramp upwards to the west. This is supported by field studies (Fard et al., 2006) and analog modelling (Bahroudi and Koyi, 2003) in the Zagros Fold-and-Thrust Belt showing buttressing, backward-dipping duplexes and décollements in the hanging wall of deep-seated faults, and by analog modelling of décollements in soft sedimentary layers with limited lateral extent (Costa and Vendeville, 2002, their model 3). Notably, Costa and Vendeville's model 3 shows that initially sub-horizontal sedimentary strata may have been tilted backwards (i.e., eastwards in Pyramiden) during contraction, and that décollement lithology (i.e., uppermost Devonian–Mississippian coal–coaly shale) may be incorporated and transported (top-west to top-WNW in Pyramiden; Figure 3a) as part of the hanging wall sequence during thrusting. This implies the presence of the Balliolbreen Fault in Pyramiden, which is discussed in section 5.1.3.

Another possibility is that the Pyramiden outcrop represents a mildly inverted extensional fault-block that was gently folded due to upward propagation of the Balliolbreen Fault (if present at all in Pyramiden; see section 5.1.3) and Odellfjellet Fault (e.g., gentle tilt to the ESE of strata of the Minkinfjellet Formation in Pyramiden; Koehl et al., 2016). Fault-propagation folds (Schlische, 1995) were discussed for the Løvehovden Fault (Maher and Braathen, 2011) and Billefjorden Fault Zone (Braathen et al., 2011; Bælum and Braathen, 2012) in cental Spitsbergen. However, this model implies the existence of the Balliolbreen Fault in Pyramiden, which is not obvious (see section 5.1.3), and, alone, does not explain the presence of bedding-parallel décollements and backward-dipping duplexes within uppermost Devonian–Mississippian coals and coaly shales of the Billefjorden Group in Pyramiden and Sassenfjorden–Tempelfjorden (Figure 3b, and Figure 4b and e). Moreover, seismic data in Reindalspasset show that a steeply east-dipping normal fault potentially representing the southwards continuation of the Billefjorden Fault Zone (Odellfjellet Fault?) is located along the eastern flank of a broad, gentle anticline (Figure 4g) and, hence, might

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be related to (or might have interacted with) the fold structure but is most likely not the cause of folding in this area.

Analog modelling of inversion in asymmetric half-graben basins shows features similar to those observed in Pyramiden, demonstrating a potential relationship between soft, early syn-rift sedimentary deposits and segments of basin-bounding faults (Buiter and Pfiffner, 2003, their figure 6a). Notably, in presence of soft, syn-rift sedimentary rocks in basin-edge fault-blocks, newly-formed shortcut shear zones or faults (McClay, 1989) may branch off preexisting inverted basin-bounding normal faults, and ramp up into soft, syn-rift sedimentary strata, potentially using décollement levels to accommodate contraction. Buiter and Pfiffner (2003) further argue that in their model, basement blocks experience much less contraction-related rotation along preexisting normal faults. Thus, a possible scenario for the Cenozoic tectonic history of the Billefjorden Fault Zone in Pyramiden might involve the formation of a shortcut shear zone or fault along an inverted portion of the Odellfjellet Fault at depth, which branched off and ramped up into rotated, soft, coal- and coaly shale-dominated syn-rift sedimentary rocks of the Billefjorden Group, forming bedding-parallel décollements (Phillipson, 2003, 2005; Molinda, 2003; Elizalde et al., 2016) and tilted backward-dipping duplexes (Figure 3b).

Alternatively, Cenozoic reverse reactivation/overprinting of the potentially upward-flattening Balliolbreen Fault (if present at all in Pyramiden; see section 5.1.3) might have triggered the development of a décollement within and of a fault-bend hanging wall anticline (e.g., the Kuqa Fold Belt in northwestern China; Wang et al., 2013; Izquierdo-Llavall et al., 2017) above uppermost Devonian–Mississippian coals, e.g., in Reindalspasset (Figure 4g). In this scenario, backward-dipping duplexes and décollements in uppermost Devonian–Mississippian coals–coaly shales may have acted as a roof décollement decoupling Mississippian–Permian strata from (Lower–Middle) Devonian rocks, passively thrusting the former over the latter (Bonini, 2001). Through this process, the length of the roof sequence (Carboniferous sedimentary strata) remains essentially the same, whereas the length of the floor sequence (Devonian sedimentary rocks) decreases through intense folding (Bonini, 2001), which may (partially) explain the significant differences of deformation between folded Devonian and Mississippian–Permian strata in central Spitsbergen without the need of a short-lived episode of contraction in the Late Devonian. The lack of uppermost Devonian–Mississippian coals and coaly shales of the Billefjorden Group directly on top of folded Devonian sedimentary rocks above the mine entrance in Pyramiden may suggest that

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uppermost Devonian–Mississippian coals–coaly shales were too thin to allow décollements to ramp all the way upwards or that Cenozoic contraction–transpression was too mild to form a complete ramp-anticline (assuming that the Balliolbreen Fault is present in Pyramiden) with roof décollement over Devonian sedimentary rocks (e.g., Faisal and Dixon, 2015).

Another plausible interpretation might be that of (a) west-directed imbricate fan(s) in Pennsylvanian evaporitic deposits and/or uppermost Devonian–Mississippian coals and coaly shales at depth in the Billefjorden Trough with east-dipping imbricate thrusts ramping upwards into coals and coaly shales of the Billefjorden Group in the footwall of the Odellfjellet Fault, in Pyramiden. This model in supported by field studies of Ringset and Andresen (1988) who discussed imbricate (thrust) fans and associated basal décollement developed along lithological boundaries within the Ebbadalen Formation in Anservika–Gipshuken (Figure 1b), Harland et al. (1988) who described sheared evaporites within the Ebbadalen and Gipshuken formations in eastern Billefjorden, and by recent field studies showing the presence of a potentially gently east-dipping, bedding-parallel thrust–décollement within the Billefjorden Group and Hultberget Formation in Anservika (Henningsen et al., pers. comm. 2019).

Based on field data, backward-dipping duplexes and bedding-parallel décollements in uppermost Devonian–Mississippian coals and coaly shales of the Billefjorden Group in Pyramiden are believed to have formed through a combination of at least two or more mechanisms, including Devonian rocks acting as a buttress to the west (e.g., Figure 4g), fault-propagation folding of (a) preexisting fault(s) like the Balliolbreen Fault and/or Odellfjellet Fault (although not very likely), shortcut faulting propagating upwards and westwards from the Odellfjellet Fault (e.g., Buiter and Pfiffner, 2003), ramp/fault-bend hanging wall anticline with roof décollement (e.g., Faisal and Dixon, 2015), and imbricate fan with basal décollement in the Billefjorden Trough (e.g., Ringset and Andresen, 1988; Henningsen et al., pers. comm. 2019).

5.1.3. Geometry and kinematics of the Balliolbreen Fault and implications for Ellesmerian and Cenozoic contraction, and Carboniferous normal faulting

Structural field analysis in the gully below the entrance of the Russian coal mine in Pyramiden has shown the presence of a sub-vertical, steeply east-dipping brittle fault tentatively interpreted as the Balliolbreen Fault and comprised of cataclastic fault rock that, half-way to the mine, crosscuts steeply east-dipping, quartzitic, Devonian sedimentary rocks involved in an east-

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verging fold (Figure 2 and Figure 3a, and supplement 3). Thin section analysis on both sides of this fault (supplement 1) shows cataclased Devonian sandstone both in the fault footwall and hanging wall, suggesting that there are no basement rocks at this locality, which is supported by geological maps of Harland et al. (1974), Lamar et al. (1986), and geological maps and logs of Arktikugol (1988; Sirotkin, pers. comm. 2019). In addition, the steeply east-dipping fault does not seem to extend upwards into overlying Mississippian clastic deposits above phyllitic coal-rich sedimentary strata. It is possible that the décollements within uppermost Devonian–Mississippian coals–coaly shales represent the upwards, low-angle continuation of the steeply east-dipping fault, but the structural location of the décollements (almost directly over the fault) would require an abrupt change of geometry of the fault from subvertical to low-angle (c. 30°; Figure 3b) within a narrow zone, which is unlikely. In addition, fault surfaces and lithological transitions switch from dominant N–S to NNW–SSE strikes and trends in uppermost Devonian–Mississippian coals–coaly shales below the coal-mine entrance (Figure 2 and Figure 3a, and stereonet 3 in Figure 2) to dominant WNW–ESE strikes and trends in Devonian rocks and uppermost Devonian–Mississippian sandstone above the mine entrance (Figure 2 and Figure 3a, and stereonet 2 in Figure 2), i.e., parallel to most outcrops sections of Mississippian strata in this part of the study area.

Above the coal mine in Pyramiden, the contact between Devonian sedimentary strata and uppermost Devonian–Mississippian sedimentary rocks is not clearly exposed (partly loose blocks) and its nature is speculative. It may be (1) a (folded?) stratigraphic unconformity and/or (2) a bedding-parallel décollement. Based on the internal geometry of bedding surfaces and deformation state of uppermost Devonian–Mississippian sedimentary strata of the Billefjorden Group, which are arranged into contractional, west-verging duplexes separated by low-angle, bedding-parallel décollements (Fig. Figure 3b), it is possible that the stratigraphic contact hosts a décollement, e.g., the potential prolongation of one of the décollements within coal- and coaly shale-rich deposits of the Billefjorden Group (Figure 2 and Figure 3b). However, Mississippian deposits above the coal mine appear to consist only of clastic deposits and, hence, lack soft coals–coaly shales into which décollements preferentially form. Thus, the contact between Lower Devonian and uppermost Devonian–Mississippian sedimentary rocks above the mine in Pyramiden most likely corresponds to a (folded?) unconformity.

Even if the décollements within uppermost Devonian–Mississippian coals and shales (Fig. Figure 3b) were to represent the upwards continuation of the steeply east-dipping fault (Figure 2),

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these most likely do not extend into Devonian and uppermost Devonian–Mississippian sandstone units above the mine entrance. Based on the similarity between the strike and dip of the steeply east-dipping fault and the trend and dip of Devonian bedding surfaces in Pyramiden (Figure 2 and Figure 3a), it is possible that the steeply east-dipping fault formed as a minor, bedding-parallel (fold-limb-parallel) fault related to post-Caledonian gravitional collapse processes (Chorowicz, 1992) and low-angle detachments (e.g., the Woodfjorden detachment in Andrée Land; Roy, 2007, 2009; Roy et al., unpublished; Figure 1a) in Devonian sedimentary rocks in northern Spitsbergen, or formed as a minor, bedding-parallel Cenozoic accommodation thrust (e.g., Cosgrove, 2015). Thus, it is probable that the Balliolbreen Fault does not crop out or is not present in Pyramiden. This is further supported by microsctructures along the steeply east-dipping fault in Pyramiden (Figure 2), e.g., mild undulose extinction and limited recrystallization and low amounts of displacement along distributed brittle cracks in fault rock (supplement 1), which indicate mild deformation associated with low-grade pressure–temperature conditions (< 280°C; Stipp et al. 2002; supplement 1).

In Reindalspasset, the planar, east-dipping normal fault that offsets Pennsylvanian–lower Permian sedimentary rocks may represent the potential continuation of the basin-bounding Odellfjellet Fault, and the Cenozoic thrust (and associated splays) localized along the boundary between uppermost Devonian–Mississippian and Pennsylvanian sedimentary successions (Figure 4g) the continuation of the (inverted?) Balliolbreen Fault. Fault relationships in cross section in Reindalspasset are comparable to what is proposed for the Balliolbreen and Odellfjellet faults in Pyramiden, e.g., possible merging at depth and hundreds of meter- to kilometer-scale lateral spacing between the faults (see previous section), assuming that the Balliolbreen Fault is present at all in Pyramiden. The presence of Devonian sedimentary rocks east of the Billefjorden Fault Zone in Reindalspasset suggests that this fault did not accommodate reverse movement in Late Devonian times as proposed by previous works (Vogt, 1938; Friend, 1961; Piepjohn, 2000; Dallmann and Piepjohn, submitted).

Based on field data in Pyramiden and seismic data in Sassenfjorden and Reindalspasset, and on previous work, it is clear that the Balliolbreen Fault displays significant geometry variations along strike. In the north, in Odellfjellet and Sentinelfjellet (Figure 1b), the Balliolbreen Fault dips c. 60–65° to the east and juxtaposes Precambrian basement unconformably overlain by uppermost Devonian–Mississippian strata of the Billefjorden Group in the hanging wall against Lower

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Devonian strata of the Wood Bay Formation supposedly unconformably overlain by uppermost Devonian–Mississippian rocks of the Billefjorden Group (Harland et al., 1974; Lamar et al., 1986; Lamar and Douglass, 1995). Both in Odellfjellet and Sentinelfjellet, it is unclear whether the Balliolbreen Fault offsets uppermost Devonian–Mississippian strata, or if the fault is unconformably overlain by uppermost Devonian–Mississippian rocks (Lamar et al., 1982, 1986; Lamar and Douglass, 1995). Although Harland et al. (1974) argue that the Triungen Member of the Hørbyebreen Formation is unfaulted in Sentinelfjellet (thus potentially supporting Late Devonian top-west thrusting along the Balliolbreen Fault and no further reactivation), stratigraphic contacts in this area are mostly covered by screes and poorly exposed (see toposvalbard.npolar.no) like in Triungen (Fig. Figure ***3***c), and the presence of décollements in the lower part of the Billefjorden Group (e.g., in Pyramiden, Sassenfjorden–Tempelfjorden and Reindalspasset; Figure 3b and Figure ***4***) questions the nature of the contact of this unit with underlying rock units, especially were covered by screes. If sedimentary strata of the Billefjorden Group are actually truncated by the Balliolbreen Fault in Sentinelfjellet (e.g., McCann, 1993, his figures 5.9 and 5.10), Cenozoic thrusting may, in conjunction with Carboniferous normal faulting, explain the observed juxtaposition of Precambrian basement and Lower Devonian sedimentary rocks (Figure 6). In this scenario, basement rocks constituting the Caledonian Atomfjella Antiform were located close to the surface at the end of the Caledonian Orogeny, thus leaving no (or limited) accommodation space east of the Billefjorden Fault Zone in Ny-Friesland (Figure 1a) during Devonian sedimentation sourced from the collapsing orogen and exhuming core complexes (e.g., Bockfjorden Anticline; Braathen et al., 2018; Figure 6a). In the Carboniferous, normal faulting and footwall rotation along the Odellfjellet Fault possibly exhumed a small portion of basement rocks in the footwall of the fault (Figure 6b–c), and subsequent Cenozoic contraction may have thrusted part of the exposed basement rocks in the footwall as a kilometer-scale lens along a possibly inverted Carboniferous normal fault, the Balliolbreen Fault (Figure 6d). In this model, Carboniferous normal and Cenozoic reverse offsets along the Balliolbreen Fault have similar magnitude, as shown in Mumien (juxtaposition of the Ebbadalen Formation and Billefjorden Group against the Wördiekammen Formation and the Billefjorden Group with no apparent offset at top Mississippian level; Dallmann et al., 2004; Dallmann, 2015; Figure 1b), and in Sentinelfjellet and Odellfjellet (top of Billefjorden Group offset by 0–40 m; Harland et al., 1974; Lamar et al., 1986; Figure 6e). Thus, it is possible that the above mentioned localities (Figure 6e) reflect different

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structural levels of the same fault system. Cenozoic inversion of Carboniferous normal faults in central Spitsbergen is supported by reverse offset and thrust-related folding along the Overgangshytta fault in Odellfjellet (Koehl and Muñoz-Barrera, 2018), and by minor reverse offset of thickened, uppermost Devonian–Mississippian and Pennsylvanian sedimentary deposits in the hanging wall of the east-dipping Billefjorden Fault Zone, near the intersection with a steeply NNE-dipping basement-seated fault in Sassenfjorden (Figure 4b).

The high degree of uncertainty in the relationship (truncated or truncating) between the Balliolbreen Fault and uppermost Devonian–Mississippian sedimentary strata of the Billefjorden Group (especially in Odellfjellet and Sentinelfjellet; Harland et al., 1974; Lamar et al., 1986; Lamar and Douglass, 1995), and the uncertainty regarding the nature of the contact (unconformity or bedding-parallel décollements–thrusts) between Lower Devonian and uppermost Devonian–Mississippian sedimentary strata shed by the presence of bedding-parallel Cenozoic décollements and thrusts in Pyramiden (Figure 3b), Sassenfjorden–Tempelfjorden (Figure 4b, c and e) and Reindalspasset (Figure 4g) call for caution and further (re-) examination of outcrops of uppermost Devonian–Mississippian rocks outcrops along the Balliolbreen Fault in central Spitsbergen. Notably, the significant, along strike differences in cross-section geometry from possibly subvertical, e.g., in Pyramiden (if present at all; Figure 2 and Figure ***3***b) to shallow dipping, e.g., in Reindalspasset (Cenozoic thrust localized along the Mississippian–Pennsylvanian boundary; Figure 4g), together with the strong contrasts in offset stratigraphic units, e.g., Pennsylvanian rocks of the Ebbadalen Formation overlain by carbonates of the Wördiekammen Formation in the hanging wall against Lower Devonian rocks of the Wood Bay Formation unconformably overlain by strata of the Wördiekammen Formation in the footwall in Yggdrasilkampen (Dallmann et al., 2004; Figure 1b), Pennsylvanian Ebbadalen Formation against uppermost Pennsylvanian–lower Permian Wördiekammen Formation in Mumien (Dallmann et al., 2004; Dallmann, 2015), Devonian rocks overlain by uppermost Devonian–Mississippian Billefjorden Group against Devonian rocks in the footwall in Pyramiden (if present at all; Figure 2 and Figure ***3***a), Precambrian basement rocks against Lower Devonian in Odellfjellet and Sentinelfjellet (Harland et al., 1974; Lamar et al., 1986), and in inferred timing and kinematics, e.g., Carboniferous normal faulting in Yggdrasilkampen (Dallmann et al., 2004), Cenozoic reverse movement in Pyramiden (if present at all; Fig. Figure ***3***b) and possibly in Reindalspasset (if present at all; Figure 4g) and Flowerdalen (Harland et al., 1974; Haremo et al., 1990; Haremo and Andresen, 1992), Carboniferous normal

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and Cenozoic reverse faulting in Mumien (Dallmann, 2015), and potential Late Devonian (e.g., Harland et al., 1974; Piepjohn, 2000; Dallmann and Piepjohn, submitted) or Cenozoic thrusting (this study; Koehl and Muñoz-Barrera, 2018) in Odellfjellet and Sentinelfjellet, suggest that the Balliolbreen Fault might consist of several, discrete, disconnected (soft-linked and/or stepping?) or possibly offset fault segments (i.e., crosscut by suborthogonal faults; McCann, 1993, his figure 5.11; Koehl, 2019; Koehl et al., in prep.).

Segmentation of the Balliobreen Fault is supported by a series of hundreds of meter–kilometer-scale, left-lateral offsets of the Balliolbreen Fault in Billefjorden and Sassenfjorden by WNW–ESE-striking faults, which appear to have accommodated significant amounts of top-SSW Cenozoic movement (e.g., Figure 4a–b, and Koehl, 2019 and Koehl et al., in prep.) and, hence, might have limited the amount of Cenozoic reactivation/overprinting (strain partitioning) along east-dipping segments of the Billefjorden Fault Zone in this area, e.g., in Yggdrasilkampen where the possible continuation of the Balliolbreen Fault juxtaposes Pennsylvanian (hanging wall) against Devonian (footwall) sedimentary rocks suggesting that Carboniferous normal faulting was followed by limited Cenozoic reactivation/overprinting if any at all, whereas east-dipping faults farther north (e.g., in Sentinelfjellet and Odellfjellet; Harland et al., 1974; Lamar et al., 1986; Lamar and Douglass, 1995; Dallmann et al., 2004; Dallmann, 2015) and farther south (e.g., in Flowerdalen; Harland et al., 1974; Haremo et al., 1990; Haremo and Andresen, 1992; Figure 1b) display clear evidence of Cenozoic top-west movements.

5.2. Reinterpretation of Ellesmerian structures in central Spitsbergen

The presence of backward-dipping duplexes and décollements localized within coal seams and coaly shales in the lower part of the Billefjorden Group in Pyramiden (Figure 3b), Sassenfjorden–Tempelfjorden (Figure 4b and e), and Reindalspasset (Figure 4g) suggests that differential deformation of Devonian and Carboniferous sedimentary rocks in central Spitsbergen may be explained by (partial) strain decoupling during Cenozoic transpression, thus not requiring the occurrence of a short-lived contractional–transpressional episode in the Late Devonian.

In Triungen (Figure 1a–b), the base of the Billefjorden Group is covered by (black) screes (Playford, 1962; Fig. Figure ***3***c). Hence, it is conceivable that, there too, the base of the Billefjorden Group consists of highly deformed, coal-rich sedimentary rocks that localized Cenozoic transpression like in Pyramiden, with potential décollements and/or roof- and floor-thrusts

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decoupling Devonian rocks from overlying Carboniferous–Permian sedimentary strata. The structural setting at the Triungen locality is, indeed, very similar to that in Pyramiden, in that it involves a major east-dipping brittle fault, the Triungen–Grønhorgdalen Fault Zone (Harland et al., 1974; McCann and Dallmann, 1996). This fault represents a potential analog to the Billefjorden Fault Zone and may have been active during the deposition of thick, uppermost Devonian–Mississippian sedimentary rocks (Harland et al., 1974; Cutbill et al., 1976; McCann and Dallmann, 1996). It is therefore possible that the Triungen–Grønhorgdalen Fault Zone might, just as the Billefjorden Fault Zone in Pyramiden, have accommodated the deposition of thickened, coal-rich sedimentary deposits (Livshitz, 1966; Cutbill et al., 1976), thus making the interpretation of Cenozoic strain (partial) decoupling relevant for the Triungen area as well. Noteworthy, the presence of black screes on the southern flank of Triungen near the presumably faulted contact between Lower Devonian and uppermost Devonian–Mississippian sedimentary strata (Fig. Figure ***3***c) may indicate the presence of thick coal seams and/or coaly shales along the Triungen–Grønhorgdalen Fault Zone and, conceivably, of bedding-parallel décollements, thrusts and duplexes similar to those in Pyramiden (Fig. Figure ***3***b).

Just west of Pyramiden, two moderately east-dipping faults, the upper and lower Munindalen thrusts, crosscut Devonian sedimentary strata and are possibly of Ellesmerian age (Michaelsen et al., 1997; Michaelsen, 1998; Figure 1b). The upper Munindalen thrust juxtaposes red sandstones of the Dicksonfjorden Member (upper Member of the Wood Bay Formation) in the hanging wall against green sandstones of the Austfjorden Member (lower Member of the Wood Bay Formation; Michaelsen, 1998), is unconformably overlain by uppermost Pennsylvanian–lower Permian sedimentary strata of the Wördiekammen Formation, and, hence, is more likely to correspond to a Devonian low-angle normal fault or detachment or to an unconformity tilted during core complex exhumation in the west (e.g., Braathen et al., 2018). The lower Munindalen thrust is similar to post-Caledonian extensional detachments mapped in Andrée Land, e.g., the Woodfjorden detachment (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished), in that both of these faults are low-angle and show syn-kinematic fault-related folding within Lower–Middle Devonian strata. Most importantly, in Andrée Land, several intra-Devonian unconformities separate folded strata crosscut by low-angle extensional detachments from overlying undeformed sedimentary rocks like, e.g., Givetian (upper Middle Devonian) rocks of the Widje Bay Formation that lie unconformably over folded Eifelian (lower Middle Devonian) strata of the Grey Hoek Formation

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(Roy, 2007, 2009; Roy et al., unpublished), thus showing that folding of Devonian strata in Spitsbergen partly occurred prior to Ellesmerian contraction and was partly related to gravitational collapse of the Caledonides. The presence of extensional shear zones in Devonian rocks in central Spitsbergen was also evidenced by Michaelsen et al. (1997, their figure 5a) and Michaelsen (1998, her figures 44 and 45) in Munindalen (Figure 1b).

By contrast, the lower Munindalen thrust (Michaelsen, 1998; McCann and Dallmann, 1996; Piepjohn, 2000; Bergh et al., 2011) thrusted Lower Devonian strata of the Wood Bay Formation over Upper Devonian sedimentary rocks of the Plantekløfta Formation. However, this thrust is not unconformably overlain by post-Devonian sedimentary rocks in Munindalen (Figure 1b) and, thus, may well be Cenozoic in age. This is supported by the probable continuation of this fault to the north-northwest in Robertsonbreen (Figure 1b), the Robertsonbreen thrust, which involves both uppermost Devonian–Mississippian and Pennsylvanian–Permian sedimentary strata, respectively of the Billefjorden Group and Wördiekammen Formation, into top-west to top-southwest Cenozoic thrusting (Dißmann and Grewing, 1997). The Robertsonbreen thrust presents strong similarities to the lower Munindalen thrust, including a NNW–SSE strike, gentle to moderate eastward dip, top-west/southwest reverse sense of shear, and alignment along a NNW–SSE-trending axis (see the alignment in Figure 1b). Shall these two thrusts represent the same fault, it is possible to explain the apparent differences in behavior, i.e., the lower Munindalen thrust potentially not crosscutting the Wördiekammen Formation (Piepjohn, 2000; Dallmann, 2015) and the relatively undeformed character of uppermost Pennsylvanian–lower Permian rocks in Kilen (Figure 1b) by the presence of a Cenozoic décollement or roof-thrust, e.g., at the base of the Wördiekammen Formation. Cenozoic décollements are indeed common in uppermost Pennsylvanian–Permian sedimentary rocks of the Wördiekammen, Gipshuken and Kapp Starostin formations in Spitsbergen, e.g., Birger Johnsonfjellet (McCann, 1993, his figure 5.6), Billefjorden (Ringset and Andresen, 1988; Harland et al., 1988), Brøggerhalvøya (Bergh et al., 2000; Saalmann and Thiedig, 2000) and Oscar II Land (Maher, 1988; Bergh and Andresen, 1990; Bergh et al., 1997), and are especially well illustrated by Cenozoic thrusts within the Gipshuken Formation that flatten downwards and die out within sedimentary strata of the Wördiekammen Formation in Sassenfjorden–Tempelfjorden (Figure 4c and f). In addition, taking into account the evidence for Cenozoic contraction in uppermost Devonian–Mississippian coals–coaly shales in Pyramiden (e.g., Fig. Figure 3b), the argument based on the relatively constant height of the Wördiekammen Formation throughout central

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Spitsbergen used by, e.g., Piepjohn (2000) and Bergh et al. (2011), to infer a Late Devonian age for the Munindalen thrust and identify Late Devonian vertical tectonic movements in the area is regarded as inappropriate since the Wördiekammen Formation in Pyramiden was obviously transported upwards to the west/WNW during Cenozoic thrusting but still lies at a similar altitude as in Munindalen and Robertsonbreen (Figure 1b). Thus, based on the possible connection between the Munindalen and Robertsonbreen thrusts, on the incorporation of Carboniferous–Permian rocks in thrusting along the Robertsonbreen thrust, and on the common occurrence of low-angle Cenozoic décollements and thrusts within sedimentary rocks of the Gipsdalen Group, and more specifically within the Wördiekammen Formation (e.g., Figure 4c and f, and figure 5.6 in McCann, 1993), the (lower) Munindalen–Robertsonbreen thrust is proposed to have formed during Cenozoic transpression and to flatten upwards into or to be truncated by a bedding-parallel Cenozoic décollement or roof-thrust at the base of the Wördiekammen Formation.

West-southwest of Pyramiden, The Blåvatnet Reverse Fault thrusted Lower Devonian green sandstones of the Dicksonfjorden Member of the Wood Bay Formation onto Upper Devonian sedimentary strata of the Fiskekløfta Formation (Michaelsen et al., 1997; Piepjohn et al., 1997). Like for the lower Munindalen thrust, the contact of the Blåvatnet Reverse Fault with Pennsylvanian–Permian sedimentary deposits of the Wördiekammen Formation is not exposed (Piepjohn et al., 1997, their figure 12), and, thus, the fault may well correspond to a Cenozoic thrust.

Another argument suggesting that folding of Devonian strata in Dickson Land and Andrée Land is (partly) Cenozoic in age is the incorporation of Carboniferous picritic dykes (Evdokimov et al., 2006; monchiquite dykes in Gayer et al., 1966 and Manby and Lyberis, 1996) intruding Devonian metasedimentary rocks in contractional deformation at Krosspynten (central–northern Svalbard; Figure 1a).

The presence of a "lower décollement level" was also speculated by Bergh and Andresen (1990) in Brøggerhalvøya (Figure 1a), in western Spitsbergen, in order to explain the observed Cenozoic deformation. They speculated that this "lower décollement level", possibly analog to those observed in Pyramiden (Figure 3b), might flatten into syn-rift Carboniferous sedimentary strata, and uppermost Devonian–Mississippian (coaly) shales and coals of the Billefjorden Group in Brøggerhalvøya (Fairchild, 1982) definitely represent suitable candidates to have localized the formation of such a décollement.

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Other arguments against the occurrence of the Ellesmerian Orogeny are the restricted extent of presumed Ellesmerian deformation belts (Piepjohn, 2000), and the undeformed character of slightly tilted Lower Devonian rocks of the Wood Bay Formation in, e.g., Pretender Mountain (western Spitsbergen; Figure 1a), which are unconformably overlain by flat-lying uppermost Carboniferous–lowermost Permian strata of the Wördiekammen Formation (Welbon et al., 1992, unpublished; Dallmann, 2012, 2015, pp. 199). If Ellesmerian contraction–transpression had occurred, it would most likely have folded Devonian strata throughout Spitsbergen, which is not the case. Instead, these are pretty much undeformed in Pretender Mountain. Hence, a probable alternative is the exhumation of a 25 km-wide, N–S- to NNW–SSE-trending core complex in Devonian–Mississippian times, the Bockfjorden Anticline (Braathen et al., 2018), which possible continuation to the south aligns with the Pretender Mountain. There, the gently tilted to subhorizontal character of Lower Devonian sedimentary rocks of the Wood Bay Formation and the absence of uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group may be explained by continued exhumation of the Bockfjorden Anticline in the Late Devonian–Mississippian, thus exposing the area to continental erosion in latest Devonian to Mississippian times (Koehl, 2019; Koehl et al., in prep.).

Core complex exhumation is widely documented in other Arctic areas in the Late Devonian–Mississippian, e.g., in northern Norway (Steltenpohl et al., 2011) and the SW Barents Sea (Koehl et al., 2018) and potentially in Northeast Greenland (Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2015), thus making it a reasonable alternative to the Ellesmerian Orogeny. Renewed or continued core complex exhumation (e.g., of the Bockfjorden Anticline) in northern Spitsbergen and associated normal brittle faulting (Braathen et al., 2018) might also be responsible for the presence of coarse-grained sedimentary deposits (Piepjohn and Dallmann, 2014) in the lower Frasnian (Berry and Marshall, 2015) Planteryggen and Plantekløfta formations in central Spitsbergen.

On Blomstrandhalvøya, in Kongsfjorden (Figure 1a), a presumably undeformed karst breccia within deformed basement marbles and Lower Devonian sedimentary strata yielded a Pennsylvanian–Permian age based on conodont fauna, thus supporting Late Devonian–Mississippian Ellesmerian contraction (Buggisch et al., 1994). However, this karst breccia is the only presumably undeformed breccia yielding a Pennsylvanian–Permian age, which is based on poorly preserved conodont fauna (Buggisch et al., 1994), and corresponds to a (few meters wide)

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small-scale structure that is, hence, potentially inappropriate to discuss the occurrence and extent of regional deformation events. For example, the breccia seems to have escaped Cenozoic deformation (Buggisch et al., 1994; Kempe et al., 1997), which resulted in intense top-NE thrusting and folding in adjacent areas on Brøggerhalvøya, just south/southwest of Blomstrandhalvøya (Figure 1a). Thus, it is conceivable that the breccia might, as well, have escaped Ellesmerian contraction, making it inappropriate to constrain the timing of thrusting and folding on Blomstrandhalvøya. Contrasts in deformation state may be explained by processes such as deformation partitioning and decoupling, which occurred during Cenozoic deformation, e.g., in Pyramiden, Sassenfjorden–Tempelfjorden and Reindalspasset, where soft Devonian shales and uppermost Devonian–Mississippian coals and coaly shales (Figure 3b, and Figure 4b and e) were strongly sheared while overlying Pennsylvanian–Permian deposits remain relatively undeformed. To further support Ellesmerian contraction in Svalbard, Thiedig and Manby (1992) and Kempe et al. (1997) argued that the west- and NW-verging thrusts observed on Blomstrandhalvøya are not typical of Cenozoic Eurekan deformation, which produced NE-verging thrusts a few kilometers to the south/southeast on Brøggerhalvøya (Bergh et al., 2000; Piepjohn et al., 2001; Figure 1a), even though NW-verging thrusts seem to have formed in the Cenozoic. Ongoing work shows that Cenozoic contraction in Spitsbergen was partitioned and that Brøggerhalvøya and Blomstrandhalvøya are separated by a major NW–SE-striking, sinistral-reverse oblique-slip fault that extends from Kongsfjorden to Sassenfjorden and the northern Barents Sea (Koehl, 2019; Koehl et al., in prep.). In addition, on the one hand, basement marbles are poorly deformed on Blomstrandhalvøya, especially in the westernmost part of the peninsula where the Pennsylvanian–Permian karst breccia crops out, away from the cracked and cataclased contact between basement marbles and Lower Devonian sedimentary rocks of the Red Bay Group. On the other hand, the Pennsylvanian–Permian karst breccia does look mildly deformed (Buggisch et al., 1994, their figure 4a–b). Hence, deformation intensity in the karst breccia and the marbles is not significantly different and, therefore, is not an appropriate indicator to constrain the timing of deformation on Blomstrandhalvøya.

New paleontological and palynological data cast new light on the potential time span of Ellesmerian contraction, which is believed to have initiated after the deposition of the Fiskekløfta Formation in the late–latest Givetian (i.e., latest Middle Devonian; Berry and Marshall, 2015) and terminated prior to the deposition of middle–late Famenian–Mississippian (Scheibner et al., 2012;

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Lindemann et al., 2013; Marshall et al., 2015; Würtzen et al., 2019; Lopes, pers. comm. 2019) coal-rich sedimentary rocks of the Billefjorden Group (Piepjohn, 2000), which implies a maximum duration of ca. 15–16 Ma or this tectonic event. In addition, Ellesmerian contraction is believed to have been recorded by the deposition of the Planteryggen and Plantekløfta formations in Dickson Land (Piepjohn, 2000; Piepjohn and Dallmann, 2014), which recently yielded early Frasnian (ca. 380 Ma) ages based on fossil and spore assemblages for both formations (Berry and Marshall, 2015). Based on these new ages, it is possible that Ellesmerian contraction was actually restricted to ca. 383–380 Ma. The intense folding and thrusting ascribed to Ellesmerian contraction by Piepjohn (2000) and other workers could hardly have formed during such a short time interval and are therefore more likely explained by Devonian collapse-related extension and Cenozoic contraction–transpression.

5.3. Reinterpretation of Ellesmerian structures in southern Spitsbergen

In southern Spitsbergen, Bergh et al. (2011) distinguished between NNW–SSE-trending, gently NNW-plunging, Ellesmerian-related folds in the Upper Devonian (–Mississippian?) Adriabukta Formation (their figure 8b), and analogous NNW–SSE-trending, upright, Cenozoic fold structures in Mississippian–Cretaceous sedimentary rocks (their figure 9a). Despite the slight difference of plunge, the two fold populations distinguished by Bergh et al. (2011) are not significantly different from one another, and may actually reflect the same episode of Cenozoic contractional–transpressional deformation, which was also suggested by Dallmann (1992).

The schematic cross-section of Bergh et al. (2011; their figure 4) was re-drawn to better fit the landscape photograph of their figure 5. As a result, the sub-sea geology of the Adriabukta outcrop section was reinterpreted (Figure 5a). The tectonic differences observed between the gently upright folded post-Mississippian sedimentary rocks of the Hyrnefjellet and Treskelodden formations and tightly folded Upper Devonian (–Mississippian?) sedimentary strata of the Adriabukta Formation are believed to arise from the abondance and relatively soft rheological properties of shales within the latter (Birkenmajer and Turnau, 1962; Birkenmajer, 1964; Cutbill and Challinor, 1965; Dallmann, 1992). Lithological contrast between interbedded fine-grained shales and coarse-grained sandstones–conglomerates within the Adriabukta Formation may have helped decoupling Cenozoic deformation and localizing shortening in this Formation rather than in overlying, homogeneous and relatively more brittle sandstones–conglomerates and limestones

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of the Pennsylvanian Hyrnefjellet and Treskelodden formations. The relatively softer rheological behavior of Upper Devonian (–Mississippian?) shales of the Adriabukta Formation is illustrated by Dallmann (1992; his figure 7, cross-sections CC', DD', and EE'), showing abundant, low-angle, bedding-parallel, Cenozoic décollements and thrusts within the Adriabukta Formation. This reinterpretation is further supported by the presence of analogous structures in Devonian and uppermost Devonian–Mississippian sedimentary strata in Pyramiden (Fig. Figure 3b), Sassenfjorden–Tempelfjorden (Figure 4b and e), and Reindalspasset (Figure 4g).

In Adriabukta, two thin bedding-parallel dolerite sills were intruded within the Adriabukta Formation near the contact with a lens of basement rocks (Birkenmajer, 1964, his figure 2). Since these two sills probably intruded along Upper Devonian (–Mississippian?) bedding surfaces they are most likely Late Devonian in age or younger. Sills typically intrude the bedrock at depth of 1–5 km (Schmiedel et al., 2017), but in places occur at a few hundreds of meter depths (Bell and Butcher, 2002). Knowing that the Adriabukta Formation is c. 600 m-thick (cumulated) in Adriabukta (Birkenmajer, 1964; Figure 1a), it is possible, though not likely, that the two dolerite sills are Late Devonian–Mississippian in age. However, the only known Devonian–Mississippian intrusions in Svalbard are dykes (Evdokimov et al., 2006; Senger et al., 2013, their Figure 1c). Thus, it is more probable that the two dolerite sills in Adriabukta are part of the Cretaceous Diabasodden Suite (Senger et al., 2013). Since sills are generally planar and that two dolerite sills in Adriabukta intruded along bedding surfaces, it is highly probable that Upper Devonian (–Mississippian?) bedding surfaces of the Adriabukta Formation were still planar (i.e., relatively undeformed) in Cretaceous times during the intrusion of the sills, which therefore suggests that folding of the Adriabukta Formation most likely initiated after sill intrusion, i.e., most likely in the early Cenozoic.

In Røkensåta (southernmost Spitsbergen; Figure 1a), gently dipping Lower Triassic sedimentary rocks overlie folded Devonian strata and, therefore, potentially support Late Devonian Ellesmerian transpression (Dallmann, 1992). However, based on the stratigraphy of the Triassic succession in southern Spitsbergen, which is dominated by interbedded sandstone and shale (Worsley and Mørk, 1978), on the stratigraphic contact between Devonian and Triassic rocks in Røkensåta being covered by screes, on the limited exposure of Triassic rocks in Røkensåta, and on the presence of sub-horizontal Cenozoic thrust faults/décollements in Triassic sedimentary rocks in Reindalspasset (Figure 4g; Eide et al., 1991), it is conceivable that a potential unidentified

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décollement or roof/floor-thrust in Triassic shales may have decoupled Cenozoic deformation between folded Devonian and overlying gently dipping Lower Triassic sedimentary strata in Røkensåta. Multiple Cenozoic décollements and low-angle–flat-lying thrusts were actually reported in Triassic sedimentary rocks in Spitsbergen (Maher, 1984; Maher et al., 1986, 1989; Andresen et al., 1988; Bergh and Andresen, 1990; Haremo and Andresen, 1992; Andresen et al., 1992; Dallmann et al., 1993b; Bergh et al., 1997), the most spectacular examples being the décollement in dark shales on the Midterhuken Peninsula (Maher, 1984; Dallmann et al., 1993b) and the Berzeliustinden thrust in Triassic–Lower Cretaceous bituminous shales (Dallmann, 1988) in southern Spitsbergen, and the "Lower Décollement Zone" in western (Andresen, 2009) and eastern Spitsbergen (Andresen et al., 1992; Haremo and Andresen, 1992). Alternatively, folding in Devonian strata in Røkensåta might reflect upwards propagation of a Cenozoic thrust fault (similar to that of Haremo et al., 1990, their figure 14) that dies out upwards or that flattens into a décollement level at the base of the Triassic succession, or post-Caledonian detachment-related folding (e.g., in Andrée Land; Roy, 2007, 2009; Roy et al., unpublished). Another alternative to the model of core complex exhumation and partial decoupling (present study) and to Ellesmerian contraction (Piepjohn, 2000) might be a potential contractional event in the Permian–earliest Triassic (Uralian Orogeny?). However, no such event was ever reported in Svalbard.

The eastern part of the Adriabukta transect was restored prior to Cenozoic deformation and Mesozoic sedimentation, and the present study reaches substantially different conclusions from Birkenmajer and Turnau (1962, their figure 4; Figure 5a–b). Once restored, the Mariekammen Shear Zone, which trends parallel in map view and cross-section to the contacts between the (Upper Devonian–Mississippian?) Adriabukta and (Lower–Middle Devonian) Marietoppen formations and between the Marietoppen Formation and Neoproterozoic basement rocks in the west, shows a eastward dip (Figure 5b). As a result, previously interpreted reverse kinematic indicators (Bergh et al., 2011) become normal after restoration, thus suggesting that the Mariekammen Shear Zone (Bergh et al., 2011) initiated as an extensional normal dip-slip to sinistral-normal oblique-slip shear zone in Devonian–Mississippian times, possibly during post-Caledonian extensional collapse, and was later tilted to the west (and inverted?) during Cenozoic contraction–transpression. Importantly, the present restoration does not require Late Devonian Ellesmerian contraction–transpression to explain the geological structures observed in Adriabukta, but rather suggests a period of continuous

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extension in the Devonian–Carboniferous and that the observed contractional structures were generated in Cenozoic times.

A possible trigger for the steep eastward dip of Devonian (–Mississippian?) sedimentary strata of the Mariekammen and Adriabukta formations (after restoration) in Adriabukta (Figure 1aFigure 5) may be core complex exhumation of Neoproterozoic basement rocks in the west (Figure 7a–d), as observed in central (Koehl, 2019; Koehl et al., in prep.) and northwestern Spitsbergen (Braathen et al., 2018). Thus, Cambrian basement rock lenses incorporated along the Mariekammen Shear Zone might represent a large clast that was eroded from a basement culmination (core complex?; Figure 7b1) and/or that was ripped off by excisement and/or incisement processes (Lister and Davis, 1989) along a bedding-parallel, core complex-bounding detachment in the west in Devonian–Mississippian times (Figure 7b2), comparable to the Woodfjorden detachment (Roy et al., unpublished). Exhumation of a N–S- to NNW–SSE-trending core complex would also explain the angular unconformity inferred by Dallmann (1992) between the Late Devonian (–Mississippian?) Adriabukta Formation and Mississippian Hornsundneset Formation in Haitana (Figure 1a), with the younger Hornsundneset Formation unconformably overlying the uplifted, tilted, and older Adriabukta Formation (Figure 7c). Core complex exhumation in the Devonian may also explain the absence of the Marietoppen Formation between basement rocks and strata of the Adriabukta Formation on Påskefjellet, south of Hornsund (Dallmann, 2015; Figure 1a), if this area represents the crest of the proposed core complex that was exhuming in the Devonian (Figure 7b–d). By contrast, the Adriabukta area may be located on the eastern flank of this proposed core complex, which is most likely offset left-laterally by a WNW–ESE-striking fault in the fjord (Koehl, 2019; Koehl et al., in prep.). A Cenozoic age for all fold structures in post-Caledonian sedimentary rocks in Hornsund is further supported by outcrop geometries in Fiskeknatten, north of Adriabukta (Figure 1a), where Lower Triassic sedimentary strata are folded in a similar fashion (i.e., into tight, east-verging folds with subvertical axial surfaces) to the Marietoppen and Adriabukta formations and incorporated as lenses into basement rocks (Birkenmajer, 1964, his figure 4).

Computational modelling shows that folding may also occur in transtension (Fossen et al., 2013; Rey et al., 2017). Examples of such folds have been documented in Andrée Land northern Svalbard (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished; Figure 1a), but also, e.g., in western Norway (Chauvet and Séranne, 1994; Osmundsen and Andersen, 1994; Osmundsen et al.,

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1998; Krabbendam and Dewey, 1998), California (Fletcher and Bartley, 1994), and eastern Canada (Schwerdtner et al., 2016). Notably, in eastern Canada and California, such folds are associated with the exhumation of metamorphic core complexes (Fletcher and Bartley, 1994; Schwerdtner et al., 2016), thus suggesting that folds in Devonian rocks in Spitsbergen (e.g., in Røkensåta; Figure 1a) might have formed during Devonian–Mississippian core complex exhumation. A formation as transtensional folds of presumed (contractional–transpressional) Ellesmerian structures in southern Spitsbergen is further supported by their NW–SE to NNW–SSE trend (Bergh et al., 2011, their figure 8b), i.e., sub-parallel to slightly oblique to the WNW–ESE- to NW–SE-oriented extension direction in Mississippian times inferred by Koehl and Muñoz-Barrera (2018), which is typical for transtensional folds (Fossen et al., 2013), e.g., in western Norway where transtensional folds in Middle Devonian collapse basins formed parallel to the extension direction during a late phase of the extensional collapse of the Caledonides (Chauvet and Séranne, 1994; Osmundsen and Andersen, 1994).

5.4. Late Devonian–earliest Mississippian amphibolite facies metamorphism in western Spitsbergen

The Ellesmerian Orogeny is believed to have halted prior to the onset of deposition of sedimentary strata of the Billefjorden Group (Piepjohn, 2000). New ages for sedimentary rocks at the base of the Triungen Member (Billefjorden Group) in Triungen (Lindemann et al., 2013; Figure 1a–b) suggest that sedimentation initiated in the middle–late Fammenian, thus implying that Ellesmerian contraction had stopped by ca. 365 Ma. Though, Piepjohn and Dallmann (2014) claim that Fammenian spore assemblages in the Triungen Member described by Lindemann et al. (2013) were reworked and are older than the actual age of sedimentation, recent data from Marshall et al. (2015) and Lopes (pers. comm. 2019) contradict this claim and further support a middle–late Fammenian age for the base of the Triungen Member. Thus, these new ages partly contradict the recent interpretation of 371–355 Ma amphibolite facies metamorphism in Prins Karls Forland (Figure 1a) as reflecting Ellesmerian deformation (Kośmińska et al., 2017; Majka and Kośmińska, 2017; Faehnrich et al., 2017; Schneider et al., 2018). In addition, fossil and spore analysis within the Fiskekløfta Member of the Tordalen Formation and in the Plantekløfta Formation show that these were deposited in the late–latest Givetian (ca. 385–382 Ma) and early Frasnian times (ca. 382–377 Ma) respectively (Berry and Marshall, 2015; Newman et al., 2019). Hence, the

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Planteryggen and Plantekløfta formations can hardly be associated with a 371–355 Ma episode of contraction as claimed by Piepjohn and Dallmann (2014).

Regardless, Th–U–Pb geochronology on monazite yielded 371–355 Ma ages, and thermobarometry in mylonitized Mesoproterozoic metapelites of the Pinkiefjellet Unit in Prins Karls Forland (Figure 1a) indicate that these rocks were subjected to amphibolite metamorphism during a latest Devonian–earliest Mississippian tectonic event (Kośmińska et al., 2017; Majka and Kośmińska, 2017). In addition, preliminary K–Ar (Schneider et al., 2018) and ^{40}Ar–^{39}Ar (Faehnrich et al., 2017) dating of muscovite yielded 360–355 Ma ages for amphibolite metamorphism and mylonitization along a one-km-thick west-dipping shear zone, the Bouréefjellet fault zone. Another possible way to explain amphibolite facies metamorphism and mylonitization in latest Devonian–earliest Mississippian time is the exhumation of basement rocks in western Spitsbergen as metamorphic core complex during late–post Caledonian collapse of the Caledonides. Amphibolite facies metamorphism and mylonitization are commonly related to late-orogenic collapse processes (Krabbendam and Dewey, 1998) and core complex exhumation (Snoke, 1980; Lister and Davis, 1989; Beaudoin et al., 2015; Yin et al., 2017). This hypothesis is supported by recent findings in northwestern (Braathen et al., 2018) and central Spitsbergen (Koehl, 2019; Koehl et al., in prep.) discussing the exhumation of a N–S- to NNW–SSE-trending core complex, the Bockfjorden Anticline, along the low-angle Devonian Keisarhjelmen detachment, which latest movement was dated to ca. 368 Ma by K–Ar geochronology of a syn-tectonic granitic dyke in detachment mylonite (Braathen et al., 2018), and by down-SW to down-NW shear senses obtained from muscovite mica fish and quartz sigma-clasts within amphibolite-facies mylonitic units of the west-dipping Bouréefjellet fault zone (Schneider et al., 2018, their figure 3b, e and f), thus suggesting extensional movement along this fault in the latest Devonian–earliest Mississippian.

Moreover, recent computational modelling suggests that contractional structures oblique to the extension direction may form in the core of exhuming basement ridges (in the present case, the Pinkiefjellet Unit), while extensional shear zones (e.g., the Bouréefjellet fault zone; see figure 3b, e, and f in Schneider et al., 2018) form in the shallow part of the ridge (Rey et al., 2017). This further supports that latest Devonian–earliest Mississippian high-pressure metamorphism in Prins Karls Forland is related to core complex exhumation regardless of the sense of shear inferred along the Bouréefjellet fault zone.

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Other common features of metamorphic core complexes are the juxtaposition of high-grade rocks in the footwall with low-grade rocks in the hanging wall of a crustal detachment, and a transition from ductile to brittle deformation from the base to the top of the detachment (Lister and Davis, 1989; Huet et al., 2011). In Prins Karls Forland, the west-dipping Bouréefjellet fault zone (Schneider et al., 2018) separates amphibolite-facies mylonitized metapelites of the Pinkiefjellet Unit in the footwall in the (south-) east from greenschist-facies siliciclastic metasedimentary strata in the hanging wall in the (north-) west (Manby, 1983; Maraszewska et al., 2016; Schneider et al., 2018), and fault-rocks within the fault zone range from dominantly mylonitic in the lower part to brittle in the upper part (Schneider et al., 2018). In addition, recrystallization processes in quartz within the Bouréefjellet fault zone, including subgrain rotation and bulging (350–450°C) in the upper part and grain boundary migration (> 500°C) in the lower part (Schneider et al., 2018), indicate temperature ranges comparable to other core complexes around the world, e.g., the high-temperature Ikaria Metamorphic Core Complex in Greece (Beaudoin et al., 2015).

Exhumation of basement ridges as core complexes is widely documented during Devonian–Mississippian times in Baltica and Laurentia, e.g., in western Norway (Dunlap and Fossen, 1998; Eide et al., 1999; Braathen et al., 2000), mid-Norway (Braathen et al., 2002; Eide et al., 2002; Kendrik et al., 2004; Osmundsen et al., 2005), northern Norway (Steltenpohl et al., 2004, 2011), the SW Barents Sea (Koehl et al., 2018), Greenland (Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2016), and Svalbard (Braathen et al., 2018; Koehl, 2019; Koehl et al., in prep.). Therefore, core complex exhumation represents a more realistic alternative to explain the latest Devonian–earliest Mississippian Th–U–Pb and K–Ar ages obtained by Kośmińska et al. (2017) and Schneider et al. (2018) for amphibolite facies metamorphism in Prins Karls Forland than a poorly constrained, short-lived episode of Ellesmerian contraction.

6. Conclusion

1. Thickened uppermost Devonian–Mississippian sedimentary deposits of the Billefjorden Group in central Spitsbergen are arranged in duplexes comprised of phyllitic coal–coaly shale interbedded with sandstone showing sigmoidal shear fabrics separated by imbricate thrusts linking an upper (roof thrust) and a lower (floor thrust) décollements that localized along lithological transitions.

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2. Cenozoic bedding-parallel décollements and thrusts in tectonically thickened, coal-rich sedimentary rocks of the Billefjorden Group and possibly in the Wördiekammen Formation and in Lower–Middle Devonian sedimentary rocks partially decoupled Cenozoic contraction, resulting in intense folding in Devonian sedimentary rocks and uppermost Devonian–Mississippian coals, and mild to no deformation in Carboniferous–Permian strata in central Spitsbergen. Folding in Devonian sedimentary strata may also be partially accounted for by syn-depositional detachment folding during the extensional collapse of the Caledonides.
3. Cenozoic backward-dipping duplexes and bedding-parallel décollements in the Billefjorden Group in Pyramiden formed through shortcut faulting propagating upwards and westwards from the Odellfjellet Fault, and/or as roof décollements of a ramp/fault-bend hanging wall anticline, and/or as part of an imbricate fan with basal décollement in the Billefjorden Trough. Cenozoic contractional structures in uppermost Devonian–Mississippian coals–coaly shales also include fault-propagation folds over preexisting basement-seated faults in Sassenfjorden, and a possible antiformal thrust stack (or ramp anticline) in Reindalspasset.
4. Lower–Middle Devonian sedimentary rocks might have been deposited east of the Billefjorden Fault Zone in Reindalspasset, thus suggesting that the Billefjorden Fault Zone did not act as a reverse fault in Late Devonian times.
5. Juxtaposition of Proterozoic basement rocks against Lower Devonian sedimentary rocks along the Balliolbreen Fault in central Spitbsergen may be explained by down-east Carboniferous normal faulting with associated footwall rotation and exhumation, and subsequent top-west Cenozoic thrusting along the Billefjorden Fault Zone.
6. The uncertain relationship of the Balliolbreen Fault with uppermost Devonian–Mississippian sedimentary strata and the poorly constrained nature of the contact (unconformity or bedding-parallel décollements–thrusts) between Devonian and uppermost Devonian–Mississippian sedimentary strata, as well as significant along strike variations in cross-section geometry, offset stratigraphy, and inferred timing and kinematics suggest that the Balliolbreen Fault consists of several, discrete, unconnected (soft-linked and/or stepping) or most likely offset fault segments that were reactivated/overprinted with varying degree during Eurekan deformation due to strain partitioning.

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7. Reinterpretation of presumed Ellesmerian structures in central, western and southern Spitsbergen suggests that short-lived Late Devonian Ellesmerian contraction is not necessary to explain the juxtaposition of folded Devonian sedimentary strata with mildly deformed–undeformed Carboniferous–Permian sedimentary strata, and that presumed Ellesmerian folds and faults formed during extensional collapse of the Caledonides and/or during Cenozoic contraction–transpression.
8. Latest Devonian–earliest Mississippian amphibolite facies metamorphism in western Spitsbergen may be related to core complex exhumation along extensional shear zones during post–late-orogenic collapse of the Caledonides.

Further work may prove valuable to further confirm or invalidate the occurrence of the Ellesmerian Orogeny in Svalbard. Potential tasks include (1) characterizing the nature of the stratigraphic contact between Lower Devonian and uppermost Devonian–Mississippian sedimentary rocks and identify potential décollements in uppermost Devonian–Mississippian rocks in Triungen and Sentinelfjellet, (2) characterizing the nature of the contact between Neoproterozoic basement and Middle Devonian sedimentary strata of the Marietoppen Formation in Hornsund, and testing the exhumation of basement rocks as core complex(es), (3) obtaining accurate time constraints (Late Devonian? Mississippian?) for the deposition of sedimentary rocks of the Adriabukta Formation, (4) studying the timing of formation (and reactivation/overprinting?) and the kinematics of faults (e.g., Triungen–Grønhorgdalen Fault Zone) and shear zones (e.g., Mariekammen Shear Zone, Woodfjorden Detachment) crosscutting Devonian sedimentary rocks in Svalbard, (5) mapping and studying the impact of potential WNW–ESE- to NW–SE-striking faults formed along preexisting Timanian grain in central Spitsbergen on the Balliolbreen Fault and related structures.

Competing interests

The author declares that he has no conflict of interest.

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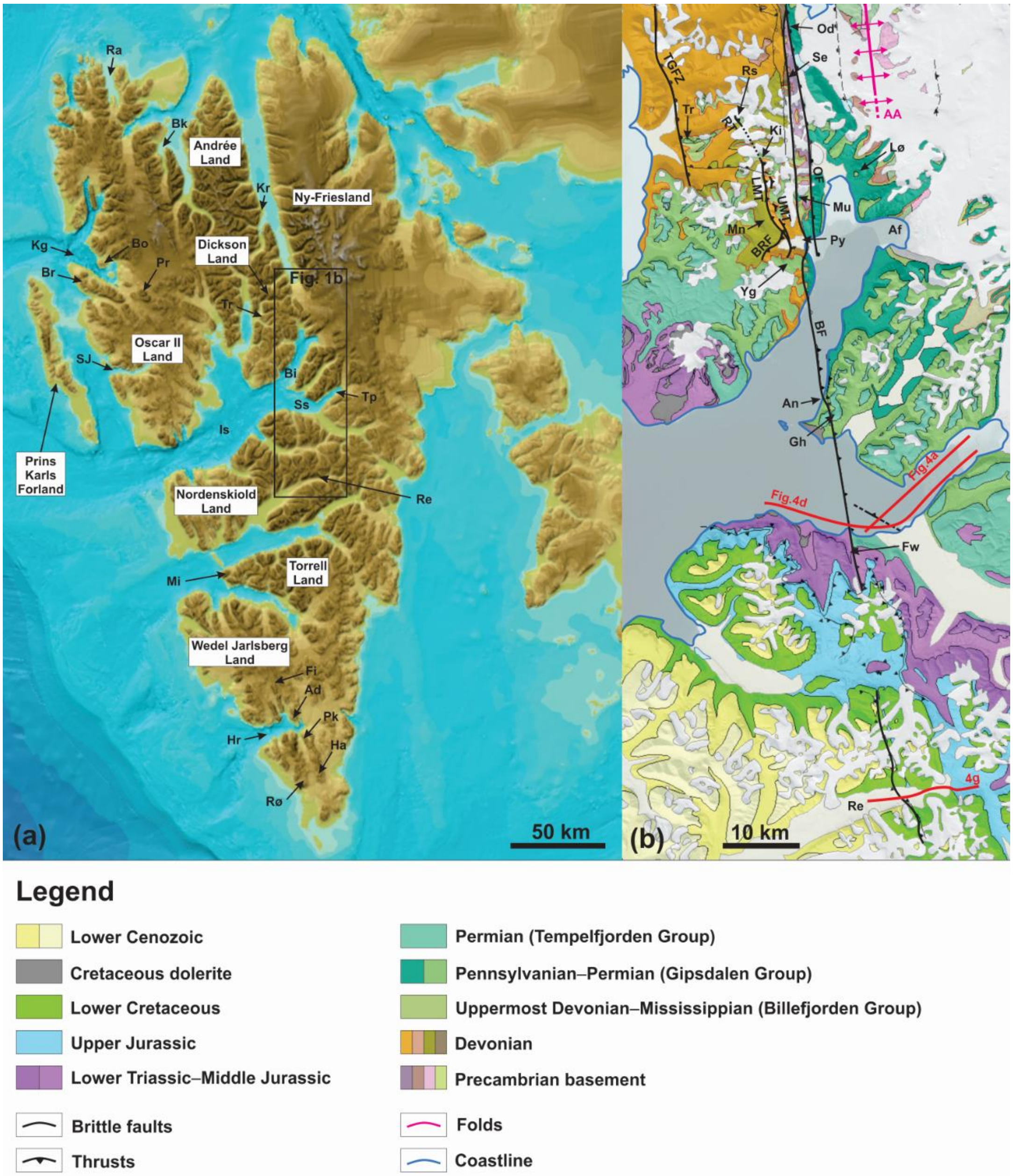

<u>Figure 1:</u> (a) Topographic–bathymetric map around Spitsbergen modified after Jakobsson et al. (2012). Abbreviations: Ad: Adriabukta; Bi: Billefjorden; Bk: Bockfjorden; Bo: Blomstrandhalvøya; Br: Brøggerhalvøya; Fi: Fiskeknatten; Ha: Haitana; Hr: Hornsund; Is: Isfjorden; Kg: Kongsfjorden; Kr: Krosspynten; Mi: Midterhuken; Pk: Påskefjellet; Pr: Pretender Mountain; Ra: Raudfjorden; Re: Reindalspasset; Rø: Røkensåta; Ss: Sassenfjorden; SJ: St-Jonsfjorden; Tp: Tempelfjorden; Tr: Triungen; (b) Geological map

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modified from svalbardkartet.npolar.no showing the main tectono-stratigraphic units and structures in the study area in central Spitsbergen. Abbreviations: AA: Atomfjella Antiform; Af: Adolfbukta; An: Anservika; BF: Balliolbreen Fault; BRF: Blåvatnet Reverse Fault; Fw: Flowerdalen; Gh: Gipshuken; Ki: Kilen; LMT: lower Munidalen thrust; Lø: Løvehovden–Hultberget; Mn: Munindalen; Mu: Mumien; Od: Odellfjellet; OF: Odelfjellet Fault; Py: Pyramiden; Re: Reindalspasset; Rs: Robertsonbreen; RT: Robertsonbreen thrust; Se: Sentinelfjellet; TGFZ: Triungen–Grønhorgdalen Fault Zone; Tr: Triungen; UMT: upper Munidalen thrust; Yg: Yggdrasilkampen.

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Figure 2: Aerial photograph of the Pyramiden coal mine showing intensely folded (dotted orange lines) Devonian rocks in the west juxtaposed against clastic- and coal-rich, uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group, which are overlain by Pennsylvanian–lower Permian strata of the Gipsdalen Group in the east. Dashed lines represent lithostratigraphic transition from red and green Lower Devonian sandstone (Wood Bay Formation) to Devonian quartzite and dark sandstone (dashed orange), from Devonian quartzite and dark sandstone to uppermost Devonian–Mississippian sedimentary rocks of the Billefjorden Group (dashed yellow green), and from the Billefjorden Group to strata of the Gipsdalen Group (dashed blue green). Dotted lines represent bedding surfaces as seen on the photograph, whereas white symbols indicate bedding trend and dip in map view (see Fig. Figure 3a). Note the Z-shaped fabrics of uppermost Devonian–Mississippian sedimentary strata (yellow lines) along potential bedding-parallel décollements (red lines) near the boundary between Lower Devonian and uppermost Devonian–Mississippian sedimentary rocks. The white frame shows the location of Figure 3b. Lower hemisphere Schmidt stereonets show (1) contoured poles of fracture surfaces in the uppermost Devonian–Mississippian Billefjorden Group (red indicates high and blue low density), (2) contoured poles of fracture surfaces within sandstone units of the Billefjorden Group, (3) great circles of fracture surfaces within coaly shale- and coal-bearing units of the Billefjorden Group, and (4) contoured poles of fracture surfaces in Devonian rocks. Photo by Åsle Strøm.

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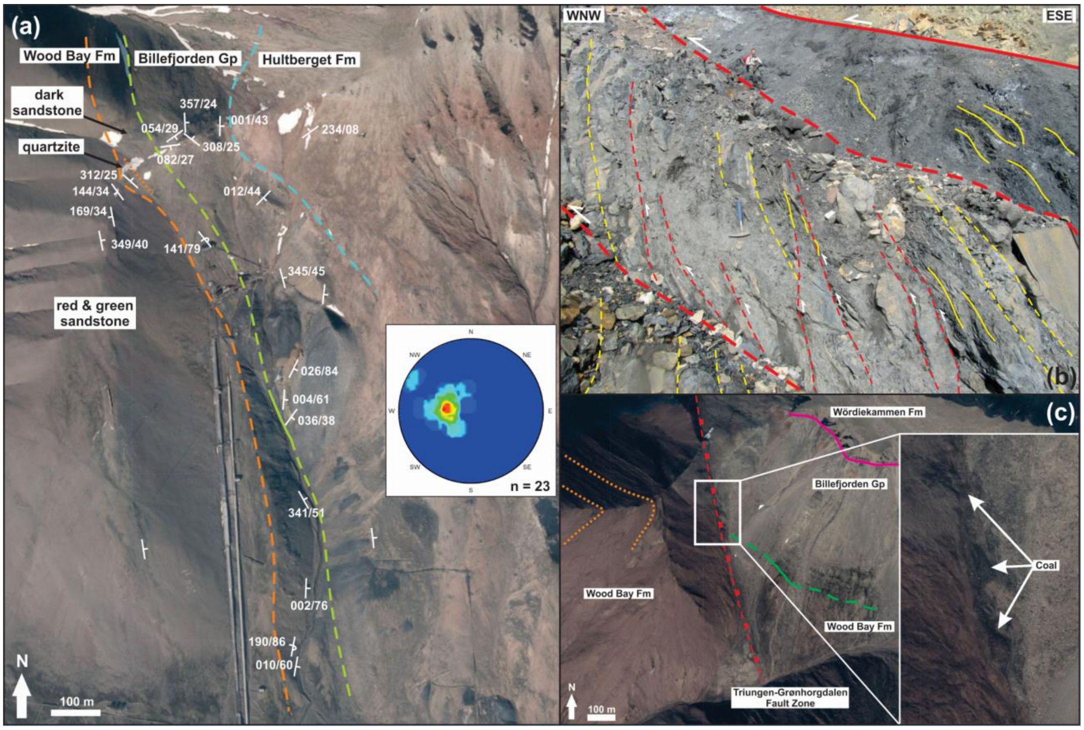

<u>Figure 3:</u> **(a) Satellite photograph of the Pyramiden locality (Figure 1b) from toposvalbard.npolar.no showing approximate lithostratigraphic contacts between Lower Devonian red and green sandstone and Devonian quartzite and dark sandstone in dashed orange, between Devonian quarzite and Devonian dark sandstone in dotted orange, between Devonian dark sandstone and uppermost Devonian–Mississippian strata of the Billefjorden Group in dashed yellow green, and between the sedimentary rocks of the Billefjorden Group and Gipsdalen Group in dashed blue green. Bedding surface measurements are shown in white. The lower hemisphere Schmidt stereonet shows bedding surface measurements in the Billefjorden Group as contoured poles (red indicates high and blue low density); (b) Field photograph of the base of uppermost Devonian–Mississippian, coaly shale- and coal-rich sedimentary rocks of the Billefjorden Group below the mine entrance in Pyramiden. The photo shows gently east-dipping stratigraphic unit boundaries that localized the formation of bedding-parallel décollements (thick red and thick dashed red lines). Within induvidual units, coal displays phyllitic, Z-shaped shear fabrics (yellow lines) parallel–subparallel to steeply east-dipping, intra-unit bedding surfaces (dashed yellow lines) that are truncated by subparallel, steeply east-dipping thrusts (thin dashed red lines). Location in Figure 2; (c) Satellite image from toposvalbard.npolar.no showing the inferred trace of the Triungen–Grønhorgdalen Fault Zone in Triungen (Figure 1b), which juxtaposes folded Lower Devonian sedimentary rocks of the Wood Bay Formation (bedding in orange) against uppermost Devonian–Mississippian strata of the Billefjorden Group that are unconformably overlain by the Wördiekammen Formation. The right hand-side inset shows a zoomed-in portion of the fault displaying dark-colored screes that may represent coal near the base of the Billefjorden Group in the hanging wall of the fault.**

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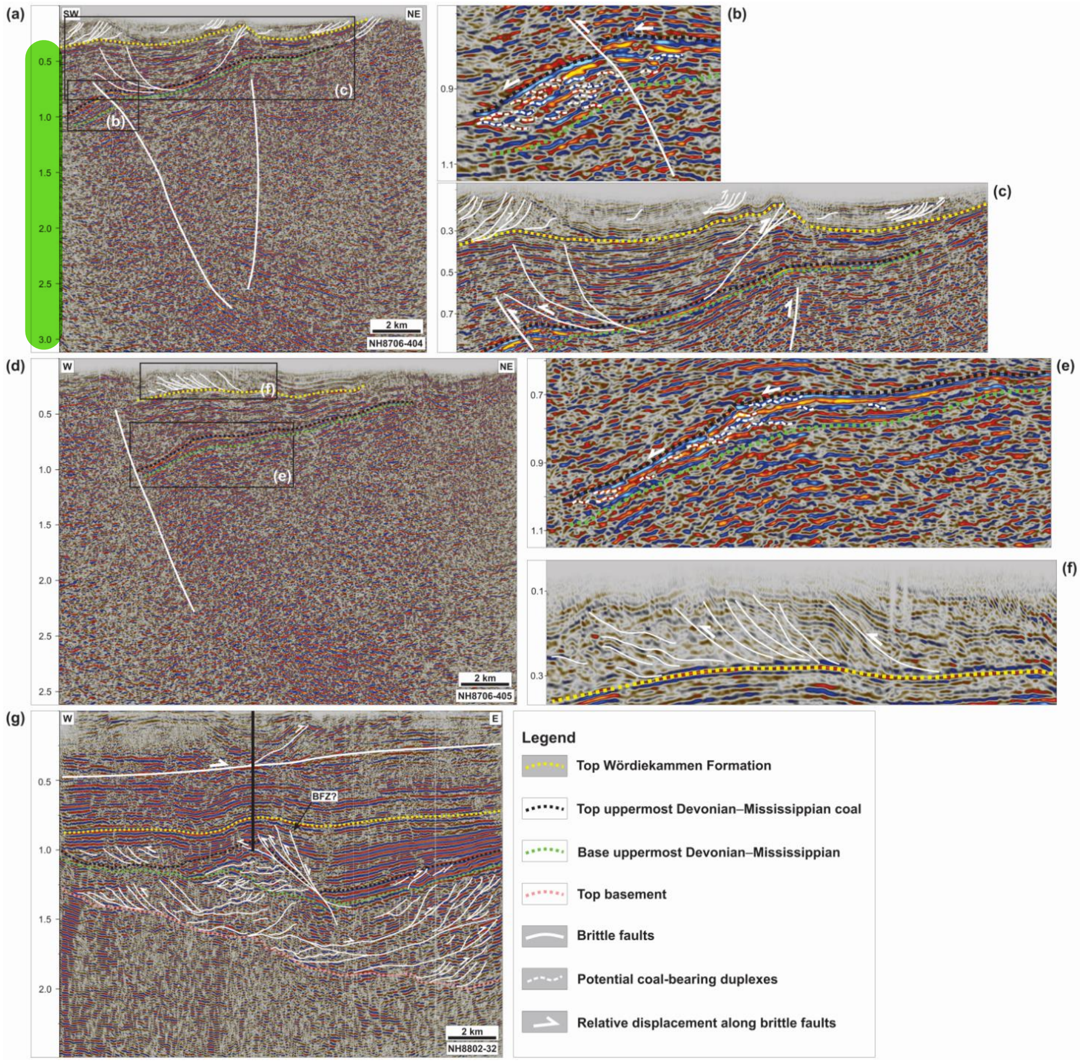

Figure 4: Seismic sections and associated zoomed-in portions in Saassenfjorden–Tempelfjorden (a–f) and Reindalspasset (g). See Figure 1b for locations. (a) NE–SW-trending section showing minor reverse offset and fault-propagation folding in thickened uppermost Devonian–Mississippian sedimentary rocks along WNW–ESE- to NW–SE-striking, deep-seated basement faults, and Cenozoic thrusts in overlying Pennsylvanian–Permian strata; (b) Zoom in SW-verging, coal-bearing duplexes acting as top-SW décollements in thickened, uppermost Devonian–Mississippian sedimentary deposits; (c) Zoom in NW–SE-striking Cenozoic thrusts that flatten into décollements within uppermost Devonian–Mississippian coals and at the top of the Wördiekammen Formation; (d) NE–west-trending, arch-shaped section showing the potential continuation of the Billefjorden Fault Zone bounding thick uppermost Devonian–Permian sedimentary deposits; (e) Zoom in coal-bearing duplexes in uppermost Devonian–Mississippian sedimentary strata indicating top-west Cenozoic movement; (f) Zoom in Cenozoic thrusts flattening into a décollement near the top of the

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Wördiekammen Formation; (g) West–east-trending section showing a top-east Cenozoic detachment in Mesozoic sedimentary rocks and a broad anticline in Devonian–Permian strata. Shale-rich Devonian–Mississippian sedimentary strata thicken into the anticline whereas Pennsylvanian–Permian sedimentary rocks thicken away from the anticline. The former are truncated by numerous Cenozoic thrusts arranged into duplex-like structures that flatten into intra Devonian–Mississippian décollements. Note that the thick vertical black line represents the location of exploration well 7816/12-1 (Eide et al., 1991). Abbreviations: BFZ: Billefjorden Fault Zone.

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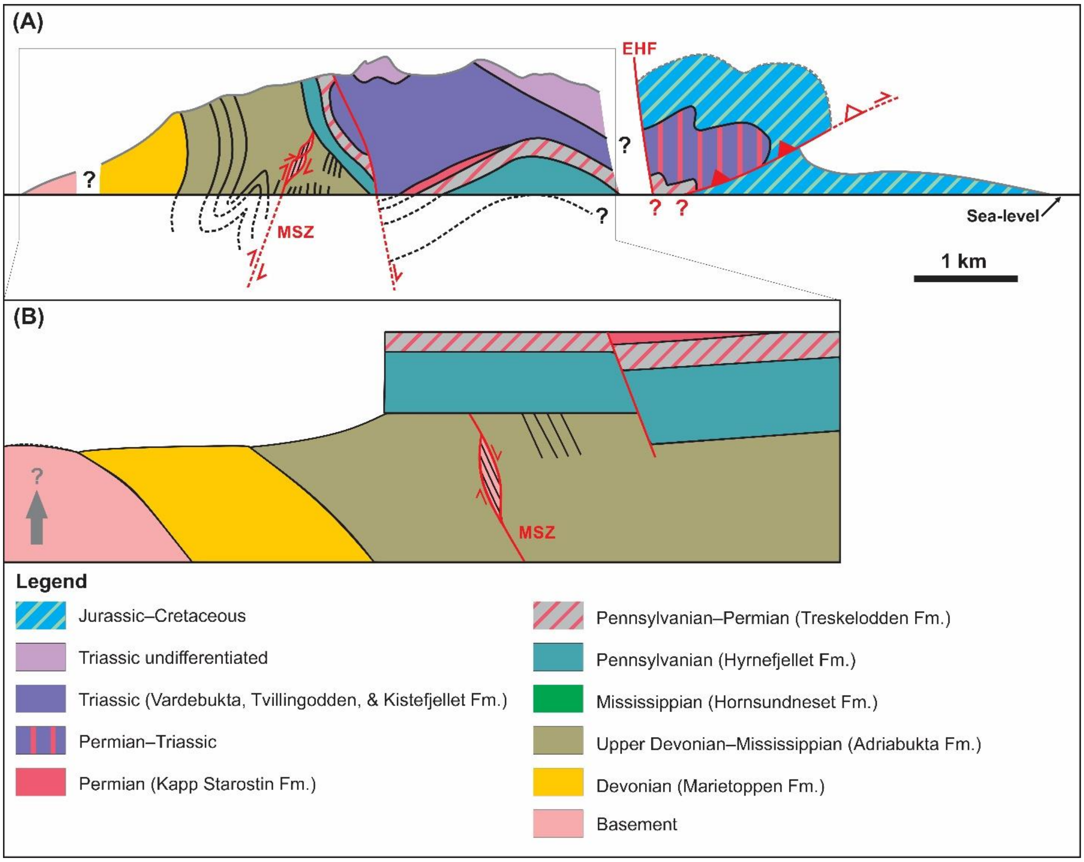

2025 **Figure 5: (a) Interpreted cross-section of the Adriabukta transect redrawn after Bergh et al. (2011), and (b) restored prior to Mesozoic sedimentation. Note the basement fabrics parallel to bedding surfaces in the Adriabukta Formation and the eastwards dip of the Mariekammen Shear Zone. Abbreviations: EHF: Eastern Hornsund Fault; MSZ: Mariekammen Shear Zone.**

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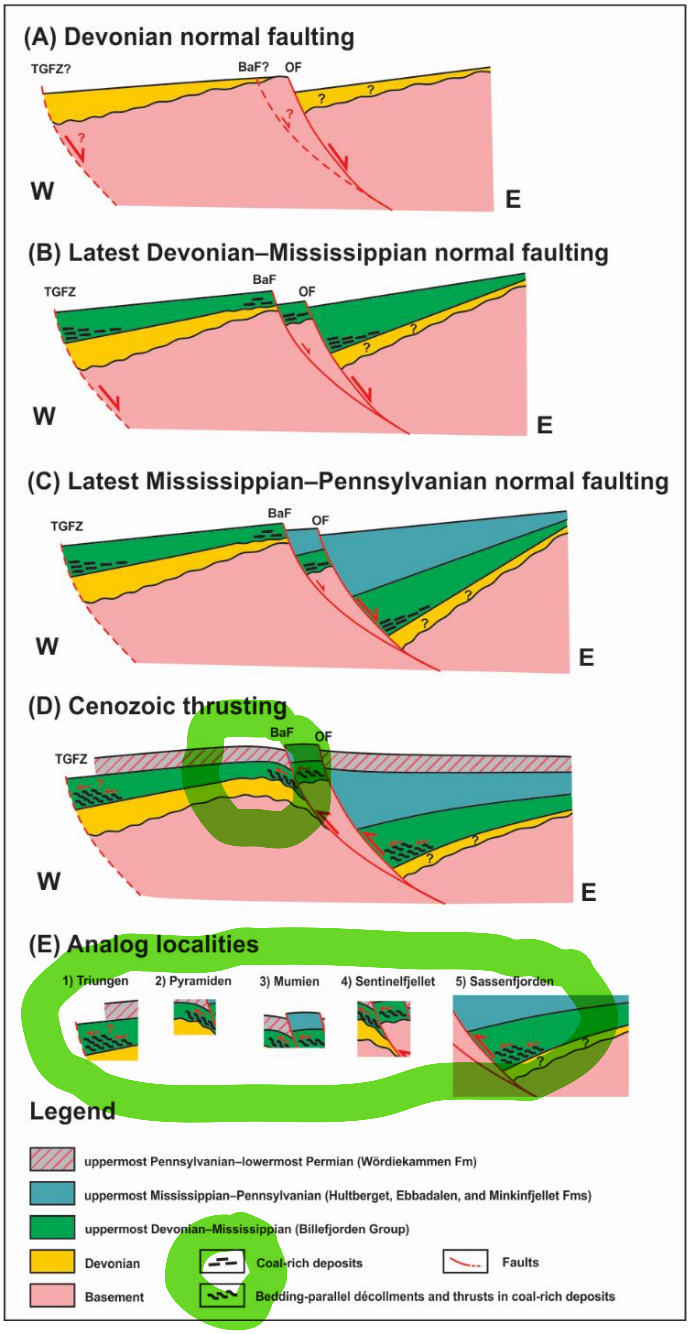

2030 **<u>Figure 6:</u> Schematic cross-sections showing the possible evolution of the Billejorden Fault Zone in Devonian–Cenozoic times. (a) Relatively high pre-Devonian basement in the east and collapse basin in the west with erosion-related exhumation of basement rocks in the footwall of the Odellfjellet Fault, (b) widespread Mississippian normal faulting and localization of**

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thick coal deposits on basin edges, (c) Pennsylvanian normal faulting localized along the Billefjorden Fault Zone (Balliolbreen and Odellfjellet faults), (d) inversion of Devonian–Carboniferous normal faults and basins during early Cenozoic Eurekan contraction, including top-west thrusting of basement onto Devonian rocks along the Balliolbreen Fault, and the formation of bedding-parallel décollements and thrusts in uppermost Devonian–Mississippian coal-rich deposits, and (e) parts of the cross-section in (d) that fit field observations in key localities discussed in the text (Figure 1a–b). Abbreviations: BaF: Balliolbreen Fault; OF: Odelffjellet Fault; TGFZ: Triungen–Grønhorgdalen Fault Zone.

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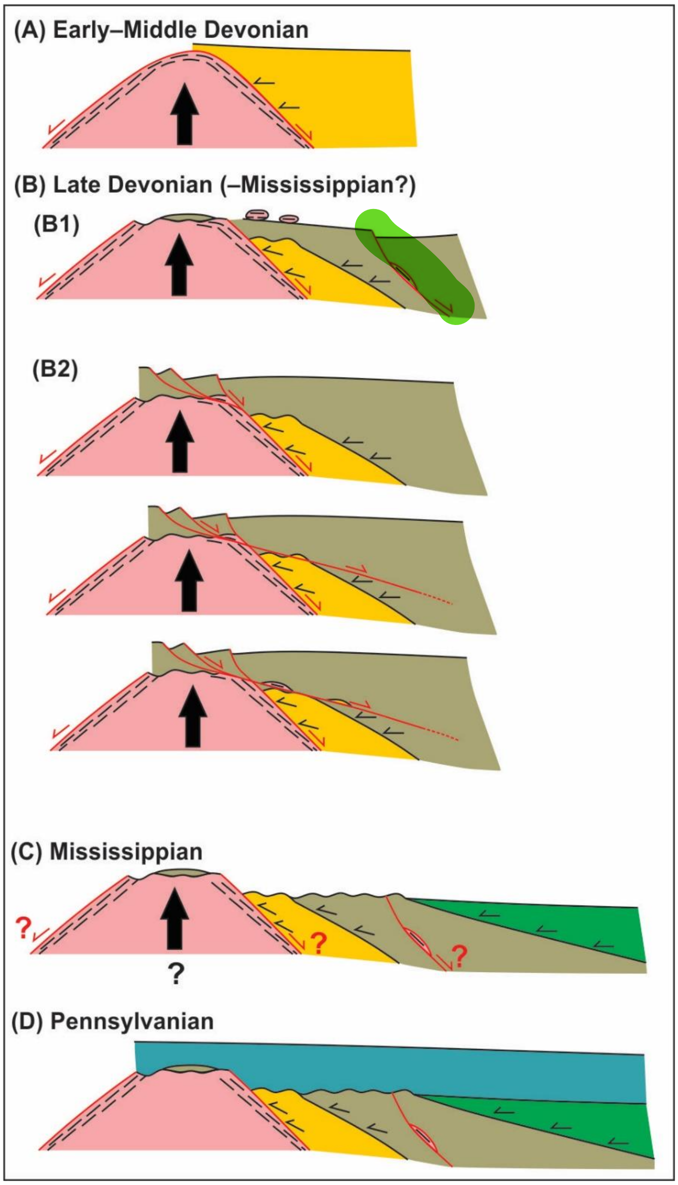

Figure 7: Conceptual sketches of the Adriabukta transect showing the development of a N–S- to NNW–SSE-trending metamorphic core complex in Hornsund (Figure 1a), including (a)
2045 initial exhumation along a bowed detachment in the Early–Middle Devonian and the deposition of the Marietoppen Formation, (b1) continued exhumation in the Late Devonian (–Mississippian?) and erosion of basement rocks along the crest of the core complex, resulting in incorporation of a lens of basement rocks along newly formed extensional faults and shear zones within the Adriabukta Formation, or (b2) excisement–incisement processes along the
2050 eastern portion of the core complex-bounding detachment and incorporation of a basement

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lens along a low-angle, bedding-parallel, top-east detachment within the Adriabukta Formation, (c) possible final episode of extension-related exhumation and normal faulting in the Mississippian as suggested by the angular unconformity between the Adriabukta and Hornsundneset formations (black arrows showing the onlaps and angle between bedding surfaces of the two formations), and (d) infill of the existing topography by Pennsylvanian sedimentary rocks of the Hyrnefjellet Formation. Black arrows show sedimentary onlaps and potential angular unconformities between stratigraphic units. See Figure 5 for color legend and Figure 5a for the impact of Cenozoic contraction on the Adriabukta transect.

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