The timing of the Svalbardian Orogeny in Svalbard: A review

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Abstract

In the Late Devonian to earliest Mississippian, Svalbard was affected by a short-lived episode of deformation named the Svalbardian Orogeny. This event resulted in intense folding and thrusting in Devonian sedimentary successions. Deformation stopped prior to the deposition of Carboniferous to Permian sedimentary strata of the Billefjorden and Gipsdalen groups, which lie unconformably over folded Devonian strata. Later on, presumed Svalbardian structures were reworked during Eurekan tectonism in the early Cenozoic and partly eroded. At present, record of Svalbardian deformation is only preserved in narrow N–S-trending belts in central and northern, western and southern Spitsbergen. Despite extensive field studies, the timing of the Svalbardian Orogeny is poorly constrained, and remains a matter of debate in places because of conflicting ages and because of the complex tectonic history of Svalbard. The present contribution aims at reviewing and discussing all available age constraints for Svalbardian tectonism, which has great implications for the plate tectonic reconstructions of Arctic regions and for the tectonic history of Svalbard. The Mimerdalen Subgroup is upper Givetian to lower Frasnian (ca. 385–380 Ma) in age and the Billefjorden Group is mid Famennian to Upper Mississippian (ca. 365–325 Ma), therefore constraining the Svalbardian event in central and northern Spitsbergen to 383–365 Ma if it ever occurred. The Adriabukta Formation in southern Spitsbergen is Middle Mississippian and, therefore, cannot have been involved in the Svalbardian event, thus suggesting that all the

deformation in southern Spitsbergen in early Cenozoic in age and that strain partitioning processes had a major role in localizing deformation in weaker stratigraphic units. The few geochronological age constraints yielding Late Devonian–Mississippian ages in Svalbard may reflect either Svalbardian contraction or extensional processes and are therefore of no use to validate or invalidate the occurrence of the Svalbardian event. On the contrary, the contradicting lines of evidence used to support the occurrence of the Svalbardian event and new regional geophysical studies suggest that Svalbard was subjected to continuous extension from the late Silurian to early Permian times.

1. Introduction

The Svalbardian Orogeny, also known as the Innuitian or Ellesmerian Orogeny, refers to a short-lived episode of contraction and/or transpression that affected all levels of the crust and occurred in the Late Devonian (to earliest Mississippian?) when parts of the tectonic plates now constituting most of the Arctic (Laurentia and Baltica) collided with each other and deformed Proterozoic to mid-Paleozoic sedimentary basins and basement rocks in northeastern Russia (Malyshev et al., 2011; Luchitskaya et al., 2015), Canada (Thorsteinsson and Tozer, 1970; Trettin, 1973, 1991; Embry and Klovan, 1976; Embry, 1991; Harisson, 1995; Harisson and Brent, 2005; Piepjohn et al., 2008, 2013; Piepjohn and von Gosen, 2017) and Alaska (Grantz and May, 1984; Lane, 2007; Kumar et al., 2011), Proterozoic to Silurian metasedimentary rocks in northern and northeastern Greenland (Higgins et al., 2000; Piepjohn et al., 2015), and Devonian collapse basins and Precambrian to lower Paleozoic basement in Norway (Roberts, 1983; Osmundsen et al., 1998) and Svalbard (Vogt, 1938; Harland et al., 1974; McCann, 2000; Piepjohn, 2000; Piepjohn et al., 2000; Figure 1).

In Svalbard, Svalbardian contraction (transpression?) followed the Caledonian Orogeny (ca. 460–410 Ma; Horsfield, 1972; Dallmeyer et al., 1990; Johansson et al., 2004, 2005; Faehnrich et al., 2020) and subsequent deposition of thick upper Silurian–Devonian sedimentary successions during late–post-orogenic collapse (Gee and Moody-Stuart, 1966; Friend et al., 1966; Friend and Moody-Stuart, 1972; Murascov and Mokin, 1979; Manby and Lyberis, 1992; Manby et al., 1994; Friend et al., 1997; McCann, 2000; Dallmann and Piepjohn, 2020), and led to the final accretion of Svalbard's three basement terranes (Harland and Wright, 1979; Ohta et al., 1989, 1995; Harland et al., 1992; Gee and Page, 1994). Although early accounts envisioned hundreds to thousands of kilometer-scale strike-slip movements along N–S-striking faults like the Billefjorden and Lomfjorden fault zones (e.g., Harland et al., 1974, 1992), more recent studies have shown that such large scale strike-slip movements are unlikely (McCann, 2000; Michalski et al., 2012). In addition, new geochronological and structural work in northern Svalbard shows that collapse-related extension leading to the exhumation of the Bockfjorden Anticline as a core complex lasted from the late Silurian to the Late Devonian (Famennian at 368.42 ± 0.81 Ma; Braathen et al., 2018), i.e, possibly overlapping with Svalbardian contraction.

Evidence of Svalbardian tectonism include dominantly west-verging folds and thrusts within several kilometer-thick, Devonian, late–post-orogenic, collapse-related sedimentary rocks in central and northern Spitsbergen (Andrée Land Group including the Mimerdalen Subgroup; Vogt, 1938; Harland et al., 1974; Manby and Lyberis, 1992; Manby et al., 1994; Friend et al., 1997; Piepjohn and Dallmann, 2014; Dallmann and Piepjohn, 2020) and dominantly east-verging folds and thrusts in Devonian (to Middle Mississippian?) sedimentary rocks in southern Spitsbergen (Marietoppen and Adriabukta formations; Dallmann, 1992; Bergh et al., 2011). The latter were interpreted to be unconformably covered by presumed undeformed, shale-rich, poorly exposed Triassic strata in Røkensåta (Dallmann, 1992). Important uncertainties around this interpretation are discussed for the first time in the present work and suggest that interpretation based on this outcrop should be given little to no credit.

Shortly (i.e., immediately up to a few million years) after the end of Svalbardian deformation, partly eroded Devonian sedimentary rocks in Spitsbergen were covered by fluvial, coal-rich deposits of the Billefjorden Group, possibly during widespread latest Devonian–Mississippian extension, and shallow marine strata of the Gipsdalen Group mostly deposited within narrow, kilometer- to tens of kilometer-wide, N–S- to NW–SE-trending basins (Cutbill and Challinor, 1965; Maher Jr., 1996; McCann and Dallmann, 1996; Braathen et al., 2011; Koehl and Muñoz-Barrera, 2018; see Figure 2 for stratigraphy). Subsequently, Svalbardian structures were reworked by Eurekan contraction and/or transpression during the opening of the Labrador Sea and Baffin Bay between Canada and Greenland (Chalmers and Pulvertaft, 2001; Oakey and Chalmers, 2012), which 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, 1993; Andresen et al., 1994; Bergh and Grogan, 2003; see location in Figure 1) and of the Central Tertiary Basin in central Spitsbergen (Larsen, 1988; Petersen et al., 2016). As a result, Svalbardian structures were overprinted and reworked and now commonly display the same trends, plunges, strikes, dips and kinematics as Eurekan structures throughout the Arctic and, in many occurrences, coincide with and are indistinguishable from Eurekan structures (e.g., Birkenmajer, 1964; Piepjohn et al., 2007, 2008, 2013, 2015; Bergh et al., 2011; Piepjohn and von Gosen, 2017; Dallmann and Piepjohn, 2020).

At present, original (unmodified) Svalbardian deformation is preserved only in a few narrow N–S-trending belts, including Dickson Land (Michaelsen et al., 1997; Piepjohn et al., 1997b; Michaelsen, 1998; Piepjohn, 2000), Andrée Land (Dallmann and Piepjohn, 2020), and Blomstrandhalvøya (Thiedig and Manby, 1992; Buggisch et al., 1994; Figure 1). The best and most well-constrained example of Svalbardian tectonism is observed in central and northern Spitsbergen, where folded Lower to lowermost Upper Devonian sedimentary rocks of the Andrée Land Group and Mimerdalen Subgroup are unconformably overlain by apparently undeformed uppermost Devonian to lowermost Permian sedimentary strata of the Billefjorden and Gipsdalen groups (Vogt, 1938; Harland et al., 1974; Piepjohn, 2000; Piepjohn et al., 2000). The structures in the Dickson Land area are actually highly questionable and are addressed in two separate manuscripts (Koehl et al., in prep.; Koehl and Stokmo, in prep.), and will therefore not be reviewed in detail in the present contribution.

Recent U–Th–Pb geochronology on monazite grains yielded 373–355 Ma (latest Devonian to earliest Mississippian) ages for amphibolite facies metamorphism along a gently west-dipping shear zone in Prins Karls Forland (location in Figure 1) crosscuting Neoproterozoic basement rocks. These data provide evidence and time constraints for Svalbardian tectonism at depth of c. 15 kilometers (Faehnrich et al., 2017; Majka and Kośmińska, 2017; Schneider et al., 2018; Kośmińska et al., 2020). Potential Svalbardian (greenschist) facies metamorphism and mylonitization was also potentially identified in Oscar II Land (location in Figure 1) and dated to 365–344 Ma through ^{40}Ar–^{39}Ar and U–Th–Pb geochronology (Barnes et al., 2020).

Nonetheless, despite extensive previous works, Svalbardian tectonism at shallow crustal levels lacks accurate time constraints and, in places, it is possible that structures ascribed to this event may have formed during the early Paleozoic Caledonian Orogeny or during the early Cenozoic Eurekan tectonic event (e.g., Rippington et al., 2010). Distinguishing Svalbardian from Eurekan structures is problematic. In Arctic Canada and Greenland, Ellesmerian structures are thought to be overprinted almost everywhere by subsequent Eurekan structures (e.g., Piepjohn et al., 2015). This is also the case to some extent in Svalbard, where Svalbardian and Eurekan folds and thrusts are believed to both show dominantly east-verging geometries in the south, but opposite vergence in the north where Svalbardian structures display mostly top-west attitudes (Dallmann and Piepjohn, 2020). Another issue arises from the complexity of the Eurekan fold-and-thrust belt throughout Spitsbergen, which involves numerous décollements localized in shale-rich stratigraphic units, such as the Lower Triassic (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., 1993; Bergh et al., 1997).

Furthermore, east- to northeast-plunging folds trending parallel to the inferred late–post-orogenic extension direction in Middle Devonian collapse basins in western Norway were initially interpreted as Late Devonian to Mississippian, Svalbardian contractional and/or transpressional structures (Roberts, 1983). These are now known to have formed as transtensional folds during extensional collapse of the Caledonides (Chauvet and Séranne, 1994; Osmundsen and Andersen, 1994; Fossen et al., 2013). Thus, it is paramount to carefully constrain the timing of Svalbardian (and Ellesmerian) deformation throughout the Arctic to be able to evaluate the extent and impact of this tectonic event from a regional perspective and understand its interplay with potentially coeval collapse processes (e.g., Braathen et al., 2018; Maher et al., 2022).

Thus far, Svalbardian deformation is thought to have occurred during the Late Devonian to Early Mississippian, possibly initiating in the late Frasnian to Famennian (Vigran, 1964; Allen, 1965, 1973; Pcelina et al., 1986; Brinkmann, 1997; Schweitzer, 1999; Piepjohn et al., 2000; Figure 2). The onset of deformation was presumably recorded by the deposition and syn-depositional deformation of coarse-grained sedimentary rocks of the Mimerdalen Subgroup in the late Famennian (Planteryggen and Plantekløfta formations in Figure 2; Piepjohn and Dallmann, 2014). Deformation is believed to have stopped prior to the deposition of sedimentary rocks of the Billefjorden Group in the late Tournaisian (Vogt, 1938; Piepjohn, 2000).

The present contribution focuses on the debate around the timing of Svalbardian tectonism throughout Spitsbergen. In northern Spitsbergen, Svalbardian deformation was constrained to the late Famennian to earliest Mississippian by the identification of one specimen of *Retispora lepidophyta* in folded rocks of the Plantekløfta Formation (Schweitzer, 1999; Piepjohn et al., 2000). However, recent palynological and paleontological studies in northern and central Spitsbergen suggest slightly revised ages for the stratigraphic units used to constrain the timing of the

Svalbardian Orogeny, including a Middle Devonian (minimum upper Givetian) age for rocks of the Tordalen Formation (Mimerdalen Subgroup; Berry and Marshall, 2015; Newman et al., 2019) and a mid Famennian age for the base of the Billefjorden Group (Scheibner et al., 2012; Lindemann et al., 2013; Marshall et al., 2015; Gilda M. Lopes pers. obs., 2019). In addition, the timing of Svalbardian deformation varies somewhat from north to south in Spitsbergen, and study of a palynological assemblage in the Adriabukta Formation in southern Spitsbergen constrained Svalbardian folding and faulting to the Viséan (Middle Mississippian; Birkenmajer and Turnau, 1962; Figure 2). The present contribution reviews time constraints for Svalbardian tectonism in central, northern, southern, and western Svalbard and briefly discusses their implications.

Constraining the timing of the Svalbardian Orogeny in Svalbard with accuracy is of importance for paleogeographic and plate tectonics reconstructions in the Arctic. It is also important for the tectonic history of Svalbard, e.g., to evaluate potential interplay between late–post-Caledonian extensional collapse, which resulted in the deposition of several kilometers thick collapse basins (e.g., Murascov and Mokin, 1979; Manby and Lyberis, 1992; Friend et al., 1997; Braathen et al., 2018), and contractional tectonic processes that resulted in intense folding of these deposits (Vogt, 1938; Piepjohn, 2000; Dallmann and Piepjohn, 2020). Furthermore, the present study has implications for the methods used by geologists to interpret tectonic events worldwide, e.g., in pointing out that field studies based on long-distance observation of poorly exposed and inaccessible transects should be given little (if any) credit.

Review of age constraints in northern and central Spitsbergen

Age of the Mimerdalen Subgroup

The identification of one specimen of *Retispora lepidophyta* within strata of the Plantekløfta Formation by Brinkmann (1997, his table 14.3) and Piepjohn et al. (2000; published in Schweitzer, 1999, plate 6 in their figure 10 and plate 7 in their figure 1) suggests a late Famennian age for the top fo the Plantekløfta Foramtion and, hence, that Svalbardian tectonism terminated during the Famennian to Tournaisian in northern and central Spitsbergen.

Recent studies clearly demonstrated that the interpretation of *Retispora lepidophyta* by Brinkmann (1997), Schweitzer (1999) and Piepjohn et al. (2000) is erroneous. Notably, the lone figured specimen interpreted as *Retispora lepidophyta* by Schweitzer (1999) and Piepjohn et al. (2000) differs in size and shows significantly different morphological structures from typical

Retispora lepidophyta (Playford, 1976; Berry and Marshall, 2015, their supplement DR3; see also Supplement S1). In addition the fovea that characterise the spore's exoexine appear to be the result of damage by cubic diagenetic pyrite. Attempts have been made to locate the *Retispora lepidophyta* specimen figured in Brinkmann (1997) and Schweitzer (1999) and used by Piepjohn et al. (2000) to date Svalbardian tectonism in central Spitsbergen for further analysis. These attempts were unfortunately unsuccessful (John E. A. Marshall pers. obs., 2020).

Berry and Marshall (2015) re-evaluated the age of the Plantekløfta Formation to be early Frasnian based on fossils and miospores (ca. 383–380 Ma; see also their supplements; Figure 2). In addition, the paleontological study of Newman et al. (2019, 2020, 2021) recorded the presence of articulated fish in the Fiskekløfta Member of the Tordalen Formation (Figure 2), i.e., undoubtedly *in situ* fossils, demonstrating a late to latest Givetian (ca. 385–383 Ma; Middle Devonian) age for this stratigraphic unit instead of late Famennian. If the relatively coarser grain-size of the sedimentary deposits of the Planteryggen and Plantekløfta formations indeed reflects the onset of Svalbardian tectonism as suggested by Piepjohn and Dallmann (2014), the new paleontological and palynological ages constrain the initial phase of the Svalbardian Orogeny at 383–380 Ma.

A late Famennian age for the Plantekløfta Formation based on the lone specimen of *Retispora lepidophyta* in central Spitsbergen is the only contradictory evidence against a mid Famennian age for the base of the Billefjorden Group and older age for the Mimerdalen Subgroup (Scheibner et al., 2012; Lindeman et al., 2013; Berry and Marshall, 2015; Marshall et al., 2015; Lopes et al., 2019; Newman et al., 2019; Gilda M. Lopes pers. obs., 2019).

Age of the Billefjorden Group

Recent palynological studies in central Spitsbergen dated the base of the Billefjorden Group in Triungen (see Figure 1 for location) to the mid Famennian (maximum ca. 365 Ma; Lindemann et al., 2013; Marshall et al., 2015; Gilda M. Lopes pers. obs., 2019; Figure 2). At least 30 samples contained characteristic Famennian spore assemblages including *Cyrtospora cristifer, Cornispora monocornata, Cornispora bicornata, Cornispora tricornata, Lophozonotriletes lebedianensis, Knoxisporites dedaleus, Grandispora gracilis, Spelaeotriletes papulosus, Cristatisporites lupinovitchi*, *Lagenosisporites* sp., *Grandispora famensis* and *Tergobulasporites immensus* (Marshall et al., 2015). Some samples from the lower part of the Billefjorden Group in Billefjorden also contained *Retispora lepidophyta* (Gilda M. Lopes obs. comm., 2019). These spore assemblages were also identified in sedimentary rocks in the lower part of the Billefjorden Group in northeastern Spitsbergen (Scheibner et al, 2012), thus strengthening a Famennian age for the base of this stratigraphic unit thoughout northern and central Spitsbergen. Note that the base of the Billefjorden Group in Bjørnøya also was also dated as Famennian based on palynology (Kaiser, 1970; Worsley and Edwards, 1976; Lopes et al., 2021). This strongly suggests that the Svalbardian deformation, which ended prior to the deposition of the Billefjorden Group (Piepjohn, 2000), must have been terminated by the mid Famennian in central and northern Spitsbergen. This implies a maximum duration of 18 Ma for this tectonic event.

Piepjohn and Dallmann (2014) proposed that the mid to late Famennian spores identified in the lower part of the Billefjorden Group were reworked based on their identification of one specimen of *Retispora lepidophyta* within the Plantekløfta Formation (Piepjohn et al., 2000). However, since this specimen clearly is a misidentification (Berry and Marshall, 2015, their supplement DR3), the claim of reworking of mid to late Famennian spores found within the base of the Billefjorden Group in Triungen no longer has any supporting argument in Svalbard, and neither does the claim of Piepjohn et al. (2000) that the older Devonian spores found in the sample with the misidentified specimen of *Retispora lepidophyta* were reworked.

Other time constraints for deformation in central and northern Spitsbergen

At least some of the deformation in Lower to lowermost Upper Devonian strata of the Andrée Land Group and Mimerdalen Subgroup in central and northern Spitsbergen is early Cenozoic in age because uppermost Devonian to Mississippian strata of the Billefjorden Group, which overlie the Andrée Land Group and Mimerdalen Subgroup in the area, are intensely sheared top-west, e.g., in Pyramiden (Koehl, 2021) and Garmdalen (Koehl et al., 2020, 2022 submitted; locations in Figure 1). This is further supported by the interpretation of seismic data adjacent nearshore portions of Billefjorden showing the presence of a bedding-parallel décollement between the Wood Bay Formation and the Gipsdalen Group (Koehl et al., 2020; Koehl et al., 2022 in prep.). These suggest a significant impact of strain partitioning during Eurekan deformation. Eurekan strain partitioning is further illustated by tight plastic folding of Lower Devonian strata of the Andrée Land Group and brittle brecciation of the unconformity with Upper Pennsylvanian to Permian strata in Yggdrasilkampen (Manby et al., 1994 their figure 11), and by décollements within Middle Devonian deposits near the Billefjorden Fault Zone in Wijdefjorden (John E. A. Marshall pers. obs., 2022; see Figure 1 for location).

Another argument corroborating these data is the involvement in folding of Carboniferous picritic dykes dated at ca. 357 Ma (Evdokimov et al., 2006; monchiquite dykes in Gayer et al., 1966 and Manby and Lyberis, 1996) intruding Lower Devonian sedimentary rocks at Krosspynten (see location in Figure 1).

In addition, part of the deformation recorded by Lower to lowermost Upper Devonian strata of the Andrée Land Group and Mimerdalen Subgroup is possibly related to extensional detachment folding in the Devonian (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished). This is also supported by recent field and geochronological studies in northwestern Spitsbergen (Braathen et al., 2018, 2020; Maher et al., 2022).

Thus, it is unclear how much (if any at all) of the deformation observed within Lower to lowermost Upper Devonian strata of the Andrée Land Group and Mimerdalen Subgroup in central and northern Spitsbergen actually reflects Ellesmerian tectonism.

Review of age constraints in southern Spitsbergen

Age of the Adriabukta Formation

In southern Spitsbergen, Lower to Middle Devonian sedimentary rocks of the Marietoppen Formation (time equivalent to the Pragian to Eifelian Wood Bay and Grey Hoek formations of the Andrée Land Group in central and northern Spitsbergen; Figure 2) unconformably overlie Precambrian to early Paleozoic basement rocks and are overlain by sedimentary strata of the Adriabukta Formation that were deformed into tight east-verging folds presumably during Svalbardian tectonism (Birkenmajer, 1964). The age of the Adriabukta Formation was dated to the Middle Mississippian through analysis of palynomorphs from black shales at the base and within the Formation (Birkenmajer and Turnau, 1962; Figure 2). Dallmann et al. (1999) noted that because of the age discrepancy between the Middle Mississippian Adriabukta Formation and the Lower to lowermost Upper Devonian Andrée Land Group in central and northern Spitsbergen, the folding of the Adriabukta Formation could not be correlated to Svalbardian folding. Nevertheless, in 2011, W. Dallmann suggested that the Adriabukta Formation is actually Late Devonian in age based on structural correlation between presumed Svalbardian structures in the Adriabukta Formation and Svalbardian fold-and-thrust belts in central and northern Spitsbergen, thus generating a debate around the actual age of the formation. This is referenced as "W. Dallmann pers. comm. 2009" in Bergh et al. (2011).

The speculation and debate initiated by W. Dallmann around the age of the Adriabukta Formation is neither based on published material nor on specific scientific evidence. By contrast, Birkenmajer and Turnau (1962) identified a count of 350 spore specimens from the Adriabukta Formation including specimens of *Lycospora*, *Tripartites* and *Triquitrites,* which were then and are still characteristic of the Middle Mississippian (Hughes and Playford, 1961; Playford, 1962, 1963; Clayton 1996). Later palynological studies in Svalbard (Billefjorden; Lopes et al., 2019) and Europe (Clayton et al., 1977) corroborate the Middle Mississippian ages obtained by Birkenmajer and Turnau (1962) for the Adriabukta Formation. Thus, the speculationdebate around the Middle Mississippian ages obtained for the Adriabukta Formation by Birkenmajer and Turnau (1962) is not justified and a Middle Mississippian age is entirely justified. The Adriabukta Formation in southern Spitsbergen is therefore a time-equivalent of the Billefjorden Group (e.g., Lopes et al., 2019).

The Middle Mississippian age of the Adriabukta Formation suggests that folding within this stratigraphic unit cannot be Late Devonian and is therefore not related to Svalbardian tectonism. A more likely origin for deformation within the Adriabukta Formation is the early Cenozoic Eurekan tectonic event. The tightly folded character of the Adriabukta Formation was previously proposed to be related to the dominance of weak shale and to Cenozoic strain partitioning by Birkenmajer and Turnau (1962). This scenario is now the most likely explanation for differential deformation of shales of the Adriabukta Formation and for folding of the Marietoppen Formation in southern Spitsbergen.

Age of the Hornsundneset Formation

In Hornsundneset (Figure 1), Siedlecki and Turnau (1964) analyzed eight samples from the Hornsundneset and Sergeijevfjellet formations of the Billefjorden Group. They proposed a Serpukhovian (Late Mississippian) age based on palynological results. However, a re-evaluation of their results showed that the Billefjorden Group in Hornsundneset (location in Figure 1) is Middle Mississippian in age (Dallmann et al., 1999; Krajewski and Stempien-Salek, 2003), i.e., contemporaneous with the Adriabukta Formation (Figure 2).

Interestingly, the Hornsundneset and Sergeijevfjellet formations are dominated by relatively hard, flat-lying beds of sandstone. Though located closer to the early Cenozoic collision zone with Greenland (i.e., within the West Spitsbergen Fold-and-Thrust Belt), these formations are relatively undeformed compared to the shale-dominanted Adriabukta Formation (Siedlecki, 1960). This further supports a significant impact of strain partitioning on deformation patterns during the Eurekan tectonic event in southern Spitsbergen.

Other time constraints

In Adriabukta (location in Figure 1), the Adriabukta Formation is truncated by a major shear zone, the Mariekammen Shear Zone, which comprises hundreds of meter-long lenses of Cambrian metasedimentary basement rocks, shows a top-east reverse sense of shear, and is unconformably overlain upwards by mildly folded Pennsylvanian strata of the Gipsdalen Group (Hyrnefjellet Formation), thus possibly reflecting Svalbardian tectonism (Birkenmajer and Turnau, 1962; Birkenmajer, 1964; Dallmann, 1992; Bergh et al., 2011). However, these previous studies did not account for the impact of Eurekan tectonism in southern Spitsbergen. A simple restoration of the shear zone prior to Eurekan deformation shows that, if this structure is indeed Mississippian in age, it must have formed as a normal fault and therefore cannot reflect Svalbardian contractional deformation (Supplement S2). It should be noted that other workers proposed that the Mariekammen Shear Zone formed as an early Cenozoic structure (Dallmann, 1992; von Gosen and Piepjohn, 2001). The fact that the shear zone does not seem to crosscut the Hyrnefjellet Formation and instead abruptly dies out at the unconformity (see sketch in figure 5 in Bergh et al., 2011) rather supports a formation as a normal fault in the Mississippian (Supplement S2).

The Adriabukta Formation was intruded by two, thin, bedding-parallel, Early Cretaceous dolerite sills of the Diabasodden Suite (Senger et al., 2013) that are folded together with bedding surfaces (Birkenmajer and Morawski, 1960; Birkenmajer, 1964). If the Adriabukta Formation was already folded in the Early Cretaceous, the sills would have truncated both fold structures and bedding surfaces. For sills to intrude along bedding surfaces, these must have remained relatively undeformed, sub-planar, and sub-horizontal until the Early Cretaceous. The Early Cretaceous sills and Middle Mississippian sedimentary strata were then folded together during subsequent Eurekan deformation. The two Early Cretaceous sills therefore further constrain the age of folding within the Adriabukta Formation and Marietoppen Formation to the early Cenozoic.

An early Cenozoic age for folding of shales of the Adriabukta Formation is further suggested by similar tight, east-verging fold geometries in Lower Triassic sedimentary strata incorporated as lenses into basement rocks in Fiskeknatten (locaton shown in Figure 1; Birkenmajer, 1964).

Svalbardian deformation may be recorded in southernmost Spitsbergen (Røkensåta; Figure 1 for location) where two outcrops of limited geographical extent (<< one km^2) show poorly exposed, gently dipping, shale-rich, Lower Triassic sedimentary rocks over folded Middle Devonian strata (Dallmann, 1992). However, the two outcrops are of small size because they were extensively eroded and the stratigraphic contact between Devonian and Triassic rocks is completely covered by loose material and located on steep mountain flanks (i.e., inaccessible for detailed inspection). In addition, Triassic successions in Spitsbergen dominantly consist of weak shale (Worsley and Mørk, 1978), which localized large amounts of Eurekan deformation and displacement along décollement levels, and strain partitioning during early Cenozoic contraction is now known to have had a considerable influence on the deformation of shale units in southern Spitsbergen (e.g., tightly folded Middle Mississippian Adriabukta Formation versus undeformed Middle Mississippian Hornsundneset Formation; Siedlecki, 1960; Birkenmajer and Turnau, 1962). Furthermore, folds within Middle Devonian rocks in Røkensåta appear to die out upwards (see figure 4a in Dallmann, 1992). It is therefore possible that deformation in Røkensåta is also early Cenozoic in age.

Such heavily eroded and limited outcrops need to be interpreted with extreme caution. Lower Triassic strata throughout Spitsbergen are well known for hosting bedding-parallel Eurekan décollements (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., 1993; Bergh et al., 1997). The most spectacular examples include the décollement in dark shales on the Midterhuken Peninsula (Maher, 1984; Dallmann et al., 1993; location shown in Figure 1) the Berzeliustinden thrust in southern Spitsbergen (Dallmann, 1988), the Triassic décollement penetrated by the 7816/12-1 exploration well and well imaged on seismic data in Reindalspasset (Eide et al., 1991; Koehl, 2021 his figure 5g; see Figure 1 for location), and the "Lower Décollement Zone" in eastern Spitsbergen (Andresen et al., 1992; Haremo and Andresen, 1992). A similar structure may very well have decoupled Eurekan deformation between folded Middle Devonian and overlying gently dipping Lower Triassic sedimentary strata in Røkensåta. Triassic are known to be much weaker than Devonian shales and to have preferentially localized Eurekan deformation at a much lower scale (e.g., décollements with kilometer-scale displacement in the Triassic shales versus open meso- to macro-scale folds with limited to no displacement within Devonian shales). This example stresses the importance of detailed inspection of extensively eroded outcrops, especially in glaciated Arctic areas, and highlights potential flaws in long-distance interpretation of kilometer-scale mountain flanks. Therefore, we propose that little to no weight should be given to any interpretation of these two poorly exposed and inaccessible outcrops until further inspection of the contact is made from very close range (e.g., using a drone?).

Review of age constraints in western Spitsbergen

Conodont age in Blomstrandhalvøya

In western Spitsbergen, Thiedig and Manby (1992) and Kempe et al. (1997) showed that west-verging thrusts crosscut Proterozoic and Devonian sedimentary rocks in Blomstrandhalvøya (location in Figure 1). They used the westwards transport direction of these thrusts to suggest that they record Svalbardian tectonism because it is comparable to observations along inferred Svalbardian thrusts in Dickson Land and Andrée Land in central and northern Spitsbergen (Vogt, 1938; Harland et al., 1974; Piepjohn, 2000).

In addition, Kempe et al. (1997) also noted the presence of small NW-verging thrusts on Blomstrandhalvøya. Notably, they argued that the size of these thrust was different from that of Svalbardian structures and concluded that they must therefore be post-Devonian. Kempe et al. (1997) argued that, even though the NW-verging thrusts seemed to have formed in the early Cenozoic, NW-directed transport directions are not typical of early Cenozoic Eurekan tectonism, which produced NE-verging thrusts and folds in adjacent areas of Brøggerhalvøya (Bergh et al., 2000; Piepjohn et al., 2001; see location in Figure 1). They therefore proposed that NW-verging thrusts on Blomstrandhalvøya formed during a discrete tectonic event in the Pennsylvanian to Cretaceous. However, such a tectonic event is, thus far, unheard of in Spitsbergen. It is therefore more likely that the NW-verging thrusts in Blomstrandhalvøya formed in the early Cenozoic.

Previous works (e.g., Kempe et al., 1997) used the strike and vergence of structures in Blomstrandhalvøya todistinguish Eurekan from presumed Svalbardian structures. This argument is not valid because a single tectonic event may very well produce structures with varying vergence and strikes, e.g., the Eurekan in Svalbard, which resulted in the formation of east-verging structures in western and southwestern Spitsbergen (e.g, Maher et al., 1986; Dallmann et al., 1988, 1993; Andresen et al., 1994) and northeast-verging folds and thrusts in Brøggerhalvøya (e.g., Bergh et al., 2000; Piepjohn et al., 2001). Furthermore, recent regional studies have shown the occurrence of major, WNW–ESE-striking, several to tens of kilometers thick, thousands of kilometers long, inherited Timanian thrust systems extending from northwestern Russia to western Svalbard (Koehl, 2020; Koehl et al., 2022). One of these structures, the NNE-dipping Kongsfjorden–Cowanodden fault zone, extends into Kongsfjorden, where it was reactivated during the Caledonian and Eurekan events as a sinistral-reverse oblique-slip fault, thus partitioning deformation between northern and southern to western Svalbard during those two events and leading to oppositely verging Eurekan thrust across (e.g., west-verging in Andrée Land and Blomstrandhalvøya and east-verging in Røkensåta and Adriabukta and Hornsund) the fault and to bending Eurekan structures in the vicinity of the fault (e.g., in Brøggerhalvøya).

In western Blomstrandhalvøya, one sample in a presumably undeformed karst infill within a few meters wide fissure in Proterozoic basement marbles yielded a Pennsylvanian to Permian age based on conodont fauna (Buggisch et al., 1994; Figure 2). Since the karst infill was apparently not deformed, Buggisch et al. (1994) argued that the conodont fauna potentially constrained the formation of folds and west-verging thrusts on Blomstrandhalvøya to the Late Devonian (Svalbardian).

Nevertheless, several aspects of this feature call for caution regarding its bearing for Svalbardian tectonism. First, despite being located in an area deformed by Eurekan tectonism, e.g., Blomstrandhalvøya (e.g., NW-verging thrusts of Kempe et al., 1997) and Brøggerhalvøya; (Bergh et al., 2000; Piepjohn et al., 2001; Figure 1), the Pennsylvanian to Permian cave seems to have escaped early Cenozoic deformation. This is possibly due to partitioning of Eurekan strain, which is known to have had a significant influence on deformation patterns in Brøggerhalvøya (e.g., Bergh et al., 2000). Thus, this small-scale karst feature is not an appropriate marker to discuss the timing of regional tectonic events in Blomstrandhalvøya.

Second, the cave is located within relatively undeformed Proterozoic marbles, and away from presumed Svalbardian west-verging thrusts and associated deformed Lower Devonian sedimentary rocks on Blomstrandhalvøya. Hence, the karst infill is inappropriate to constrain the timing of Svalbardian deformation in Blomstrandhalvøya. The deformation in basement marble (if any at all at the location of the karst) could very well be Caledonian as previously suggested by Michalski (2018).

Third, the karst is the only one of its kind yielding a Pennsylvanian to Permian age and is, moreover, based on only one sample with a poorly preserved conodont fauna (Buggisch et al., 1994). In their study, Buggisch et al. (1994) specified that the assignation to published species was difficult due to the poor preservation of the elements. Hence, further studies of caves and conodont fauna on Blomstrandhalvøya are therefore needed to further assess the reliability of the age obtained by Buggisch et al. (1994) and its implication (if any at all) for Svalbardian tectonism. Considering all pieces of evidence gathered thus far, the folds and thrusts in Proterozoic to Lower Devonian rocks in Blomstrandhalvøya may all be Caledonian and Eurekan in age since no appropriate constraints are available to date any potential Svalbardian deformation.

Amphibolite facies metamorphism in Prins Karls Forland

In Prins Karls Forland (see Figure 1 for location), amphibolite facies metamorphism was dated to 373–355 Ma by ion microprobe and ^{40}Ar–^{39}Ar geochronology, and was postulated to be prograde and, thus, to record deep-crustal Svalbardian tectonism (c. 15 kilometers depth; Majka and Kośmińska, 2017; Faehnrich et al., 2017; Schneider et al., 2018; Kośmińska et al., 2020). This episode of deep-crustal metamorphism is coeval with shallow-crustal Svalbardian tectonism in central and northern Spitsbergen dated to ca. 383–365 Ma by recent paleontological and palynological studies (Scheibner et al., 2012; Lindemann et al., 2013; Marshall et al., 2015; Berry and Marshall, 2015; Newman et al., 2019; Gilda M. Lopes pers. obs., 2019). However, none of the ages in Prins Karls Forland are of any use in discussing the timing of the Svalbardian event since they could either reflect crustal thickening or late–post-orogenic collapse.

Kinematic indicators along the dated west-dipping shear zone display top-SW to top-NW normal sense of shear (Schneider et al., 2018 their figure 3b, e and f), which is incompatible with a formation during contractional (Svalbardianrian) tectonism. Instead, the shear sense rather suggests a close relationship with Devonian extensional collapse of the Caledonides. Notably, amphibolite-facies metamorphism in Prins Karls Forland is also coeval with and occurred at comparable depth as deep-crustal, late Caledonian, high-pressure metamorphism along the conjugate eastern to northeastern Greenland margin (Gilotti et al., 2004; McClelland et al., 2006; Augland et al., 2010, 2011), which developed synchronously with the deposition of Devonian to

Mississippian collapse basins along low-angle extensional detachments at the surface (Stemmerik et al., 1991, 1998, 2000; Larsen and Bengaard, 1991; Strachan, 1994; Larsen et al., 2008). During late–post-orogenic collapse, deep contractional tectonics occurring typically at greenschist- to amphibolite-facies conditions (Snoke, 1980; Lister and Davis, 1989; Krabbendam and Dewey, 1998) are commonly associated with near-surface extension (Platt, 1986; Rey et al., 2001, 2011; Teyssier et al., 2005).

Amphibolite-facies metamorphism in Prins Karls Forland was also coeval with collapse-related core complex exhumation in northwestern Spitsbergen (latest movement at 368 Ma; Braathen et al., 2018). Hence, despite the postulated prograde character of amphibolite-facies metamorphism in Prins Karls Forland, its timing appears to coincide with Late Devonian extensional events in nearby areas. If the postulated prograde character of amphibolite-facies metamorphism in Prins Karls Forland is to be reconciled with the observed overall top-SW to top-NW normal sense of shear (Schneider et al., 2018 their figure 3b, e and f) and with extensional tectonics in northwestern Spitsbergen (Braathen et al., 2018), then the shear zone and associated prograde metamorphism may reflect gradual burial linked to the deposition of thick collapse sediments and/or normal movements along the shear zone.

Since the Late Devonian to Mississippian (373–355 Ma) amphibolite-facies metamorphism in basement rocks in Prins Karls Forland probably occurred at c. 15 kilometers depth, the timing and nature of metamorphism may not have any implications for the nature of paleostress and resulting deformation in shallow-crustal Devonian sedimentary rocks in Spitsbergen (e.g., coeval ultra-high pressure metamorphism at depth and extensional collapse at the surface in Greenland in the Devonian to Mississippian; Strachan, 1994; Gilotti et al., 2004; McClelland et al., 2006).

Furthermore, the geochronological ages obtained by Kośmińska et al. (2020) show broad ranges (430–336 Ma for monazite population I, 419–261 Ma for population II, and 443–226 Ma for population III) all ranging from the Silurian (Caledonian?) to the Carboniferous–Triassic. In addition, the ages obtained are associated with large σ_1 errors (12.4–20.2 Myr for population I, 19.6–49.9 Myr for population II, and 17.1–64.4 Myr for population III; see online supplement S1 in Kośmińska et al., 2020). Since the length of Svalbardian tectonism in shallow-crustal Lower to lowermost Upper Devonian sedimentary rock in central and northern Spitsbergen is constrained to a maximum time span of 18 million years (383–365 Ma), i.e., a time span comparable with the σ_1

errors associated with the ages obtained by Kośmińska et al. (2020), these ages are inappropriate to discuss the timing of Svalbardian tectonism in Svalbard (Schaltegger et al., 2015).

Greenschist facies metamorphism and thermal overprints in Oscar II Land

Geochronological ages in Oscar II Land (location in Figure 1) are also useless in discussing the timing of the Svalbardian event since they may equally reflect extensional processes. Greenschist facies metamorphism that yielded 365–344 Ma ^{40}Ar–^{39}Ar and U–Th–Pb ages (Barnes et al., 2020) were re-evaluated to ca. 410 Ma (Early Devonian) by Ziemniak et al. (2020), who obtained comparable ages for the same unit without the 365–344 Ma disturbance, which they attribute to fluid circulation. This is also partly supported by the poorer statistical reliability of the 365–344 Ma ages as documented by Barnes et al. (2020). The 365–344 Ma episode of low-grade metamorphism was coeval with the deposition of Lower Devonian sedimentary rocks in central and northern Spitsbergen in the Devonian Graben during late–post-orogenic collapse of the Caledonides and, thus, may as well be related to extensional processes (Gee and Moody-Stuart, 1966; Friend et al., 1966; Friend and Moody-Stuart, 1972; Murascov and Mokin, 1979; Manby and Lyberis, 1992; Friend et al., 1997; McCann, 2000).

In addition, Michalski et al. (2017) provided evidence of two episodes of thermal overprints at 377–326 and ca. 300 Ma in pre-Caledonian rocks in Oscar II Land using ^{40}Ar–^{39}Ar geochronology. The latter event is believed to be related to rifting. The former event at 377–326 Ma partly overlaps with the presumed timing of the Svalbardian Orogeny in central and northern Spitsbergen at ca. 383–365 Ma (Scheibner et al., 2012; Lindemann et al., 2013; Marshall et al., 2015; Berry and Marshall, 2015; Newman et al., 2019; Gilda M. Lopes pers. obs., 2019) and with the timing of 373–355 Ma amphibolite facies metamorphism in western Spitsbergen (Majka and Kośmińska, 2017; Faehnrich et al., 2017; Schneider et al., 2018; Kośmińska et al., 2020). It is, however, not possible to infer tectonic stress orientation and this event may very well be related to Svalbardian tectonism or to late Caledonian extensional processes in northeastern Greenland and Prins Karls Forland (Stemmerik et al., 1991, 1998, 2000; Larsen and Bengaard, 1991; Strachan, 1994; Larsen et al., 2008; Schneider et al., 2018; see also previous section) and in northern Spitsbergen (Chorowicz, 1992; Roy, 2007, 2009; Braathen et al., 2018, 2020; Roy et al., unpublished; Maher et al., 2022).

Discussion and re-evaluation of the timing and extent of Svalbardian tectonism

The present brief review of age constraints in Spitsbergen shows a few noteworthy aspects of dating Svalbardian tectonism in Svalbard. In southern Spitsbergen, Middle Mississippian palynological ages for the tightly folded, shale-rich Adriabukta formation (Birkenmajer and Turnau, 1962) and its intrusion by two Early Cretaceous dolerite sills that are folded together with bedding surfaces (Birkenmajer and Morawski, 1960; Birkenmajer, 1964) show that folding in this area may be exclusively and entirely early Cenozoic in age. Comparable Middle Mississippian palynological ages for the contemporaneous but undeformed, sandstone-dominated Hornsundneset Formation c. 20 kilometers to the southwest (Siedlecki, 1960; Siedlecki and Turnau, 1964) and mild folding of clastic-rich Pennsylvanian to Permian rocks in Adriabukta (Birkenmajer, 1964; Bergh et al., 2011) illustrate the strong impact of Eurekan strain partitioning on deformation patterns in southern Spitsbergen as previously considered by Birkenmajer and Turnau (1962) and Koehl (2020a).

The only potential record of Svalbardian tectonism in southern Spitsbergen occurs at Røkensåta. However, as previously discussed, the low quality of the only two exposures (stratigraphic contact covered by loose material), their very limited extent (<< one km^2), their inaccessibility for detailed inspection (located on steep mountain flanks), the significant impact of early Cenozoic strain partitioning in southern Spitsbergen (Birkenmajer and Turnau, 1962), and the geometry of folds within Middle Devonian rocks at this locality (dying out upwards; Dallmann, 1992) call for caution and further detailed investigation of structural and stratigraphic relationships at this locality. Nevertheless, if Eurekan tectonism alone produced the intense deformation in Adriabukta, it is possible that deformation in Røkensåta is exclusively early Cenozoic as well.

In central and northern Spitsbergen, Svalbardian tectonism was constrained to ca. 383–365 Ma (i.e., a maximum duration of 18 million years) by recent paleontological and palynological studies in sedimentary rocks of the Mimerdalen Subgroup (Berry and Marshall, 2015; Newman et al., 2019, 2020, 2021) and Billefjorden Group (Scheibner et al., 2012; Lindemann et al., 2013; Marshall et al., 2015; Gilda M. Lopes pers. obs., 2019). The only contradictory late Famennian age obtained by Piepjohn et al. (2000) via identification of one specimen of *Retispora lepidophyta* in one sample of the Plantekløfta Formation of the Mimerdalen Subgroup is now known to be a clear misidentification (Berry and Marshall, 2015 their supplement DR3).

Despite the accurate and precise paleontological and palynological time constraints for Svalbardian tectonism in central and northern Spitsbergen, no geochronological constraints exist yet for discrete Svalbardian structures. In addition, the central and northern part of Spitsbergen was strongly affected by early Cenozoic Eurekan tectonism during which strain partitioning played an important role in localizing deformation in weak, shale-rich lithostratigraphic units like the Billefjorden Group (e.g., Koehl, 2021). Moreover, evidence for extensional detachment-related folding in northerwestern (Braathen et al., 2018, 2020; Maher et al., 2022) and northern Spitsbergen (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished) in Middle to Late Devonian may also have contributed to deformation patterns observed within Lower to lowermost Upper Devonian strata of the Andrée Land Group and Mimerdalen Subgroup. Thus, it is unclear how much (if any at all) of the deformation observed within Lower to lowermost Upper Devonian strata in central and northern Spitsbergen actually reflects Svalbardian tectonism. Further studies are therefore clearly needed to quantify the impact of the Svalbardian Orogeny and to segregate discrete Svalbardian from Devonian extensional (detachment) faulting and folding and from early Cenozoic Eurekan folding and thrusting.

Another line of controversy is the increadibly rapid switch from extension-related normal faulting in the Early to Middle Devonian to Svalbardian contraction in the Late Devonian, and back to dominantly extensional setting in the mid Famennian in central and northern Spitsbergen. Notably, the Wood Bay Formation and Fiskekløfta Member of the Tordalen Formation are downfaulted by normal faults in southern Hugindalen and unconformably covered by the Planteryggen Formation (Hugindalen Phase in Piepjohn, 2000 and Dallmann and Piepjohn, 2020). The Fiskekløfta Member was dated to the latest Givetian (top of the unit at ca. 383 Ma) and the Plantekløfta Formation to the early Frasnian (383–380 Ma; Berry and Marshall, 2015; Newman et al., 2019, 2020, 2021). Since the conglomeratic beds of the Planteryggen and Plantekløfta formations are advocated by Piepjohn and Dallmann (2014) to reflect the onset of Svalbardian tectonism, this would therefore imply an abrupt switch in plate tectonic movements and stresses at exactly 383 Ma, i.e., completed within one million year maximum. In addition, mid Famennian to Upper Mississippian sedimentary rocks of the Billefjorden Group and Pennsylvanian to lower Permian rocks of the Gipsdalen Group, which overlie the Andrée Land Group in central and northern Spitsbergen, are believed to have been deposited in extensional basins (Cutbill et al., 1976; Aakvik, 1981; Gjelberg, 1984; Braathen et al., 2011; Koehl and Muñoz-Barrera, 2018; Smyrak-

Sikora et al., 2018). This implies another rapid reversal in regional plate tectonics movements from contraction to extension at ca. 365 Ma. Since regional plate tectonics reorganization and tectonic stress reorientation are known to be relatively slow and gradual processes, such abrupts switches are regarded as highly unlikely. Considering the extensional setting inferred in both the Early to Middle Devonian (Chorowicz, 1992; Piepjohn, 2000; Roy, 2007, 2009; Braathen et al., 2018, 2020; Dallmann and Piepjohn, 2020; Roy et al., unpublished; Maher et al., 2022) and mid Famennian to early Permian (Cutbill et al., 1976; Aakvik, 1981; Gjelberg, 1984; Braathen et al., 2011; Smyrak-Sikora et al., 2018), it is more likely that Svalbardian contraction never occurred and that the area was subjected to continuous extension throughout the Devonian to Carboniferous. This is also supported by late Silurian to Late Devonian extensional detachment faulting and folding at 430–368 Ma in northwestern Spitsbergen (Braathen et al., 2018) and in the Middle to Late Devonian in northern Spitsbergen (Chorowicz, 1992; Roy, 2007, 2009; Roy et al., unpublished).

The 383–365 Ma estimate for tentative Svalbardian deformation in shallow-crustal Lower to lowermost Upper Devonian sedimentary rocks in central and northern Spitsbergen partly overlaps with the timing of deep-crustal, 373–355 Ma, amphibolite facies metamorphism in Prins Karls Forland (Majka and Kośmińska, 2017; Faehnrich et al., 2017; Schneider et al., 2018; Kośmińska et al., 2020) and thermal events in Oscar II Land at 377–326 Ma (Michalski et al., 2017). However, the 383–365 Ma estimate reflects the age of stratigraphy in central and northern Spitsbergen, not the age of any specific Svalbardian structure. In addition, due to conflicting lines of evidence (e.g., postulated prograde metamorphism associated with normal sense of shear), the nature of tectonic stresses during tectonothermal events in Prins Karls Forland and Oscar II Land remains debatable.

Paleomagnetic and ^{40}Ar–^{39}Ar geochronological data from Michalski et al. (2017) do not support a pre-Caledonian link or proximity between the Pearya terrane and western Spitsbergen. On the same trend, detrital zircons in western and central Spitsbergen show affinities with northern Baltica rather than Laurentia in the Paleozoic (Gasser and Andresen, 2013). This suggests that western and central Spitsbergen were located away from the main Ellesmerian belt in northern Greenland and Arctic Canada and, thus, may have escaped Ellesmerian tectonism. This is further supported by the recent discovery of several kilometers thick, thousands of kilometers long, late Neoproterozoic thrust systems crosscutting the whole Barents Sea and the Svalbard Archipelago, thus suggesting that the Svalbard Archipelago was already accreted and attached to Baltica in the late Neoproterozoic (Koehl, 2020b; Koehl et al., 2022).

Conclusion

There should be no debate as to the age of the Mimerdalen Subgroup and Billefjorden Group. These are respectively upper Givetian to lower Frasnian (ca. 385–380 Ma) and mid Famennian to Upper Mississippian (ca. 365–325 Ma). The single palynomorph specimen that was not in line with these ages was found in the Mimerdalen Subgroup is a clear misidentification of *Retispora lepidophyta*. Thus, the timing of Svalbardian tectonism in central and northern Spitsbergen is constrained to 383–365 Ma. Nonetheless, because of the strong impact of Eurekan strain partitioning and extensional detachment-related folding and faulting, much is left to do to quantify the impact, extent and timing of Svalbardian tectonism in this area (if it ever occurred). Future studies should focus on geochronological dating of presumed Svalbardian thrusts.

There is also no debate either about the age of the Adriabukta Formation in southern Spitsbergen. This formation is Middle Mississippian in age and is therefore a time-equivalent of the undeformed, sandstone-rich Hornsundeneset Formation. Hence, folding in the Adriabukta Formation is entirely and exclusively ascribed to Eurekan tectonism and the tight character of folding to strain partitioning in the early Cenozoic. Due to lack of robust minimum time constraints, the occurrence of Svalbardian tectonism in southern Spitsbergen is highly doubtful. Future studies could, if feasible, focus on establishing clear tectonic and stratigraphic relationships in Røkensåta.

Postulated prograde amphibolite-facies metamorphism at 373–355 Ma in pre-Caledonian basement rocks in Prins Karls Forland occurred at a depth of c. 15 kilometers and, thus, has no bearings on the nature of tectonic stress and associated deformation in shallow-crustal Devonian to Mississippian sedimentary rocks. Top-SW to top-NW normal sense of shear along the dated shear zone suggests that this episode of postulated prograde metamorphism may actually be related to shallow-crustal, extensional collapse processes, possibly reflecting progressive burial and movements along the shear zone during the deposition of collapse sediments. Similar processes are well documented on the conjugate margin of Svalbard in northeastern Greenland, and in northwestern Spitsbergen, and these processes involve deep, late Caledonian, high-pressure metamorphism and shallow-crustal extensional detachments.

Considering the dominantly extensional tectonic settings inferred for shallow-crustal rocks in late Silurian to early Permian times and the multiple inconsistencies and contradicting lines of evidence associated to the Svalbardian Orogeny throughout Svalbard, the accretion of Svalbard to Baltica as early as the late Neoproterozoic, and the two abrupt and rapid switches in tectonic stress orientation required in the Late Devonian to account for Svalbardian tectonism, it is much more likely that the whole archipelago was subjected to continuous extension from the late Silurian to early Permian times and escaped Svalbardian deformation.

Author contributions

JBPK wrote the manuscript and designed the figures (contribution: 50%). John E. A. Marshall and Gilda M. Lopes provided critical input and corrections to the manuscript and figures (contritution: 25% each).

Competing interests

The authors declare that they have no conflict of interest.

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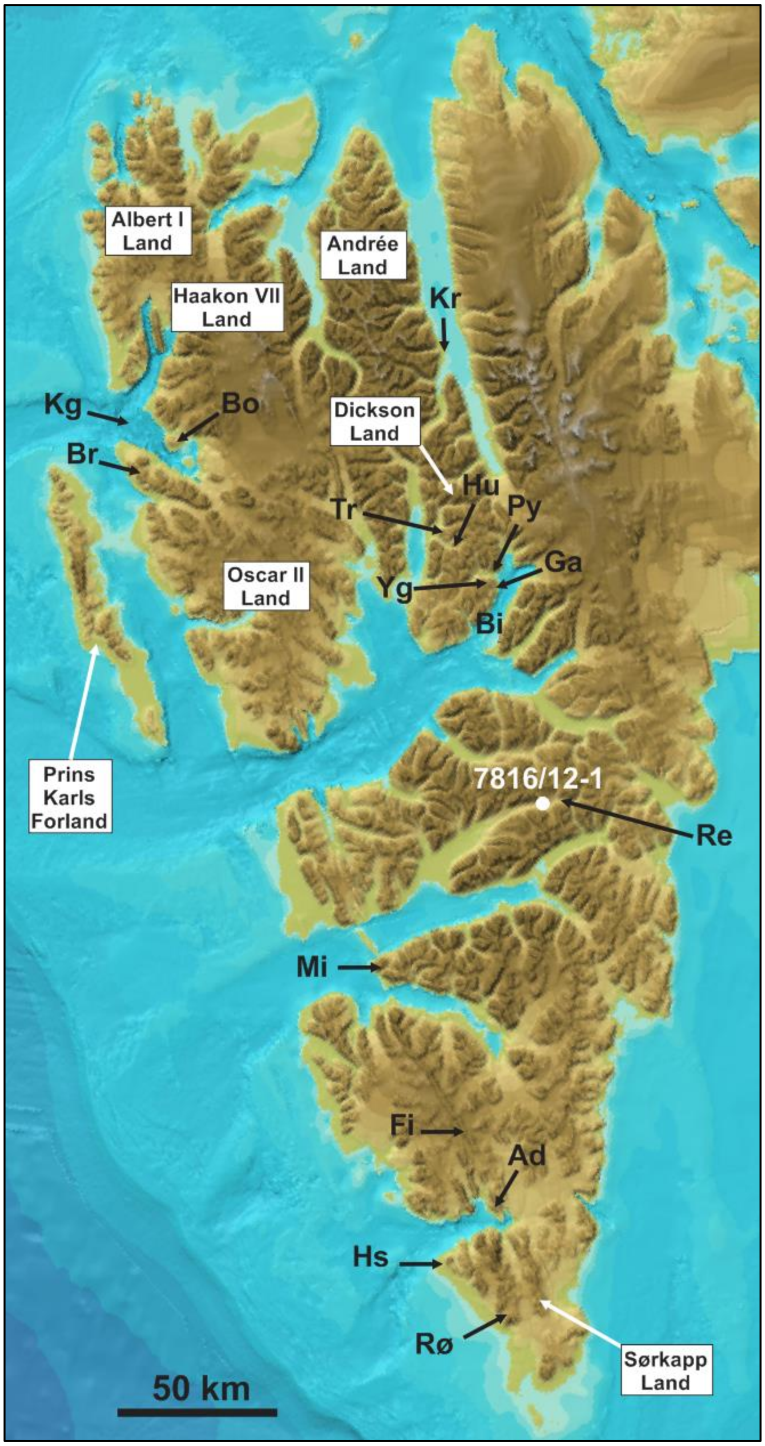

Figure 1: **Topographic and bathymetric map around Spitsbergen modified after Jakobsson et al. (2012). The location of exploration well 7816/12-1 is shown in white. Abbreviations: Ad: Adriabukta; Bi: Billefjorden; Bo: Blomstrandhalvøya; Br: Brøggerhalvøya; Fi: Fiskeknatten; Ga: Garmdalen; Hs: Hornsundneset; Hu: Hugindalen; Kg: Kongsfjorden; Kr:**

Krosspynten; Mi: Midterhuken; Py: Pyramiden; Re: Reindalspasset; Rø: Røkensåta; Tr: Triungen; Yg: Yggdrasilkampen.

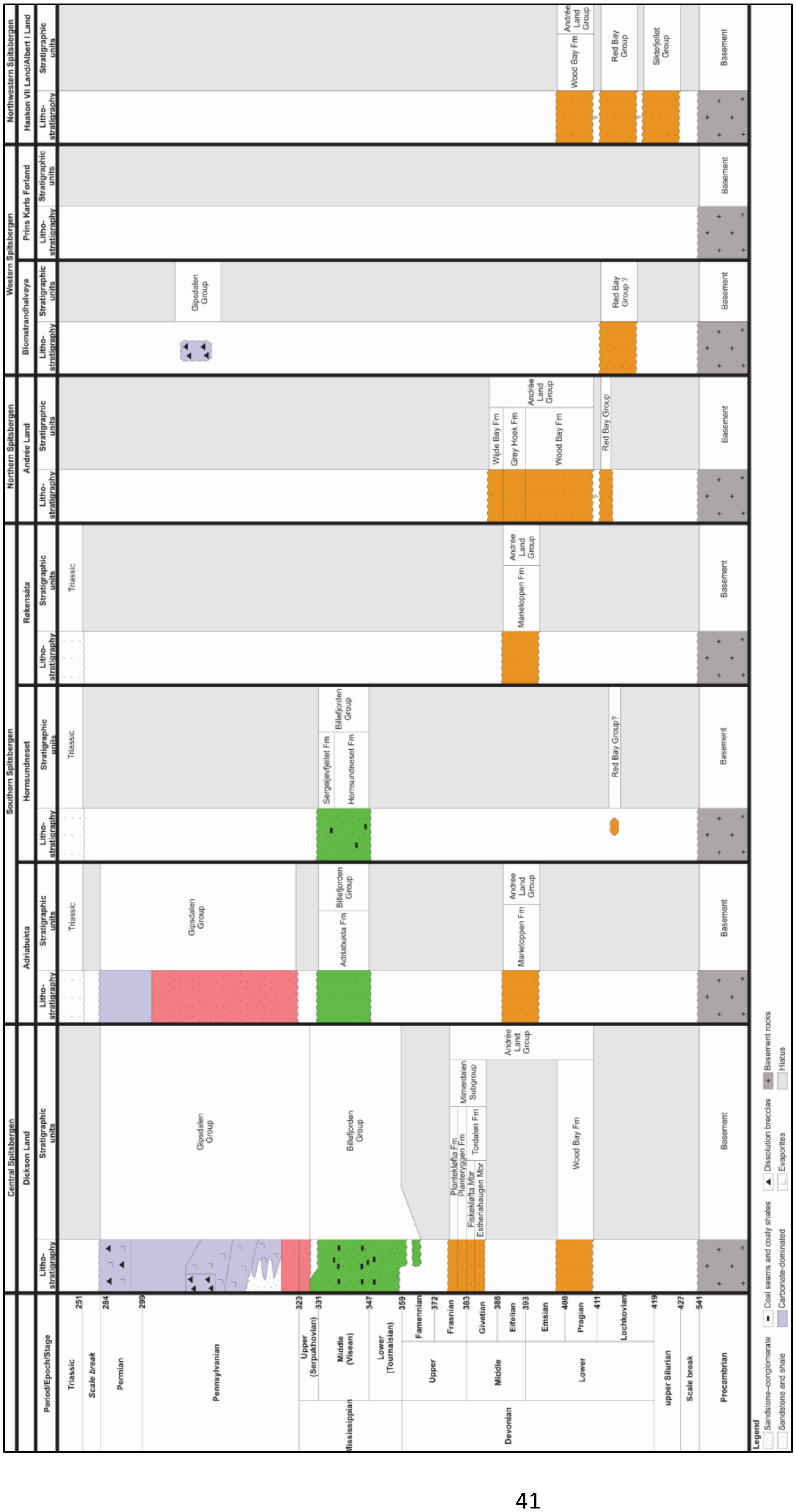
Period/Epoch/Stage
Triassic
Scale break
Permian
Pennsylvanian
Mississippian
Upper (Serpukhovian)
Middle (Visean)
Lower (Tournaisian)
Devonian
Upper
Famennian
Frasnian
Middle
Givetian
Eifelian
Lower
Emsian
Pragian
Lochkovian
upper Silurian
Scale break
Precambrian
251
284
299
323
331
347
359
372
383
388
393
408
411
419
427
541
Central Spitsbergen
Dickson Land
Adriabukta
Southern Spitsbergen
Hornsundneset
Røkensåta
Northern Spitsbergen
Andrée Land
Western Spitsbergen
Blomstrandhalvøya
Prins Karls Forland
Northwestern Spitsbergen
Haakon VII Land/Albert I Land
Litho-stratigraphy
Stratigraphic units
Gipsdalen Group
Billefjorden Group
Planteklofta Fm
Planteryggen Fm
Fiskekløfta Mbr
Estheriahaugen Mbr
Tordalen Fm
Mimerdalen Subgroup
Andrée Land Group
Wood Bay Fm
Basement
Triassic
Adriabukta Fm
Marietoppen Fm
Sergeijevfjellet Fm
Hornsundneset Fm
Red Bay Group?
Wijde Bay Fm
Grey Hoek Fm
Red Bay Group
Red Bay Group ?
Siktefjellet Group
Legend
Sandstone–conglomerate
Sandstone and shale
Coal seams and coaly shales
Carbonate-dominated
Dissolution breccias
Evaporites
Basement rocks
Hiatus

Figure 2: Late Paleozoic stratigraphic chart of the areas discussed in the text. The ages in the time scale are in Ma and are from Walker et al. (2018).