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PERSPECTIVE

Some issues related to the Svalbardian tectonic event (Ellesmerian Orogeny) in Svalbard

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Abstract

Svalbard has long been thought to represent the easternmost realm of the Ellesmerian Orogeny in the late Devonian or early Mississippian (Svalbardian tectonic event). Several authors do not agree and present alternative interpretations of the observed structures in older and more recent articles. This article discusses a number of issues that, in our opinion, are not sufficiently considered in those works, but which are essential for the understanding of the Svalbardian tectonic event: (1) the possibility of re-deposited palynomorphs in the discussion of the deformational ages, (2) the age and structural setting of the crucial Adriabukta Formation in southern Spitsbergen, and (3) the presence and nature of the Svalbardian angular unconformity in central and southern Spitsbergen.

Keywords

Geology of Svalbard; Devonian; angular unconformity; convergent deformation; palynomorph ages; Adriabukta Formation

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Abbreviations

STE: Svalbardian tectonic event

Introduction

Since the beginning of the 20th century it has generally been accepted that the Devonian Old Red Sandstone basins of Svalbard (Fig. 1) were affected by crustal shortening during the STE (e.g., Holtedahl 1914; Stensiø 1918; Vogt 1928; Friend & Moody-Stuart 1972; Burov & Semevskij 1979; Manby & Lyberis 1992; Piepjohn 1994, 1997, 2000; McCann & Dallmann 1996; Piepjohn et al. 1997; Piepjohn & Thiedig 1997; McCann 2000; Piepjohn et al. 2000; Bælum & Braathen 2012; Piepjohn & Dallmann 2014; Dallmann & Piepjohn 2020). The term "STE" is here used to describe the convergent and strike-slip tectonism in Svalbard thought to be related to the Ellesmerian Orogeny in northern Greenland and Canada (Lamar et al. 1986; McCann 2000; Piepjohn 2000; Dallmann & Piepjohn 2020).

Before the opening of the Arctic Ocean in the Palaeogene, Svalbard was placed in the eastern continuation of the Ellesmerian Fold-and-Thrust Belt, which was situated at the northern margin of the continent Laurentia, from the western Canadian Arctic to northern Greenland (e.g., Trettin 1991; Harland 1997; McCann 2000; Piepjohn et al. 2015; Dallmann & Piepjohn 2020 and figure 85 therein). The Ellesmerian orogen is thought to be the final result of the approach and docking of the Pearya Terrane at the north coast of Ellesmere Island and Svalbard to the northern margin of Laurentia (Trettin 1987, 1991; Bjørnerud & Bradley 1994; Piepjohn et al. 2013; Majka et al. 2021).

The climax of the Ellesmerian Orogeny in the Canadian Arctic and in northern Greenland took place in the early Tournaisian. The age constraints of the STE indicate a time window between the late Famennian and the late Tournaisian (Pčelina et al. 1986; Schweitzer 1999; Piepjohn et al. 2000). This coincides with the age of the Ellesmerian Orogeny reported from the western Canadian Arctic (Mayr et al. 1994), the Canadian Arctic Archipelago (Beauchamp et al. 2018) and northern Greenland (Springer 1981; Springer & Friderichsen 1994).

The palynological record of the youngest pre-unconformity strata in Svalbard, however, points towards a late Frasnian or early Famennian age, so that the Svalbardian unconformity could be as early as the Famennian (Berry & Marshall 2015; Marshall et al. 2015). This does not necessarily represent a dilemma.

Koehl et al. (2022) present a new approach, offering a dramatic change of the structural and geological framework of Svalbard, which attempts to explain Svalbardian structures in alternative ways. They propose the elimination of the STE in southern Spitsbergen and suggest that there were hardly any convergent Svalbardian tectonics at all—explaining the crucial structures with younger (Eurekan, i.e., Cenozoic) detachments involving strain partitioning.

Herein we discuss a number of earlier established relevant stratigraphic and structural field relationships. They do not involve new data, but they have not necessarily been well documented in previous publications. They disprove basic ideas of some of the above-mentioned recent

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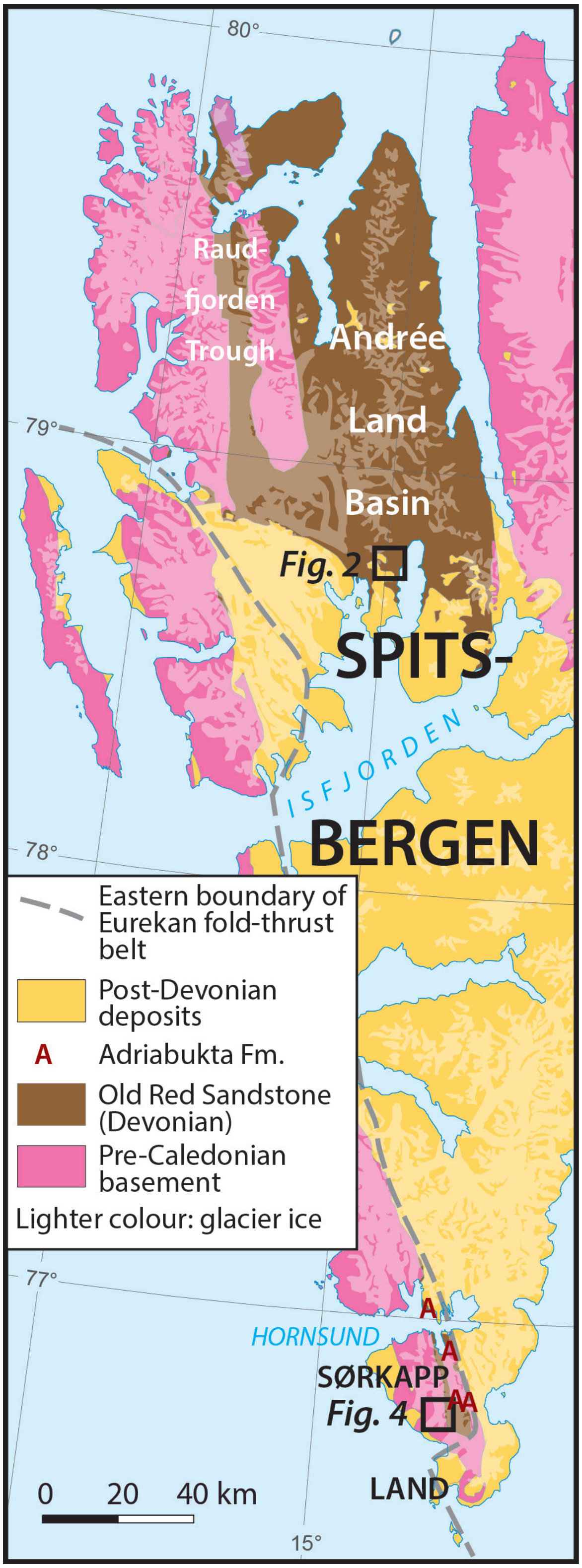

Fig. 1 Geological map of western Spitsbergen, Svalbard, showing occurrences of Devonian in relation to older and younger rocks (modified from Dallmann & Piepjohn 2020).

articles, especially the idea of Koehl et al. (2022) that Svalbardian tectonics were insignificant and that crucial structures were Eurekan.

The role of re-deposited palynomorphs in the age discussion of the STE

The ambivalent palynological age constraints of the STE, which took place between the deposition of the Plantekløfta Formation (youngest strata before the STE) and the Triungen Member (oldest strata after the STE) have been discussed and reviewed in detail by Piepjohn & Dallmann (2014), Berry & Marshall (2015) and Koehl et al. (2022).

When it comes to palynologically obtained ages—especially in relation to tectonic events—one should always consider the possible reworking of spores and plant fossils in younger deposits (Utting et al. 2004). In describing the uppermost exposed strata of the Plantekløfta Formation at the western slope of Reuterskiöldfjellet, Brinkmann wrote:

> The samples are characterized by poor preservation of the spores. The reason is that the spores were partly eroded, transported, reworked, and re-deposited. The sediments consist partly of re-sedimented Devonian strata. The clasts in the Plantekløfta conglomerates consist of older Devonian rocks (Austfjorden Sandstone, Wood Bay Formation), which were eroded during the deposition of the Plantekløfta Member. This explains the poor preservation of spores in this member and explains that spores from various Devonian strata are mixed. (Brinkmann 1997: 83; authors' translation)

Even if the Plantekløfta Formation were as old as Frasnian, as is argued by several authors (Lindemann et al. 2013; Berry & Marshall 2015; Marshall et al. 2015), this would not necessarily place the Ellesmerian Orogeny in the Famennian. It would merely widen the possible time window. It is also possible that the Plantekløfta Formation ranges over a very long period, so that the upper conglomerate-rich parts might be significantly younger than the lower, shale-prone parts from which the spores were retrieved.

Famennian spores are very stable and are often eroded and re-deposited in younger strata. On Ellesmere Island, reworked Famennian spores even occur in Triassic deposits (Utting et al. 2004)! The middle to late Famennian bonebed in the undeformed, mainly Carboniferous Hörbyebreen Formation (Lindemann et al. 2013) might also consist of re-deposited material, especially as it occurs close to the basal conglomerate.

Critical for the timing of the STE is the age of the unconformably overlying Triungen Member. Cutbill & Challinor (1965) and Scheibner et al. (2012) argue for a Tournaisian age of the unconformity, on the basis of general approaches. Scheibner et al. (2012) established a Famennian age of the base of the Billefjorden Group only in Lomfjorden and on the island of Bjørnøya, provided the analysed material is not reworked there. In these areas, there is no indication of any Svalbardian deformation. But in all other areas of Svalbard, including central Spitsbergen, they indicate a Tournaisian age of the Billefjorden Group. They conclude that, until a reliable age determination of the lower Triungen Member has been generally accepted, a late Tournasian age for the onset of deposition of the Billefjorden Group should be considered.

Sedimentological observations also indicate that the material is reworked (Friend 1961); the presence of an angular unconformity, often with a basal conglomerate, above the deformed strata makes it very probable that the basal layers of the Triungen Member are reworked deposits (Figs. 2, 3). However, clear evidence remains to be found that all Famennian spores in the Triungen Member really are reworked.

As to the timing of the STE, Koehl et al. (2022: 1363) argue that "Another line of controversy is the incredibly 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." This statement is based on the supposed early upper Devonian age of the STE. Even if this timing were true, we are speaking about millions of years; in orogenic settings, especially if transform settings are involved that include restraining and releasing regimes, this would not be a problem (Lamar et al. 1986; Dewey & Stachan 2003). Assuming that Svalbardian tectonism in Svalbard occurred in the earliest Tournaisian, like the Ellesmerian Orogeny along the northern margin of North America, as favoured here, there is a 20 million year period after mid-Devonian and a 25 million year period prior to the Serpukhovian onset of extensional events in the Billefjorden Trough. The extension during the Tournaisian and Viséan deposition was very moderate (McCann & Dallmann 1996). This provides sufficient time for the change from the Devonian extensional basins to Svalbardian convergence and then again to regional extension from the Serpukhovian onwards.

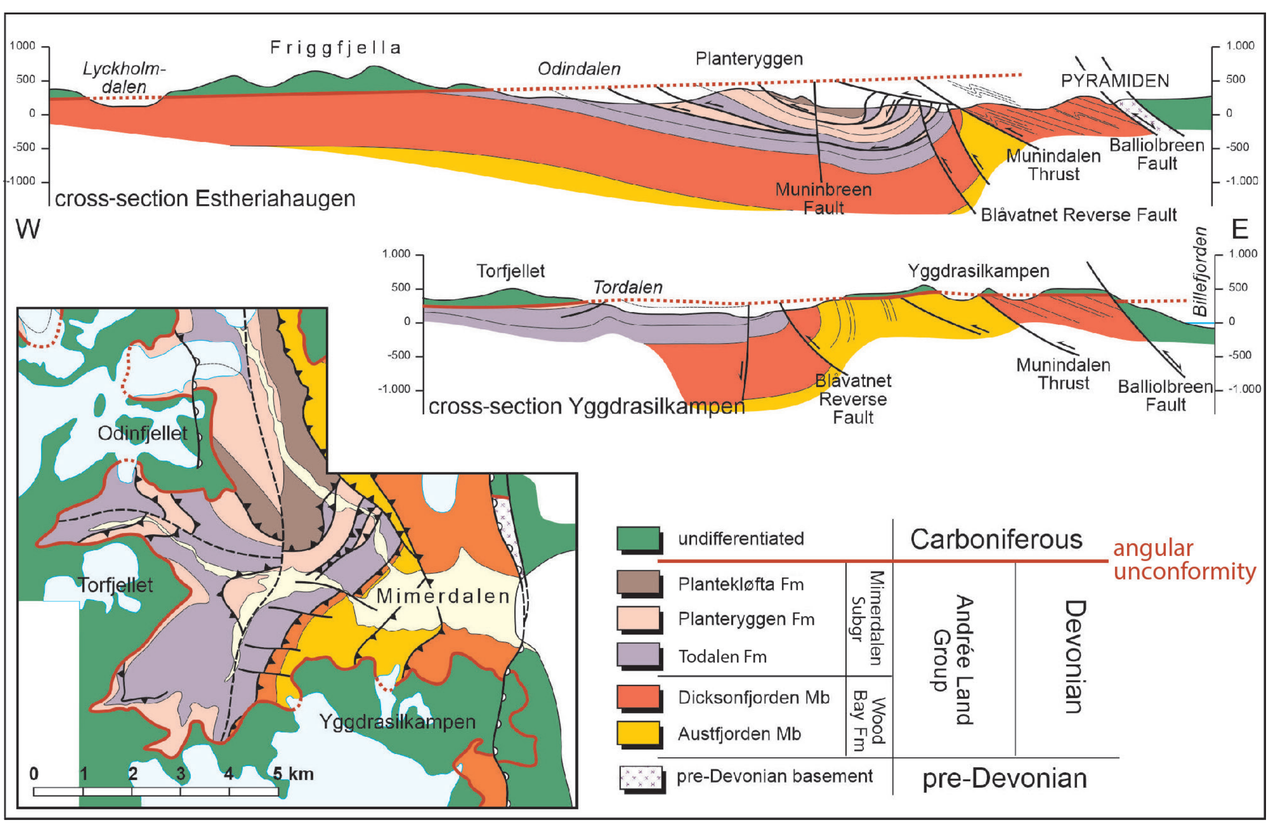

Fig. 2 Geological map of central Dickson Land with two cross-sections showing the structural relationships between the folded, thrust-faulted and cleaved Devonian rocks and unconformably overlying, undeformed Carboniferous rocks (redrawn from Michaelsen et al. 1997; Piepjohn et al. 1997; Dallmann & Piepjohn 2020).

Fig. 3 Angular unconformity of undeformed Moscovian strata (Wordiekammen Formation) with a basal conglomerate overlying folded Devonian (Wood Bay Formation) at the entrance of Asvindalen, west coast of Billefjorden. The contact is intact and not affected by any tectonic shear. View towards the south. (Photo by Dr Dierk Blomeier, formerly at Norwegian Polar Institute, with permission.)

The Svalbardian angular unconformity in central Spitsbergen

Koehl et al. (2022) have argued that the STE may not exist and question the significance of the Svalbardian angular unconformity, despite its widespread regional character. There is no doubt that some Cenozoic (Eurekan) tectonic overprint occurs in the Devonian strata of northern Spitsbergen in places. Koehl et al. (2020) provide a seismic interpretation of a bedding-parallel décollement between the Wood Bay Formation and the Gipsdalen Group in Billefjorden, suggested to be of Eurekan age. They further suggest that this Eurekan deformation may be responsible for the folds and thrusts in the Devonian (Koehl et al. 2022), which earlier were thought to belong to the STE. It is a striking contradiction that the postulated Eurekan décollement is not seen anywhere in the field, where the corresponding strata are exposed.

Décollements are indeed located in the Mimerdalen Subgroup, where they partly repeat Devonian stratigraphic units. They are thought to belong to an early stage of the Svalbardian deformation and were folded during a later stage (Fig. 2, upper cross-section). In most areas where the contact between the undeformed Gipsdalen Group and underlying deformed Devonian rocks is exposed, the contact is depositional and displays a distinct angular unconformity. No structural evidence for a major contractional décollement exists (Fig. 3). As mapping has revealed, the structural inventory in the Devonian rocks (west-verging folds of different scales, west-directed thrusts and reverse faults, décollements within the Devonian strata, intense cleavage) is cut by the unconformity and is absent in the overlying Carboniferous sediments (Fig. 2). This is also reflected in most of the previous literature cited in the introduction. In only a few locations has the contact been obliterated by minor Eurekan reverse faults. If the assumption by Koehl et al. (2022) of Eurekan strain partitioning were correct, the base of the Gipsdalen Group would be a regional tectonic detachment across the entire area. However, the basal contact of Carboniferous and younger rocks overlying the unconformity is always a sedimentary contact across all of Svalbard, on top of: (1) folded Devonian Old Red Sandstone in northern Spitsbergen; (2) metamorphosed Palaeozoic rocks in Sørkapp Land (e.g., Fig. 4); (3) metamorphosed Neoproterozoic successions in the West Spitsbergen Fold-and-Thrust Belt; (4) metamorphosed Meso- and Palaeoproterozoic successions in Ny-Friesland; or (5) Neoproterozoic sedimentary successions in Ny-Friesland and Nordaustlandet (Dallmann & Piepjohn 2020; compare also overview map by Dallmann et al. 2002).

Furthermore, Koehl et al. (2022) refer to Chorowicz (1992), Braathen et al. (2018a, b, 2020) and Maher, Braathen, Ganerød, Osmundsen et al. (2022) to explain some deformation in the Devonian by extensional detachment-related folding. This raises the question of whether Koehl et al. (2022) interpret the folding in the Devonian strata to be due to Devonian extension or to Cenozoic (Eurekan) convergence. If both causes were real, there should be distinguishing parametres (verging directions, fold styles, different tectonic transport directions, etc.) and they should at least partly overlap and overprint each other. It should be noticed that the Devonian detachment structure in northern Haakon VII Land has been interpreted in contradictory ways, as (1) a Late Caledonian ductile shear zone (Piepjohn & Thiedig 1995) formed between 421 and 425 Mya (Koglin et al. 2022), and, to the contrary, as (2) an extensional detachment related to the development of a metamorphic core complex (Maher, Braathen, Ganerød, Myhre et al. 2022).

Chorowicz's (1992) model proposes that folding in the Andrée Land Basin was extensional and forced by gravitational processes above a gently east-dipping detachment resulting in the folding and thrusting of the Devonian Andrée Land Group. It is questionable, how such an extensional detachment could have created the intense cleavage that has affected most of the deformed Devonian rocks; also, by far, most of the structures verge westward (Dallmann & Piepjohn 2020). It is also worth mentioning that there are no hanging wall extensional features in the overlying strata that would indicate crustal thinning, for

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example, rotated fault blocks, as are found in other extensional detachment systems (Braathen et al. 2018a).

Koehl et al. (2022) also compare Chorowicz's detachment with the crustal décollement suggested by Braathen et al. (2018) in the Raudfjorden Trough. Braathen et al. (2018) were first to interpret a metamorphic core complex with a constrictional, low-angle detachment and overlying rotated fault blocks, where previous work saw a basement-cored, contractional anticline overprinted by strike-slip tectonics (McCann 2000; Dallmann & Piepjohn 2020). It is noteworthy that the interpreted transport direction of the crustal décollement in the Raudfjorden Block is to the north, and its larger context is a system of sinistral transtension, which is not compatible with Chorowicz' model, which includes passive transport to the east—although the age of the affected strata is different.

The age and structural setting of the Adriabukta Formation in southern Spitsbergen

The age and structural position of the Adriabukta Formation (Birkenmajer 1964; Dallmann et al. 1999) in southern Spitsbergen is of major significance for the interpretation of the STE in southern Spitsbergen. This clastic sedimentary unit shows intensive folding and cleavage, similar to the Devonian, in certain areas south of Hornsund, while younger rocks in the area are unfolded (km-scale Eurekan folds occur in the wider area but did not affect the mesoscale outcrops referred to here). Birkenmajer & Turnau (1962) dated the formation to be Viséan based on palynomorphs. To explain the folds, Birkenmajer (1964) claimed the existence of a strictly local, convergent "Adriabukta Phase" of folding during the otherwise divergent regime in the Viséan (McCann & Dallmann 1996). This scenario is hard to believe.

Another circumstance is also quite implausible: the Adriabukta Formation (accumulated thickness 1750 m) occurs in the immediate vicinity of the apparently coeval, undeformed Hornsundneset Formation (sandstones, thickness up to 1100 m), situated both east and west of it (thicknesses from Dallmann et al. 1999). It is not reasonable to assume that these two thick formations that had completely different sedimentary environments (Birkenmajer 1964) were deposited closely side by side for a long period. Consequently, it would be necessary to assume that the Hornsundneset sandstones were later brought into their present position by Eurekan thrusts from a rather distant place in the west, or by strike-slip from the north or south. This hypothesis does not comply with the fact that the base of the Hornsundneset sandstones, wherever it is exposed in southern Spitsbergen, is a depositional contact with the underlying pre-Caledonian basement rocks. The same is true for the base of the Adriabukta Formation, where it overlies either the Devonian Marietoppen Formation or the Precambrian basement (Birkenmajer 1964; Dallmann et al. 1993; Dallmann et al. 1999). Later juxtaposition by major strike-slip is also quite improbable, because the Hornsundneset sandstones occur on both sides of the fault blocks, in which the Adriabukta Formation is exposed.

These circumstances were demanding a different explanation, when one of us (WD) mapped that area in about 1990. Not believing the existence of the "Adriabukta Phase," and presuming the existence of a Svalbardian angular unconformity in the area, the folds in the Adriabukta Formation could only belong to the STE. This again would mean that the postulated Viséan age of the Adriabukta Formation (Birkenmajer & Turnau 1962) must be wrong.

There is no doubt that the published spore assemblages in the Adriabukta Formation indicate a Viséan age identical with that of the adjacent exposed Hornsundneset Formation. Birkenmajer & Turnau (1962) said that their samples A1 and A2 were taken close to the boundary with the underlying Middle Devonian Marietoppen Formation and they belong to the uppermost part of the Julhøgda Member (middle member of the Adriabukta Formation [Dallmann et al. 1999]). Sample A3 was taken in an area of poor exposure, probably in the Meranfjellet Member, close to the contact with the unconformably overlying strata; poor exposure hides all structural relations there.

Birkenmajer & Turnau (1962) did not know that approximately 600 m of sandstones (Julhøgda Member) and locally 400 m of coarse immature conglomerate (Haitanna Member), all belonging to the Adriabukta Formation, lie below the allegedly sampled horizons farther south (Dallmann 1992; Dallmann et al. 1993; Dallmann et al. 1999), because that area had not been mapped at that time.

So, how to explain the Viséan palynology of Birkenmajer & Turnau's samples? Dallmann's suggestion was that the palynomorph samples were mixed up in 1962 and in fact had come from the Billefjorden Group (Hornsundneset or Sergeijevfjellet formations). Having this possibility in mind when working with Prof. Krzysztof Birkenmajer in Hornsund in 1990, we took new samples at the stratigraphic level of Birkenmajer & Turnau's (1962) samples A1 and A2, of the same facies and in the same coastal outcrops. Birkenmajer volunteered to date them again but said later that he did not find any spores in the new samples. The data of his and Turnau's work from 1962 could therefore not be confirmed. Until such a confirmation is provided, there are reasonable doubts that these layers contain any spores at all. The published Viséan age of the formation is therefore not reliable, and a pre-STE (Late Devonian) age of the Adriabukta Formation is plausible.

Unfortunately, the circumstances described above have never been explicitly published, except for a short "pers. comm." reference in Bergh et al. (2011). Of course, these reflections are only applicable if the angular unconformity of the STE really exists in southern Spitsbergen, a fact doubted by Koehl et al. (2022), as discussed next.

The Svalbardian angular unconformity in southern Spitsbergen

An angular unconformity of the STE above folded Devonian in southern Spitsbergen has been described and confirmed by numerous scientists (Mørk et al. 1982; Nakrem & Mørk 1991; Dallmann 1992; Winsnes et al. 1992; Dallmann et al. 1993; Dallmann et al. 1999; Thiedig et al. 2001; Krajewski & Weitschat 2015). The map of the area around Karentoppen, Lebedevfjellet and Røkensåta (Winsnes et al. 1992), where the unconformity is most obvious (Fig. 4), shows Triassic strata overlying both pre-Caledonian basement marbles (Karentoppen; Fig. 5a) and folded Devonian rocks (Røkensåta, Smerudknausen; Fig. 6). The Devonian strata are deposited above a distinct karst surface on the basement marbles (Lebedevfjellet; Fig. 5b). Where Triassic strata overlie the basement, a basal marble conglomerate is developed (Karentoppen; Fig. 5c), which indicates reworking at a depositional base. Such a basal conglomerate has been mapped and/or logged in all Triassic deposits overlying the pre-Devonian basement of western Sørkapp Land (Mørk et al. 1982; Nakrem & Mørk 1991; Krajewski & Weitschat 2015). Eurekan thrusts have been recognized in the Mesozoic succession overlying the basement of Sørkapp Land (Dallmann 1992; Dallmann et al. 1993; Tessensohn et al. 2001), but not at the contact between the basement and the Triassic.

At Røkensåta and Lebedevfjellet the crucial boundary is not exposed. It is unnecessary to assume a thrust contact between the Triassic and the underlying folded Devonian given the same contact is a distinct angular unconformity just a few hundred metres across the glacier at Karentoppen (Fig. 4).

These considerations make it obvious that Svalbardian folding occurred in Sørkapp Land, because the observed folds must be older than the undeformed, unconformably overlying Triassic (in adjacent areas the overlying undeformed strata is as old as Viséan). Was the Adriabukta Formation affected by the STE, too? The very few good exposures of contacts between the latter and overlying, undeformed younger deposits are situated close to Hornsund, where they are too tectonized by young Eurekan structures, so that a possible depositional contact would not be preserved.

Whether the Adriabukta Formation was affected by the STE therefore depends on the age of the Adriabukta

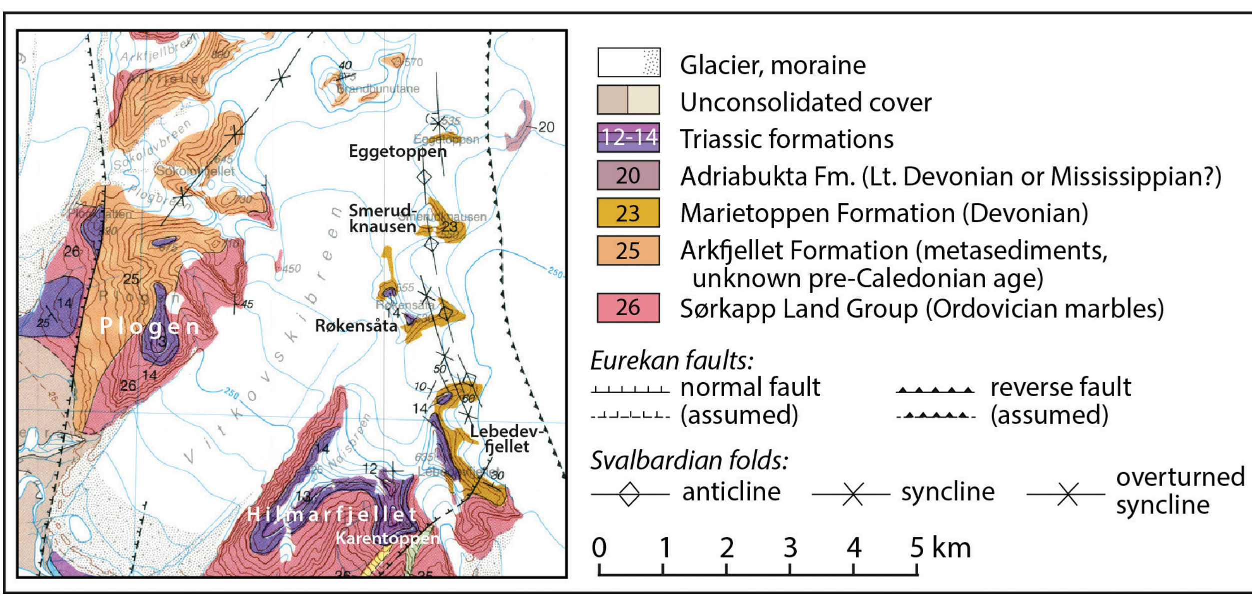

Fig. 4 Excerpt of the Norwegian Polar Institute's geological map of Sørkapp Land (Winsnes et al. 1992), at a scale of 1:100 000, showing the area around Karentoppen and Røkensåta. This is the key area for the establishment of an angular unconformity above folded Devonian, formed prior to the deposition of the overlying Triassic.

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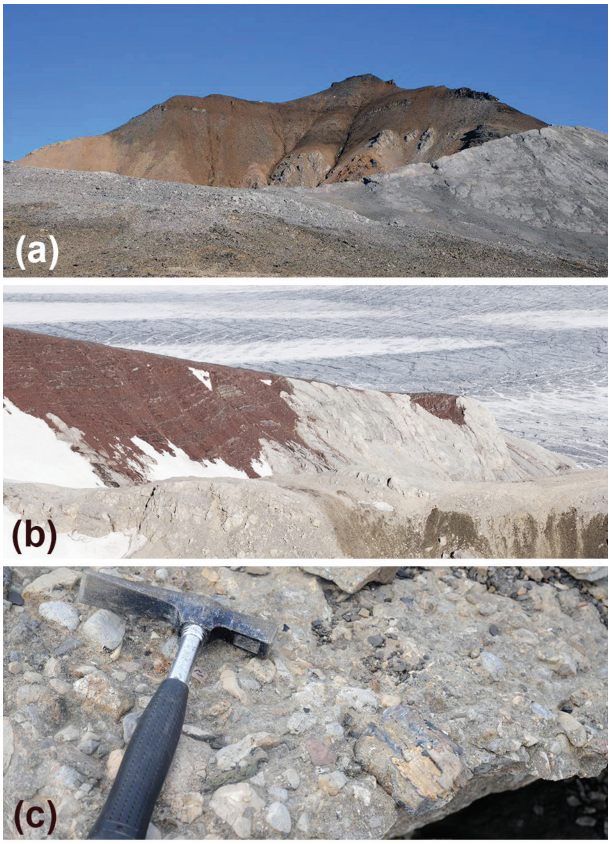

Fig. 5 Field photographs illustrating the geological situation in the Karentoppen area shown in Fig. 4. (a) Karentoppen, view from the south-west, Triassic succession overlying karstified Ordovician marbles. (b) Lebedevfjellet, view from west, with Devonian infilling a karst relief on the surface of Ordovician marbles. (c) Karentoppen, basal Triassic conglomerate; this conglomerate overlies the karstified Ordovician marble. (Photos by Prof. Snorre Olaussen, The University Centre in Svalbard, with permission.)

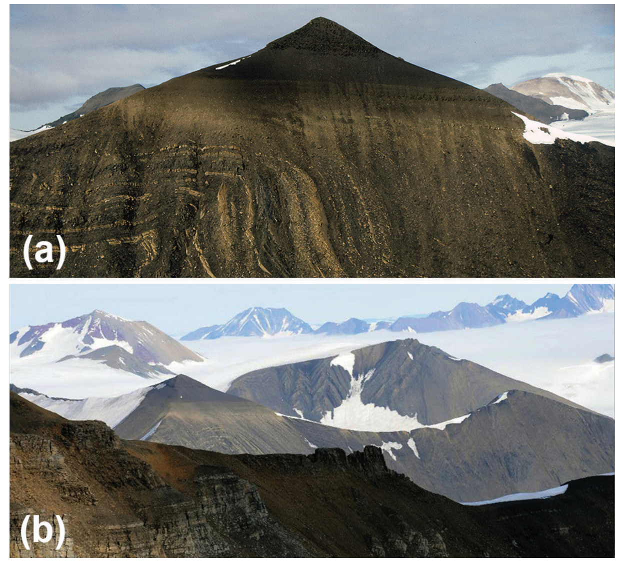

Fig. 6 Field photographs illustrating the geological situation in the Røkensåta area shown in Fig. 4. (a) Røkensåta with Triassic, unconformably overlying folded Devonian. (Photo by W. Dallmann.) (b) Triassic succession of Hilmarfjellet (foreground), Røkensåta with Triassic unconformably overlying folded Devonian (middle, same view as Fig. 6a) and Smerudknausen with folded Devonian (behind to the right), seen from the south-west. (Photo by Prof. Snorre Olaussen, The University Centre in Svalbard, with permission.)

Formation, whether its folds in Sørkapp Land are of Svalbardian or Eurekan, or even both ages. (This does not have any bearing on the prominent shear zone north of Adriabukta, mentioned by Koehl et al. (2022), which is indeed of Cenozoic age, as also shown by Dallmann (1992) and Gosen et al. (2001). As said above, the age of the Adriabukta Formation is, strictly speaking, unknown. But an age distinctly older than the Viséan age of the Hornsundneset Formation is favoured, because it is highly unlikely that these two very thick formations—in close proximity but stemming from very different depositional environments—were deposited during the same period at this short distance. Also in favour of a Devonian age is the fact that sedimentation at Adriabukta is continuous from the Devonian Marietoppen Formation to the Adriabukta Formation, without any unconformity.

Synthesis and conclusion

As discussed, Svalbardian convergent deformation (STE) and a related angular unconformity are definitely present in both northern/central and southern Svalbard. Eurekan (Cenozoic) tectonics later affected the area (e.g., Dallmann 1992; Gosen & Piepjohn 2001; Thiedig et al. 2001; Tessensohn et al. 2001).

The timing of the STE is still controversial. A Tournaisian age fits best with the regional tectonic framework and the relation to the Ellesmerian Orogeny, while palynomorph ages point to a Famennian age. There are good arguments for the possibility that palynomorphs are re-deposited, which might solve the problem.

The Viséan palynological age of the Adriabukta Formation (Birkenmajer & Turnau 1962) could not be confirmed and may have been caused by mix-up when handling the samples. It is far more probable that the formation is of late Devonian age and is stratigraphically situated below the angular unconformity of the STE.

The idea of Eurekan strain partitioning in Svalbard (Koehl et al. 2022)—being responsible for the folds and thrust in the Devonian—lacks any field-based evidence. In other areas where such strain-partitioning has taken place during the Eurekan, like in the West Spitsbergen

Fold-Thrust Belt, it can easily be seen where weak, shale-rich lithostratigraphic units accommodate tectonic shear (Dallmann 2015 and references therein). Nothing similar has ever been described from the shales of the Mississippian strata above the Svalbardian unconformity.

The comparison of the unconformity with the extensional detachment proposed by Braathen et al. (Braathen et al. 2018; Braathen et al. 2020) is problematic, because it occurs at a different time (only Early Devonian is affected) and in a restricted place (Raudfjorden Trough). Chorowicz's (1992) extensional hypothesis is also problematic to apply, because his gravitational detachment would imply directions of tectonic transport that are the opposite of those observed.

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Disclosure statement

The authors report no conflict of interest.

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