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Winfried K. Dallmann, Maciej Manecki,
Krzysztof Michalski and Piotr Głowacki (eds.)

SVALGEOBASE:

Proterozoic and Lower Palaeozoic basement of Svalbard – state of knowledge and new perspectives of investigations
Workshop report

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Workshop report

Norsk Polarinstitutt er Norges hovedinstitusjon for kartlegging, miljøovervåking og forvaltningsrettet forskning i Arktis og Antarktis. Instituttet er faglig og strategisk rådgiver i miljøvernsaker i disse områdene og har forvaltningsmyndighet i norsk del av Antarktis. Instituttet er et direktorat under Klima- og miljødepartementet.

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Preface

The SvalGeoBase workshop was organised to fulfill the needs expressed by a broad group of geologists working in the Arctic. A conventional conference meeting may easily turn into simple exchange of achievements, while a field workshop always stimulates creative discussion of problems, questions and controversies. Svalbard was a natural choice of region due to its unique palaeogeographical position. Although now it constitutes an integral part of the Baltic plate, Proterozoic/Lower Palaeozoic successions of Svalbard show affinities with the Laurentian continent (East Greenland, Ellesmere Island). Svalbard is also a key region for reconstruction of tectonic systems of the northern branches of the Atlantic and Iapetus ocean systems, and according to recent models may constitute a part of the Timanide Orogen.

The initiative of the SvalGeoBase workshop came from two Polish institutions working independently in two regions of Svalbard:

1. AGH University of Science and Technology in Kraków – from the 1980s involved in investigations of the Proterozoic basement of Wedel Jarlsberg Land (southwestern Spitsbergen); co–organiser together with Uppsala University (Sweden) of a conference in Bukowina Tatrzańska (Poland) in 2011: "Tectonics of the Caledonides and Uralides, and the origin of the Arctic: Cooperation between Swedish, Polish and Russian geoscientist (COSPRA)" (coordinators: Maciej Manecki – AGH; Jarosław Majka, David G. Gee, Henning Lorenz – Uppsala University). COSPRA 2011 was an important first step in developing the idea of the SvalGeoBase workshop.

2. IGF PAS – Institute of Geophysics Polish Academy of Sciences in Warsaw – involved in multidisciplinary investigations of pre-Caledonian complexes of Western and Northern Spitsbergen as well as Western Nordaustlandet – project PALMAG "Integration of palaeomagnetic, isotopic and structural data to understand Svalbard's Caledonian terrane assemblage" (coordinators: Krzysztof Michalski – IGF PAS, Geoffrey Manby – Natural History Museum of London, UK).

Initial AGH/IGF PAS cooperation resulted in creating an ambitious plan of the workshop hosted on board of a scientific vessel, with a sailing route covering substantial pre-Caledonian exposures along the western and northern coasts of Spitsbergen. The final framework of the SvalGeoBase crystalized in early 2013 when representatives of NPI - Norwegian Polar Institute (coordinator: Winfried Dallmann) kindly agreed to join and support the project. Established NPI/IGF PAS/AGH cooperation resulted in a successful grant by the Svalbard Science Forum, with NPI as the grant host institution.

In the final stage the workshop was organised and managed by a consortium of three institutions: (1) Norwegian Polar Institute (Tromsø, Norway, coordinator: Winfried K. Dallmann); (2) Laboratory of Palaeomagnetism and Department of Polar Research, Institute of Geophysics, Polish Academy of Sciences (Warsaw, Poland, coordinators: Krzysztof Michalski and Piotr Głowacki); (3) Department of Mineralogy, Petrography and Geochemistry AGH University of Science and Technology, (Kraków, Poland, coordinator: Maciej Manecki). Scientists from Norway, Sweden, Denmark, UK, Germany, Poland, USA and Russia invited to participate in the workshop represented a wide range of geosciences: large-scale geotectonic reconstructions, palaeogeography, metamorphic petrology, mineralogy, structural geology, geochemistry and geochronology, palaeomagnetism, mineral and oil industry.

The workshop was organised onboard the Polish research vessel RV Horyzont II (Gdynia Maritime University) chartered by the Institute of Geophysics, Polish Academy of Sciences. Both, participation in the programme of the workshop and financial support from Svalbard Science Forum are greatly acknowledged. The organisers are very thankful to the Captain and crew of RV Horyzont II for their hospitality and creative assistance.

The vessel R/V Horyzont II, photographed during landing by Zodiak in Mosselbukta, Ny-Friesland. Photo: W.K. Dallmann.

Contents

Scientific background and justification of the topic

The Proterozoic and Lower Palaeozoic (pre-Caledonian) basement of Svalbard represents an old geotectonic complex with elements of several earlier tectonic terranes, orogeneses and other tectonothermal events. Our knowledge of the early Earth's history of the Arctic region depends on its understanding. Although individual researchers and research groups concerned with the Proterozoic and Lower Palaeozoic (= pre-Caledonian) basement of Svalbard have had some contact in the past, they have mainly worked independently of each other and developed various experiences, which not necesssarily are mediated through scientific publications.

The fundamentals of our understanding of the pre–Caledonian geotectonic evolution of Svalbard were constituted during the 20th Century. They need, however, redefinitions using modern investigation and analytical methods. More reliable dating methods, for example, are presently redefining the order of events in the western basement region of Svalbard. Better understanding of the geology of basement is necessary to improve our understanding of the geology and structures in younger stratigraphic sequences. Increased communication within the relevant scientific community is an important precondition for gaining an overall understanding. This should include scientists working in adjacent Arctic basement areas such as Greenland and Ellesmere Island.

Major geological issues behind the workshop agenda included, but were not limited to:

- unifying correlation of Proterozoic/Early Palaeozoic metamorphic basement sequences across Svalbard and across the Atlantic;
- exchange of modern interpretations on the origin and age of Neoproterozoic/Early Palaeozoic metavolcanites of Svalbard and their correlation with contemporaneous volcanism in Scandinavia, Siberia, Greenland and Northern Canada;
- modern interpretation of regional palaeogeographic and tectonic position of this part of Arctic in the late Precambrian and Early Palaeozoic;
- implications for the offshore crustal structure profiling of the Western Barents Sea and potential oil resources.

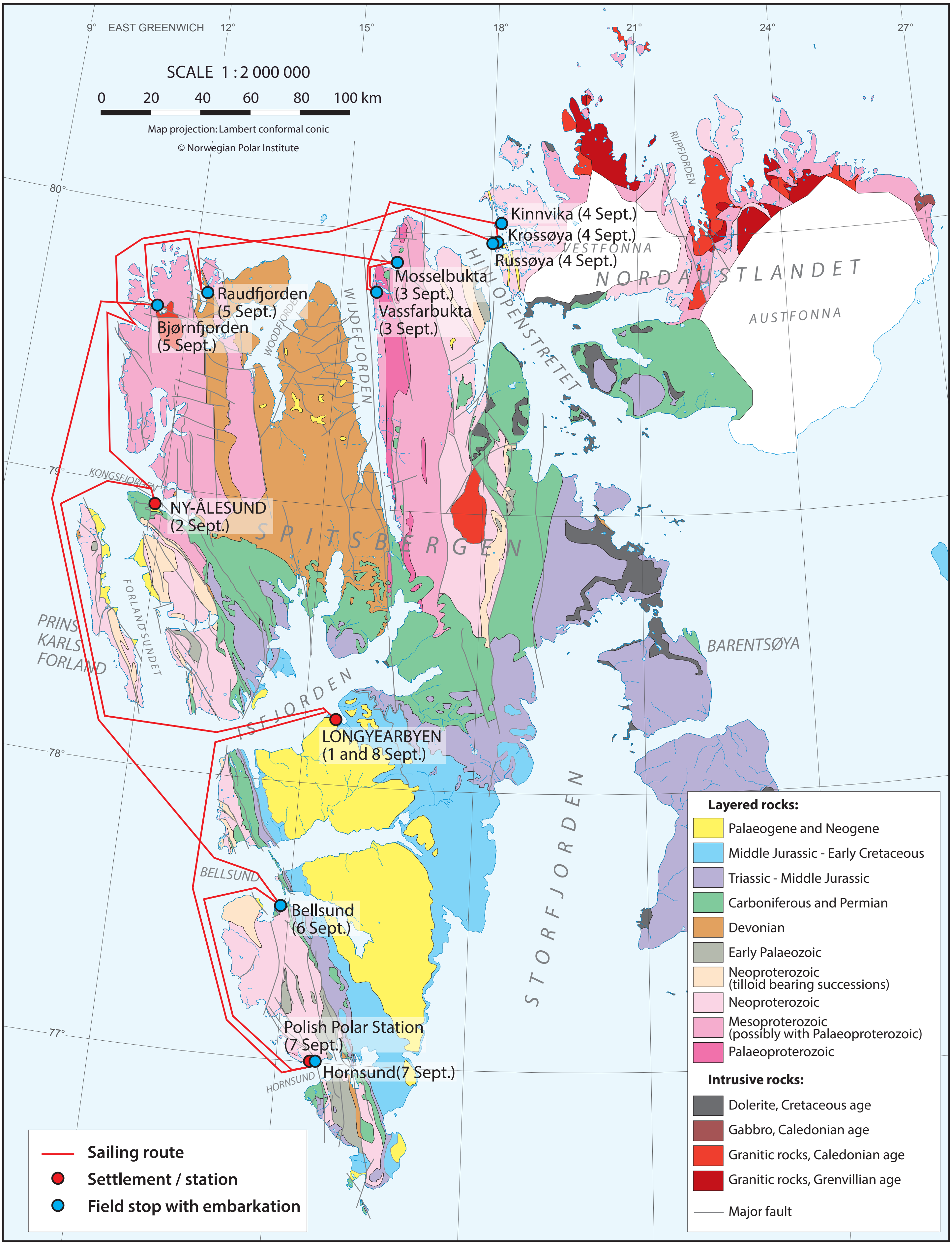
In most countries in question a deficiency of young geologists interested in research in Arctic is observed. A necessity for field interaction of senior researchers with geologists in the beginning of their career was recognised, to stimulate the activities, pass on the knowledge and experience, and confront classical methods and approaches with cutting-edge innovative approaches often represented by young researchers.

As expected, the relatively informal, field-oriented concept of the workshop allowed for identification and recommendation of key problems to be addressed in future geological activities, which should be the objective of collaborative efforts between the involved institutions and countries. This may speed up the the progress of our understanding of the geological history of the region.

There is a need for the exchange of experience in the fields of fund generation and improvement of logistic solutions for geological field activities in the Arctic, which always are challenging. Direct interaction of representatives of key institutions, who are working in the Arctic, allowed for tightening of the collaboration and for formulation of new joint efforts. This leads to better, cheaper and more efficient field research in the future for everybody's benefit.

The members of the workshop after arrival in Longyearbyen with the vessel RV Horyzont II. Photo: M. Manecki

Sailing route



Description of field excursions

by Winfried Dallmann, Synnøve Elvevold, Jarosław Majka, Krzysztof Michaski and Geoffrey Manby

Mosselbukta

Objective

Ultramafic rocks situated along the tectonic boundary between the Atomfjella Complex (medium-grade, Palaeo- to Mesoproterozoic) and the Planetfjella Group (also called Mosselhalvøya Group; medium- to low grade eastward decrease, Mesoproterozoic)

Excursion

Landing at Polhemhamna, walk across coastal plain to Villdalen and back – in total 8 km.

Observations and discussion

The coastal plain is made up of quartzites and amphibolites of the Polhem unit (Atomfjella Complex). The main foliation strikes north-south. Outcrops are only good close to the coastline, where the dip is subvertical to steeply west.

At the rise to the hills at Villdalen, a segment of an old beach terrace with rounded beach boulders was found at 70-80 m a.s.l.

The hills north of Villdalen consist of ultramafic rocks and form lenses of 100 metres to kilometres length and 10s of metres to 200 m width, elongated north-south, parallel with the boundary between the Atomfjella Complex and the Mosselhalvøya Group. The foliation of the quartzites (Polhem unit) seems to bend around the ultramafites. The ultramafites themselves are massive and contain few shear zones.

In the visited locality, litholgies of the Mosselhalvøya Group occur first 50-100 m east of the untramafite, while the boundary itself is covered with scree. The nature of the contact cannot be observed, but it is suggested to be vertical as concluded from the structure of the adjacent rocks.

The Planetfjella Group is here represented by the Flåen Formation, which consists of garnet-mica schist and mica gneiss. Penetrative stretching lineations plunge south (170°). Leucosomes in the gneisses suggest temperatures close to anatexis during metamorphism, while the metamorphic grade decreases rapidly eastwards from here to low-grade across a distance of only 6 km. It is therefore suggested that the succession is tectonically thinned after metamorphism. Significant vertical displacement must have taken place at the same time in order to lift up the ultramafites from a great depth during the Caledonian Orogeny.

Ultramafic lenses (dark) form the hills of Polhemhøgdene, seen from Mossellaguna across the coastal plain Polhemflya. The plain is entirely made up of quartzites (see rocks in front) and amphibolites of the Polhem unit. Photo: W.K. Dallmann.

Vertical eastern boundary of an ultramafic body at Villdalen. The quartzitic scree just in front of it shows that lithologies of the Polhem unit surround the body. The darker-coloured exposures show close-to-anatectic mica gneiss of the Planetfjella Group. Photo: W.K. Dallmann.

Massive ultramafites at Polhemhøgdene, close to Villdalen. Photo: W.K. Dallmann.

Polhemhøgdene with their ultramafic bodies (yellowish brown colour), which were emplaced in a tectonic shear zone between quartzites and amphibolites of the Atomfjella Complex (front) and mica gneisses of the Planetfjella Group (background to the right). Photo: W.K. Dallmann.

Polhem Coastal Section

Objective

To understand the tectonic setting of the amphibolites and associated rocks sampled for palaeomagnetic and isotopic analyses along the coastal section in the vicinity of the Polhem trappers hut.

Excursion

After landing close to the Polhem trappers hut the amphibolites and associated quartzites were sampled and their structural and compositional features were examined in detail over approximately 500m x 1km section.

Observations and Discussion

The general strike of the succession is approximately N-S and the rocks were found to be repeated by folding across the area studied. The amphibolites show a variety of textural and structural features, which indicate that their protoliths were most likely to have been sheet-like bodies intruded into the quartzites at different times. Although the subsequent Caledonian metamorphism and deformation was intense enough to almost obliterate the cross-cutting relationships as they were rotated in near parallelism, the intrusive nature of the amphibolite protoliths can be recognised. The quartzites preserve evidence of a pre-existing (Proterozoic?) tectonically and metamorphically induced foliation, which is intruded by the amphibolites.

The superimposition of the Caledonian deformation on the pre-existing folds has produced some good examples of fold interference patterns. Although a meaningful analysis of the separate fold geometries was not possible in the time available over the area investigated it would appear that the metamorphically enhanced compositional banding (D1, F1, S1) exhibited by the quartzites was first folded by flat-lying isoclines overprinted by folds with axial surfaces inclined to the west indicating an east-directed tectonic transport direction. There is, however, evidence indicating the occurrence of an intermediate fold event between the latter two phases.

Juxtaposition of coarse and fine grained amphibolites suggesting different compositions and, possibly, separate intrusive events for this body. Photo: G.M. Manby.

Amphibolite sheet (dark material) to right and centre intruding light coloured quartzites to left. Photo: G.M. Manby.

Quartzite-amphibolite relations: The compositional banding in the quartzite is a product of an earlier fold-metamorphic event(s), which is cut by the amphibolite protolith and the two have been folded together during the later Caledonian(?) tectogenesis. Photo: G.M. Manby.

An example of a so-called sheath fold, which in this case is clearly the result of fold interference and cut effect. Photo: G.M. Manby.

In this view, looking south, a series of medium scale flat-lying isoclinal folds (e.g. bottom right) are imposed on a pre-existing metamorphic foliation in the quartzites. The structures are affected by later folds with axial planes inclined to the west suggesting an easterly tectonic transport direction. Photo: G.M. Manby.

Vertical compositional banding in the quartzites on the eastern limb of an east vergent fold. In the centre of the view isoclinally folded quartz feldspar (QF) segregations transecting the compositional banding are refolded by south plunging west vergent folds. If the effect of the latest folding is removed then the isoclines affecting the QF segregations would be slightly inclined to the west suggesting that the early isoclines (e.g. above) were east vergent. Photo: G.M. Manby.

Vassfarbukta, Wijdefjorden

Objective

To investigate the highly sheared and retrograded rocks along the coastal section in the vicinity of Vassfarbukta that represent the Late Caledonian ductile to semi-brittle deformation in a wide zone parallel to the Billefjorden Fault Zone.

Excursion

Landing and traverse a 5-600m section of the coastal zone to the south of Vassfarbukta.

Observations and discussion

The section investigated consists largely of quartzo-feldspathic schists and amphibolites that are repeated by folding. The sequence compares with that found along the coastal section visited earlier in the day at Polhem, except at this locality the rocks are strongly sheared and display well-developed, mylonite characteristics including, in some cases, kinematic indicators with a sinistral sense of shear. The mylonite fabric is steeply west-dipping to vertical and strikes N-S. The quartzo-feldspathic schists are commonly very platy although shallowly, north and south, inclined intersection lineations provide evidence for pre-existing foliations that have been overprinted by the mylonitic foliation. Relict earlier folds are abundant as are those affecting the mylonitic fabric. A 450 Ma old laser ablation $^{39}Ar/^{40}Ar$ age has been obtained on mica extracted from these mylonites.

The associated amphibolites contain abundant actinolite and chlorite, and these again show a strong, platy fabric. It is evident that these rocks were retrograded from higher-grade amphibolites that can be found outside of the mylonite zone. Like the quartzofeldspathic rocks the retrograded amphibolites are affected by more than one generation of folding. They show considerable changes in thickness, often pinching out, by boudinage, along-strike. The zone of mylonitization runs onshore from Wijdefjorden, just south of Dirksodden and then offshore north of Vassfarbukta. The broad zone of dominantly sinistral shearing examined shows everywhere evidence of later brittle deformation, which may reflect the continued reactivation of the Billefjorden Fault Zone during the ascent of the exposed block from amphibolite facies depths to higher crustal levels.

Horizontal section of highly sheared QF rock with feldspar porphyroclasts showing sinistral shear sense. Photo: G.M. Manby.

Mylonitic QF schist showing early isoclinal folds refolded by crenulation to kink-like folds and flexures cut by shallow brittle fractures. Photo: G.M. Manby.

QF schists showing upright crenulation folds refolding mylonite fabric with at least two earlier fold phases evident in the foliation. Photo: G.M. Manby.

The section of the coastline visited during this excursion shows the steeply dipping, well-developed mylonite fabric exhibited by the affected rocks. The lighter bands are the quartzofeldspathic rocks while the darker more prominent bands are the amphibolites. Photo: G.M. Manby.

Boudinaged, highly sheared, retrograded amphibolite with interfolds of QF schists, North Vassfarbukta. Photo: G.M. Manby.

Kinnvika

Objective

1) Visit Kinnvika research station.
2) Neoproterozoic/Lower Palaeozoic section of Nordaustlandet

Excursion

Landing at Tvillingneset and walk 0.5 km along the beach towards the cultural remains of Kinnvika station.

Observations and discussion

The Kinnvika research station was build for the International Geophysical Year (IGY) 1957-58 by a Swedish-Finnish-Swiss expedition. The station was manned from 1957 to 1959, and monitored meteorological and upper atmospheric physical parameters. The buildings are made from wood and even 50 years after the buildings are solid and in good shape. Piotr Głowacki gave a guided tour of the station, which at that time was built to quite high standards. Electricity was produced with generators, and there were separate storage and research buildings, as well as sauna. Some technical equipment still remains at the station.

The discussions of geological nature were focused on correlations between the East Greenland and the Svalbard Caledonides. Almost identical Neoproterozoic-Ordovician successions were deposited in both Svalbard and East Greenland. The Murchinsonfjorden Supergroup of eastern Svalbard and the Eleonore Bay Supergroup of central East Greenland, are both overlain by similar Vendian tillites and Cambro-Ordovician carbonate formations. The correlation of the Neoproterozoic-Ordovician succession is largely based on fossil evidence and lithostratigraphic associations. Furthermore, there are striking similarities in the tectonothermal evolution of the crystalline basement. The Neoproterozoic successions in East Greenland and Nordaustlandet are both underlain by comparable late Mesoproterozoic basement complexes. In both areas the basement complexes comprise two generations of anatectic granites of similar ages (Early Neoproterozoic and Caledonian) as well as metasediments.

D. Gee giving an introduction on the correlations between the East Greenland and the Svalbard Caledonides. Photo: S. Elvevold.

The main building at the Kinnvika station had room for 15 people. Photo: S. Elvevold.

Stromatolite of the Roaldtoppen Group, in the environs of Kinnvika. Photo: W. Dallmann.

The silvery grey buildings in Kinnvika blend in with the natural colours of the surroundings. Photo: S.E. Elvevold.

Krossøya

Objective

Early Cambrian sediments.

Excursion

Landing on southeastern shore, walk northward and to eastern cape, and to the Russian Cross – total less than 1 km.

Observations and discussion

At the landing site a few coastal exposures occur behind the strand flat. The area between here and the eastern cape of the island shows a number of isolated exposures, while a non-continuous coastal cliff occurs locally and at the cape. The sedimentary strata dips gently to 50°W. Minor east-west striking faults seem to offset the beds.

Most of the island consists of dolomitic limestones which, based on their brachiopod and trilobite content, have been assigned an Early Cambrian age. The lithologies are, however, difficult to correlate with other Early Cambrian sections at Kapp Sparre and in Ny-Friesland.

The dolomites are layered, often with stylolitic surfaces. There is very little bioturbation; macrofossils were not seen. In the northern part of the visited area, calcite-filled cavities occur, which may be recrystallised fossils.

The lower part of the stratigraphy on the island, in the area around the eastern cape, consists of clastic sediments comparable with other Cambrian sections in northeastern Svalbard. These are mainly quartzites, both lightly and darkly coloured as well as yellowish weathering varieties. In one place, a tight spaced cleavage with steep easterly dip occurs in a light quartzite. One outcrop reveales a brownish and yellow, banded mudstone with plastic diagenetic structures, and subsequently irregularly fractured and folded – probably close to a fault.

Dolomites close to the landing site in the southeastern part of the island; the most representative lithology. Photo: W.K. Dallmann.

Dolomites with bedding-parallel stylolitic seams and calcite-filled cavities, the latter possibly replacing earlier fossils. Photo: W.K. Dallmann.

Coastal cliffs with clastic lithologies in the area around the eastern cape. Photo: W.K. Dallmann.

A peculiar yellowish-brown mudstone with irregular folding, probably close to a fault. Photo: W.K. Dallmann.

Detail of the mudstone (left) showing plastic deformation during diagenesis like ball-and-pillow structures. Photo: W.K. Dallmann.

A tight, east-dipping spaced cleavage in light-coloured quartzites in the clastic part of the Krossøya stratigraphy. Photo: W.K. Dallmann.

The Russian Cross from the 1700s, hence the name of the island (Krossøya = Cross Island). One of two remaining ones in NE Svalbard. Photo: W.K. Dallmann.

Søndre Russøya

Objective

The Neoproterozoic section of Nordaustlandet.

Excursion

Landing at the northwestern coast of Søndre Russøya. Walk along the coastal plane to the southwestern cape of the island. Total distance – 4 km.

Observations and discussion

The western coastal plain of Søndre Russøya is characterised by numerous distinct exposures of carbonates of the Murchisonfjorden Supergroup (probably Roaldtoppen Group). At the southwestern end of the island there are exceptionally well preserved examples of Neopretorozoic stromatolites (upper part of Murchisonfjorden Supergroup – probably Roaltoppen Group) and diamictites (lower part of Hinlopenstretet Supergroup – Gotiahalvøya Group). It is notable that the pressure solution type cleavage in these rocks is steep to vertical and is seen in many instances to wrap around the clasts.

Main scientific topics of discussion:

1. Limited stratigraphic and structural control of the Neoproterozoic succession of western Nordaustlandet – poor outcrop, lack of fossils, lithostratigraphy difficult due to unrecognised tectonic repetitions.

2. Difficult correlation between the the Neoproterozoic succession of Nordaustlandet and its equivalents in Ny-Friesland (e.g., Akademikarbreen and Polarisbreen groups) due to different tectonothermal styles on opposite sides of Hinlopenstretet.

3. Range of Caledonian deformation and metamorphism around Hinlopenstretet.

4. Palaeogeographic context – correlation of the Neoproterozoic succession of western Nordaustlandet with East Greenland.

Tillite with clasts of carbonates, Gotiahalvøya Group. This unit is underlain by stromatolites of upper Murchisonfjorden Supergroup (below). Photo: S. Elvevold.

Distinctively separated stromatolites of the Roaltoppen Group on a weathered surface. Photo: S. Elvevold.

Geologists have a good time in the Neoproterozoic. Photo: S. Elvevold.

Cross section across stromatolitic structures. Photo: S. Elvevold.

Coastal plain of the northwestern part of Søndre Ryssøya. Photo: S. Elvevold.

Raudfjorden

Objective

Various Devonian conglomerates (Red Bay and Siktefjellet groups), eclogite-bearing succession in the earliest Neoproterozoic Richarddalen Complex.

Excursion

Landing in central part of Svalisstranda, walk into lower part of Rabotdalen, climbed into Lilljeborgfjellet conglomerate to the south, and eclogite location to the north on Prinsesse Alicefjellet – in total 4 km.

Observations and discussion

The first kilometre of the route crosses the Prinsesse Alicefjellet Formation, a wide-spread quartz conglomerate in the Early Devonian Red Bay Group, which has both matrix- and clast-supported beds of rounded to subangular quartz pebbles and small boulders. The beds dip gently to moderately WSW, towards the centre of the Raudfjorden Graben. The underlying Rabotdalen Formation (300 m wide belt of sandstone, siltstone and beds of limestone) was not exposed along the route, but is seen on the ridges. Yellowish-brown, coarse-grained sandstone scree occurs on the valley bottom.

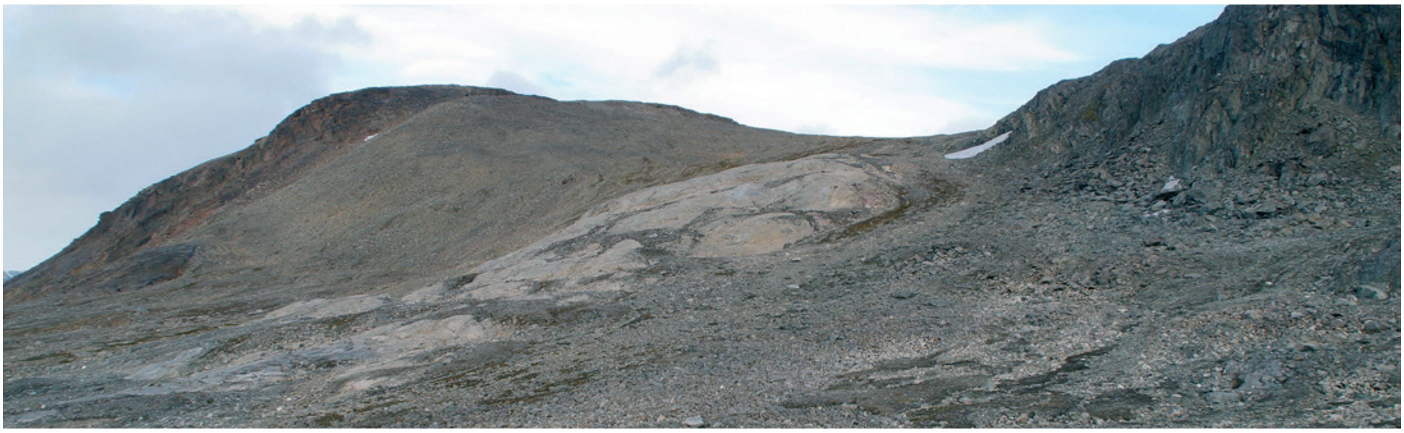
A relatively thin section through the lowermost formation of the Red Bay Group, the Wulffberget conglomerate, shows two different facies here. Most of the rock mass is a light-coloured limestone conglomerate with sub-rounded to sub-angular marble boulder and a carbonate-rich matrix. The other facies, a polymict and mostly more angular conglomerate with reddish weathering colours, occurs here only as loose blocks. The marble clast content has no obvious source in the underlying basement, which suggest either that the source rock formation was completely eroded.

Alternatively, subsequent strike-slip during the Monacobreen Phase (end of Red Bay Group deposition) may have moved the site away from the outcrops of the Generalfjella Formation farther south, which could constitute the source rock. The graben boundary fault towards the pre-950 Ma old Richarddalen Complex is not exposed nor is the unconformity with the overlying Lilljeborgfjellet conglomerate (Siktefjellet Group). The latter is the oldest post-Caledonian sediment which accumulated very soon after the last phase of Caledonian metamorphism at 420 Ma (latest Silurian or earliest Devonian).

The Lilljeborgfjellet Formation is mainly a chaotic, polymict conglomerate with unsorted, up to metre-sized boulders consisting mainly of underlying basement lithologies. Exotic lithologies occur occasionally, like a quartz porphyry or older conglomerate from an unknown source.

The basement of the late-lower to upper Devonian Andrée Land Group, which covers vast areas to the east, is unknown, which opens for the possibility that the erratic boulders in the Wulffberget and Lilljeborgfjellet conglomerates are derived from there.

East of the boundary fault, a thin unit of garnet-micaschist with mylonitic textures occurs (Montblanc unit) which is followed by a garnet biotite-amphibolite gneiss of the Richarddalen Complex. An augen gneiss from higher up the valley occurs in loose blocks. Importantly, on the southern slope of Prinsesse Alicefjellet, north of Rabotdalen an eclogite lens is found within biotite-amphibolite gneisses. The protolith of this body was probably a basic dyke intruded into the gneisses prior to the Caledonian Orogeny during which event it was metamorphosed under high pressure/low temperature conditions like those found in subduction zone complexes.

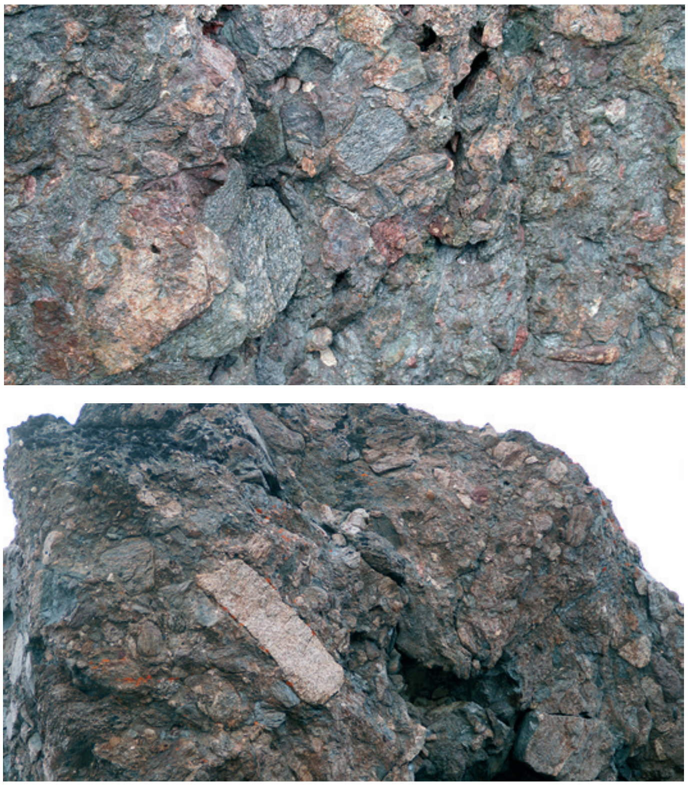


Succession at the southern slope of Prinsesse Alicefjellet, from right: Mylonitic garnet-micaschist (Montblanc unit; dark), Wulffberget conglomerate (light, massive), Rabotdalen Formation (yellowish-grey), Prinsesse Alicefjellet conglomerate (red). Photo: W.K. Dallmann.

Eclogite lenses surrounded by garnet-bearing orthogneiss represent mafic dykes metamorphosed under high-pressure conditions indicative of a Caledonian continental collision. Southeastern slope of Prinsesse Alicefjellet. Photo: S. Elvevold.

Two main facies of the Wulffberget conglomerate from Rabotdalen. Above an almost monomict marble-dominated, calcareous conglomerate; below a polymict variety with boulders and pebbles of sandstone, quartz, marble and other basement rocks. Photo: W.K. Dallmann.

Scale:
Above - long edge of photo ca. 150 cm.
Below - long edge of photo ca. 60 cm.

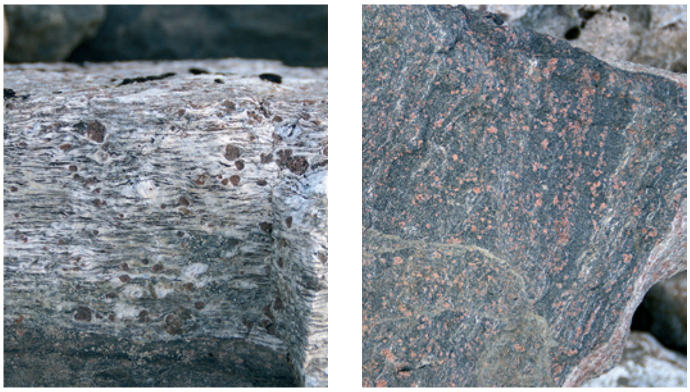


Two photos above: The Lilljeborgfjellet conglomerate, a polymict, chaotic, immature mass transport sediment deposited during rapid uplift of the Caledonian Orogen. Southern side of Rabotdalen. Photo: W.K. Dallmann.

Scale:
Above - long edge of photo ca. 80 cm.
Below - long edge of photo ca. 3 m.

Exotic boulders from the Lilljeborgfjellet conglomerate: A quartz porphyry and an older quartz conglomerate. Photo: W.K. Dallmann.

A micaschist with mylonitic texture of the Montblanc unit in Rabotdalen. Photo: W.K. Dallmann.



Lithologies from the Richarddalen Complex, loose blocks found in the outer part of Rabotdalen: Augen gneiss (left) and eclogite (right). Photo: W.K. Dallmann.

Mafic lenticular pod, containing eclogite facies parageneses, surrounded by garnet-bearing orthogneiss. Richarddalen Complex, southeastern slope of Prinsesse Alicefjellet. Photo: S. Elvevold.

Bjørnfjorden

Objective

The target at this locality is metamorphic and intrusive rocks of the Smeerenburgfjorden Complex, Northwestern Basement Province.

Excursion

Landing at the northern shore of Bjørnfjorden below Fjellback-ryggen and walk southeastwards along the shore.

Observations and discussion

The moraine in front of Viksbreen comprises boulders of various rocks of the Smeerenburgfjorden Complex; orthogneisses, migmatite, grey granites and coarse-grained granite. As we walk southeastward the first outcrop is a polished exposure of banded orthogneiss. The orthogneiss contains irregular veins and layers of granitic rocks as well as elongated pods, lenses and layers of amphibolite. The next outcrop southeast of the banded gneiss displays a massive granitoid with abundant xenoliths of migmatite. This unit might represent the marginal zone of the Hornemantoppen batholith.

The gneisses and migmatites of the Smeerenburgfjorden Complex are thought to be high-grade metamorphic equivalents of the Krossfjorden Group. The general structural axes plunge to the south and deeper levels are thus exposed in the north.

Banded gneiss of the Smeerenburgfjorden Complex. Photo: S. Elvevold.

Boulder of massive, coarse-grained Hornemantoppen granite, with 1-2 cm large phenocrysts of orange-pink K-feldspar. Photo: S. Elvevold.

Coastal exposures of gneisses and granites of the Northwestern Basement Province. Photo: S. Elvevold.

Granite including xenoliths of migmatite. Photo: S. Elvevold.

Smeerenburgbreen in the innermost Bjørnfjorden. The nunataks surrounding the glacier are made up of granite of the Hornemantoppen batholith. The nunatak named Hornemantoppen can barely be seen in the low clouds in the middle-right part of the photograph. Photo: S. Elvevold.

Antoniabreen, Bellsund

Objective

Meta-igneous rocks situated on Berzeliuseggene, Aldegondaberget and Martinfjella, on both sides of Antoniabreen.

Excursion

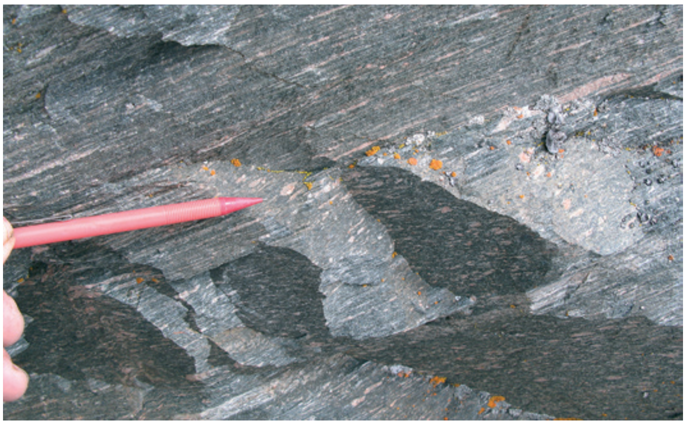
Landing at Malbukta and Richardodden, walk across coastal plain towards Antoniabreen and back to Richardodden – in total 8 km.

Observations and discussion

The Caledonian basement in the vicinity of Antoniabreen is represented predominantly by low- to medium-grade metasedimentary units. However, recent studies revealed that strongly deformed polymetamorphic augen gneisses are also present. The age of protoliths of these rocks is late Grenvillian, whereas subsequent metamorphic overprints are thought to be connected with the Torellian and Caledonian events.

In the visited localities, at the base of Aldegondaberget, there are outcrops of different petrographical varieties of the augen gneisess. Discussion was focused on the tectono-stratigraphical position of this meta-igneous suite. Field relations show that the rocks in question are thrust top-to-south onto the typical Neoproterozoic metasedimentary units of the Deilegga and Sofiebogen groups. On the eastern slopes of Martinfjella, the meta-igneous suite is in reverse-fault contact with slightly metamorphosed carbonates of inferred early Palaeozoic age. Importantly, the meta-igneous suite is unconformably covered by Carboniferous sediments. The unconformity is well seen on Aldegondaberget, where it dips steeply towards ENE. This suggests that prior to Carboniferous deposition the Caledonian structures were more steeply dipping than they are today. This has important implications for the interpretation of the north-dipping thrusts observed within this basement.

Typical augen gneiss of the Berzeliuseggene Igneous Suite (previously known as part of the Magnethøgda Group). Photo: J. Czerny.



Strongly sheared augen gneiss of the Berzeliuseggene Igneous Suite. Photo: J. Czerny.

Late metasomatic alteration zones developed along the fractures in the augen gneiss of the Berzeliuseggene Igneous Suite. Photo: J. Czerny.

David Gee, Karsten Piepjohn, Jerzy Czerny and Jarosław Majka discussing basement-cover relationships in the vicinity of Aldegondaberget by an outcrop of pegmatite belonging to the Berzeliuseggene Igneous Suite. Photo: K. Košmińska.

Martinfjella, seen from NE. The dark unit in the middle of the picture is composed of high grade augen gneisses. It is in the reverse fault contact with Palaeozoic carbonates (gray lithologies to the right) and thrust onto the Sofiebogen and Deilegga metasediments (to the left). Photo: K. Košmińska.

Isbjørnhamna, Hornsund

Objective

Late Palaeoproterozoic, mainly meta-igneous lithologies of the Eimfjellet Group and metasedimentary rocks of the Neoproterozoic Isbjørnhamna Group. Visit to Polish Polar Station.

Excursion

Landing at Isbjørnhamna close to Baranowskiodden, walk across Baranowskiodden, then to Wilczekodden and visit to Polish Polar Station – in total 3.5 km.

Observations and discussion

At Baranowskiodden, a shortened profile of the Eimfjellet Group crops out. This group is composed of a suite of meta-igneous rocks including dyke-intruded gabbros and granites, dolerites and other rocks of probable volcanic affinity. The meta-igneous suite is underlain and overlain by quartzites (not well exposed at Baranowskiodden). Main emphasis was given to the so-called Eimfjellbreane Formation, which might be in fact a strongly tectonised zone (thrust or mélange) within the Eimfjellet Group. Dyke-intruded gabbros and granites were also discussed, as well as relationships between different intrusive rocks.

The Eimfjellet Group is thrust onto a thick metasedimentary succession of pelites, greywackes, calc-silicates and carbonates belonging to the Isbjørnhamna Group. Outcrops of the carbonate-dominated Ariekammen Formation were visited at Wilczekodden. The Isbjørnhamna Group yielded first evidence for a late Neoproterozoic (Torellian, ca. 640 Ma) tectono-metamorphic event within the Caledonian basement of the Southwestern Basement Province. Torellian metamorphism and deformation is well developed in this succession and can be best observed in the near-by inner part of Revdalen. It is now evident, however, that the Torellian event affected much wider areas within the Southwestern Basement Province, which requires complete re-thinking and revision of the prevailing geological models.

Polish Polar Station, located at Isbjørnhamna, was established during the International Geophysical Year (IGY) 1957-1958 by Professor Stanisław Siedlecki (geologist). After that time the Station was operating occasionally until 1978. Since 1978, the Station is operated all year round and the wintering staff is collecting and processing meteorological, environmental and geophysical data. The Station is governed by the Institute of Geophysics of the Polish Academy of Sciences. Piotr Głowacki guided a tour around the station followed by a lecture describing history, development and the current status of available facilities.

Mafic dykes intruding gabbros of the Skålfjellet Formation (Eimfjellet Group) at Baranowskiodden. Photo: J. Majka.

Close-up at dyke-intruded gabbros of the Skålfjellet Formation (Baranowskiodden). Photo: W. Dallmann.

Tectonised zone within the Eimfjellbreane Formation (Eimfjellet Group) at Baranowskiodden. Photo: W. Dallmann.

View from Wilczekodden at the Polish Polar Station. Garnet-calcite-mica schists of the Ariekammen Formation (Isbjørnhamna Group) in the foreground. Photo: W. Dallmann.

Contrasting metamorphic terranes of Ny-Friesland and their place in the Arctic Caledonides

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Ny-Friesland, which is often compared with East Greenland (Gee & Tebenkov 1996), is characterized by two contrasting tectono-metamorphic successions (Fig. 1) whose relationships have, until recently, been controversial (*cf.* Manby 1990; Lyberis & Manby 1999 and Harland 1997). The high grade poly-deformed and metamorphic succession that occupies the western part of the peninsula is now known to consist of rocks that record both ca 1750 Ma and Caledonide (ca. 430 Ma) tectono-thermal events (Lyberis & Manby 1999; Gee & Page 1994; Gee et al. 1995). Previously, they were considered to be the deeper part of a continuous Proterozoic – Early Palaeozoic Helca Hoek Geosynclinal succession whose lower grade, less deformed, part is found occupying the eastern part of Ny-Friesland and western part of Nordaustlandet (Harland 1997).

The high grade rocks along the western margin of Ny-Friesland are bordered by the Billefjorden Fault Zone (BFZ) which records a sequence of oblique ductile to brittle shearing events with left lateral sense (Figs 2 A-D). White micas extracted from onshore mylonites, parallel to the BFZ, in western Ny-Friesland have yielded a 450 Ma $^{39}Ar/^{40}Ar$ suggesting that ductile motion along this zone had ceased by this time (Michalski et al. 2012). The BFZ also separates the high grade rocks from the Devonian Basin sequence of Northern Svalbard to the west, which were deformed by the Late Devonian Svalbardian event. Offshore seismic reflection profiles show a large normal fault close to the western margin of Ny-Friesland that displaces Quaternary sediments indicating that the Billefjorden Fault Zone is still active.

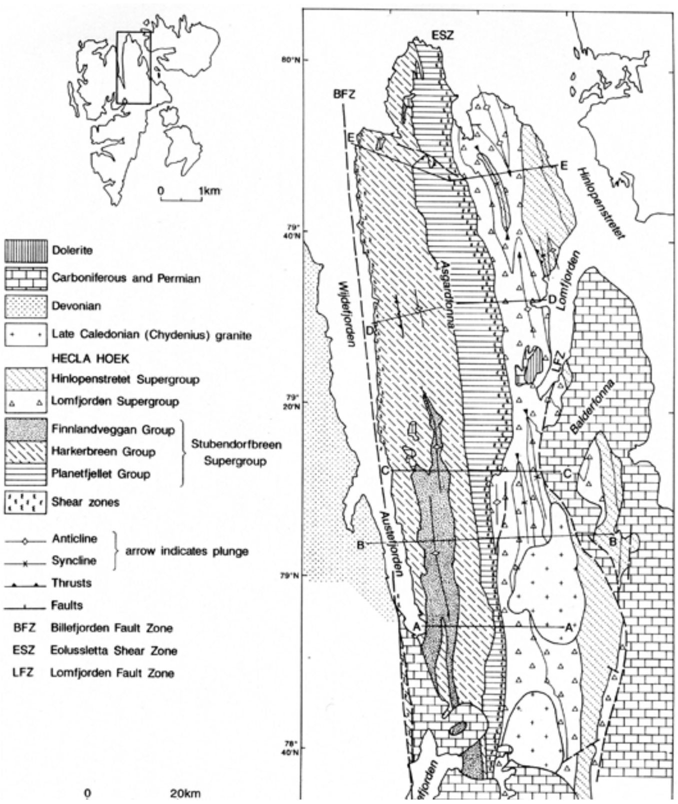

Fig. 1: Simplified geological map of Ny Friesland showing the location of the contrasting tectono-metamorphic successions and the major fault zones.

The eastern low grade Late Proterozoic to apparently un-metamorphosed Early Palaeozoic rocks of Nordaustlandet are separated from the high grade rocks to the west by a shear zone (Eolussletta Shear Zone, after Lyberis & Manby 1999) whose character is not clear. Along the northeastern margin of Ny-Friesland the transition from the high grade to low grade rocks is marked by a wide zone of retrograded and sheared schists with kinematic indicators suggesting an oblique (left lateral) sense of slip while in central Ny-Friesland the sheared high grade rocks appear to be thrust faulted over the weakly metamorphosed rocks to the east (Fig 3).

Structurally, the low grade to un-metamorphosed eastern succession is affected (cf Harland et al., 1997) by doubly plunging (periclinal) folds that are known to be fault propagation structures that developed ahead of thrust faults possibly rising as splays from a blind floor thrust ahead of the thrust carrying the western sheared high-grade rocks over the eastern low-grade rocks. The implication of such an interpretation would be that the foreland lay to the east and the main tectonic transport direction was also eastwards.

Reconstructions of the Arctic Caledonides, which have been based primarily on lithostratigraphic comparisons, have considered that Svalbard is a collage of terranes that were assembled, in Late Devonian time, from widely disparate locations along the Laurentian Margin by large scale left lateral motion along bounding fault zones such as the Billefjorden Fault Zone. In these reconstructions the terranes to the east of the BFZ are considered to have been close to Central Greenland prior to Devonian time.

Recent palaeomagnetic and isotopic data suggest, however, that the Central and Eastern Terranes were already a part of Baltica by Silurian time (Michalski et al. 2012) and that the ductile motion along the BFZ had ceased by this time. Large scale mobilistic models (e.g., Harland 1997) are not supported by such observations and a new approach to account for the present day juxtapositioning of Svalbard's contrasting tectono-metamorphic basement blocks is needed.

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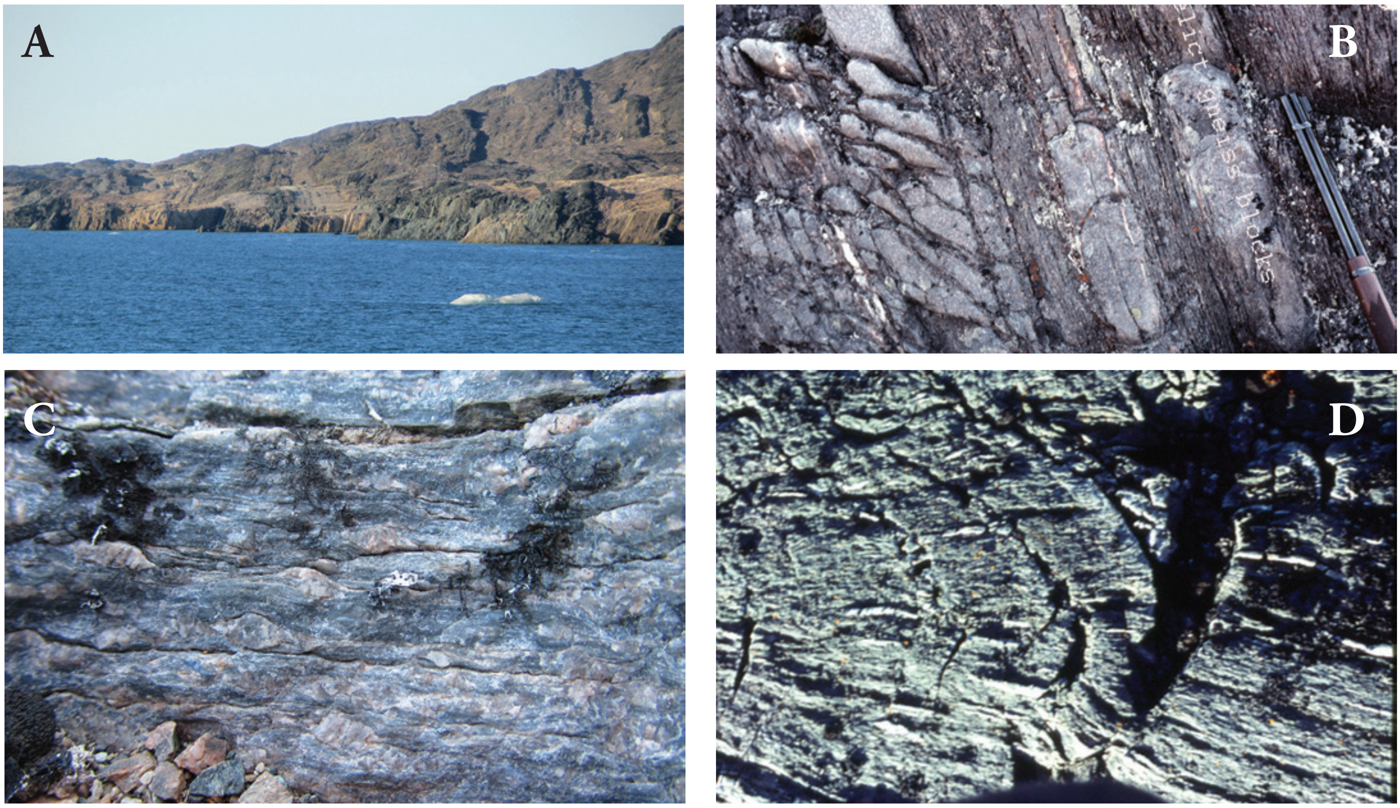

Fig. 2:
A. Low ground to left (west) with highly sheared and retrograde gneisses and amphibolites; North of Dirksodden Western Ny Friesland.
B. Close-up of mylonitc gneiss at location A shows relict blocks of gneiss in thinly banded ultra-mylonite. Note west-dipping shear surfaces to left of view suggesting a component of orthogonal compression.
C. View looking on upper surface of B (north is to left), rotated feldspar porphyroclasts show a sinistral sense of motion.
D. Sigmoidal semi-brittle shears in retrograded amphibolite associated with B & C indicate later sinistral shear.

Fig. 3: View of Malloryfjellet looking north across Edinburghbreen.The Planetfjellet Group schists and gneisses in the high ground are highly sheared and retrograded in the lighter green central band. The contact between these highly sheared rocks is a steep west dipping reverse fault which carries the Planetfjella Group over the low grade, dark coloured rocks of the Kortbreen Formation which occupy the ground to the right of the view. The folds (not visible in this view) affecting the footwall rocks (Kortbreen Formation) are periclinal and are, probably, fault propagation folds developed ahead of splay thrusts rising from a blind basal detachment implying an eastward tectonic transport direction consistent with the steep reverse fault mentioned above.

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The West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya, NW Spitsbergen

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On Brøggerhalvøya, the West Spitsbergen Fold-and-Thrust Belt is exposed over a width of 15 km between the undeformed foreland northeast of Kongsfjorden and the boundary to the Forlandsundet Graben in the west. The Tertiary deformation is characterised by a nappe-stack of nine nappes (Piepjohn et al. 2001; Saalmann & Thiedig 2001, 2002). The lower five nappes in the northeast are dominated by flat-and-ramp geometries which repeat the post-Caledonian succession several times (Garwoodtoppen, Kongsfjorden, Kvadehuken, Kjærfjellet, Ny-Ålesund nappes). In the south and southeast, they are overthrust by four nappes with steeply SW-dipping listric basal thrusts which almost entirely consist of basement rocks (Nielsenfjellet, Bogegga, Trondheimfjella, Moefjellet nappes). From southwest to northeast, the basal thrusts progressively climb up-sequence from the basement into the post-Caledonian cover sequence. The Caledonian basement and the post-Caledonian cover rocks are folded and thrust-faulted together demonstrating the active involvement of the basement in the fold belt deformation.

Although the structure on Brøggerhalvøya is dominated by nappes (Fig. 2), a kilometric-scale NE- to N-vergent large-scale fold structure is developed which is similar in dimensions to the ENE-vergent folds in the segments of the West Spitsbergen Fold-and-Thrust Belt, to the south of Oscar II Land (e.g., Braathen & Bergh 1995; Braathen et al. 1995; von Gosen & Piepjohn 2001; Manby & Lyberis 2001; Piepjohn & von Gosen 2001). This fold structure has been overthrust by the Nielsenfjellet nappe in the central part of the nappe stack (Fig. 2).

The Tertiary deformation on Brøggerhalvøya can be separated into three stages (Piepjohn et al. 2001; Saalmann & Thiedig 2001, 2002): The first stage D1 is represented by thrusting along flats and ramps, predominantly in the post-Caledonian sediments. The second stage D2 is dominated by kilometric-scale folding (F2) of the post-Caledonian sequence, the post-Caledonian cover succession and the D1-thrust sheets. The third stage D3 is characterized by basement-dominated nappes which have been carried along listric thrust planes over the lower D1-part of the nappe stack and have truncated the F2-fold structure. The successive stages of thrusting and folding can be explained by a continuous shortening process or a stepwise evolution.

The tectonic transport of thrust units and the vergences of the folds are directed to the northeast and north which differs from the east-northeast directed transports in the southern continuation of the fold-and-thrust belt in Oscar II Land (Manby & Lyberis 2001). The deviating vergences, despite the originally ENE-directed shortening during D2 also in this area, have been interpreted as result of pre-existing basement topography causing oblique ramping on the sole thrust in Kongsfjorden and buttressing against the Nordfjorden High that was uplifted already in early Tertiary times (Saalmann & Thiedig 2001).

Based on a simple line-length balancing in the nappe-stack to the west of the Schetelig Fault, a shortening from 27 km to 11 km along a cross section through Kjærfjellet and Scheteligfjellet can be estimated (Piepjohn et al. 2001). An appropriate amount of shortening for the basement-dominated nappes has to be added to this figure. The shortening of more than 60% in the Scheteligfjellet cross section which is only one part of the fold belt, represents one of the highest amounts within the entire West Spitsbergen Fold-and-Thrust Belt.

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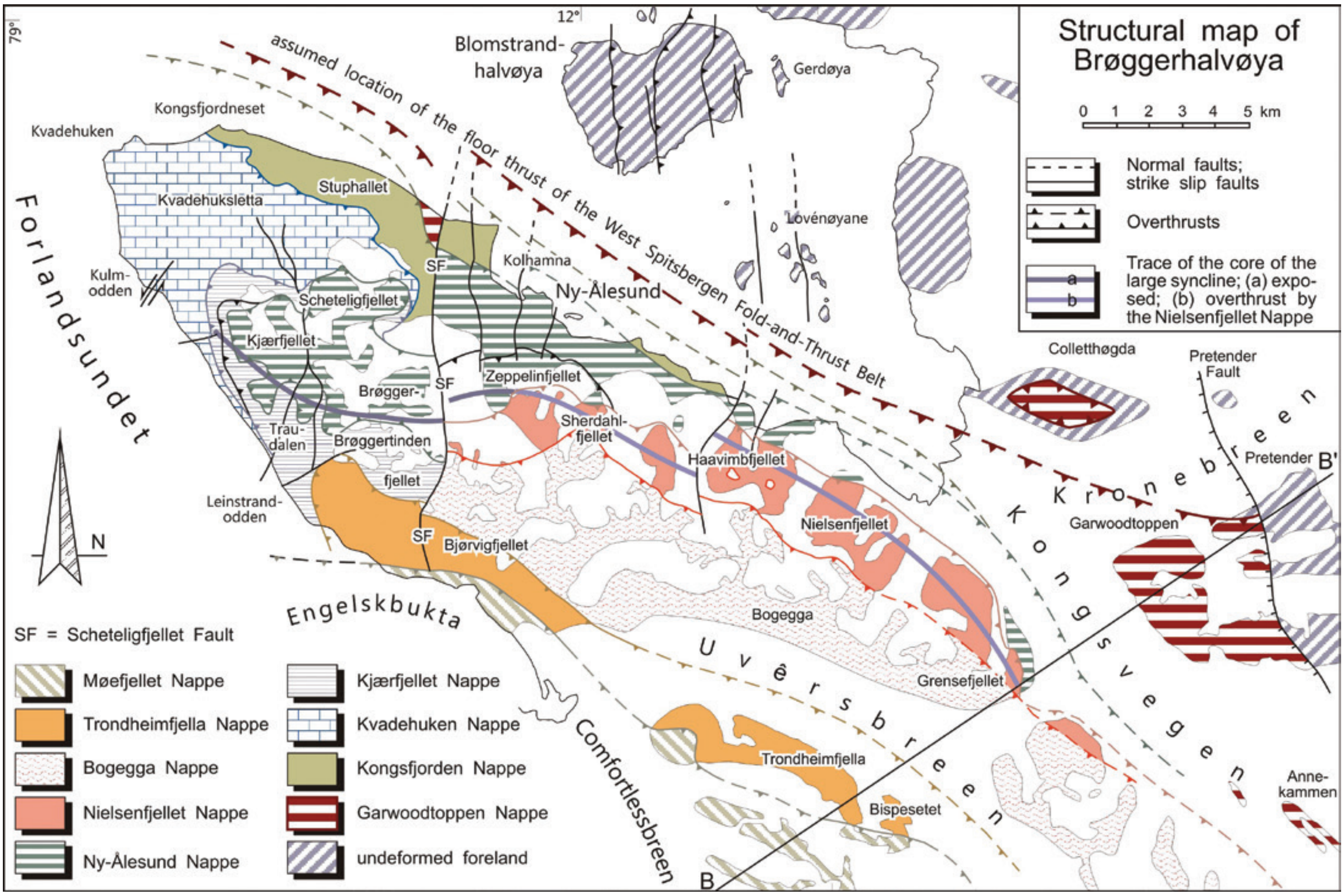

Fig. 1: Structural map of the Brøggerhalvøya area showing the distribution of the nine nappes of the nappe stack of the West Spitsbergen Fold-and-Thrust Belt (Piepjohn et al. 2001).

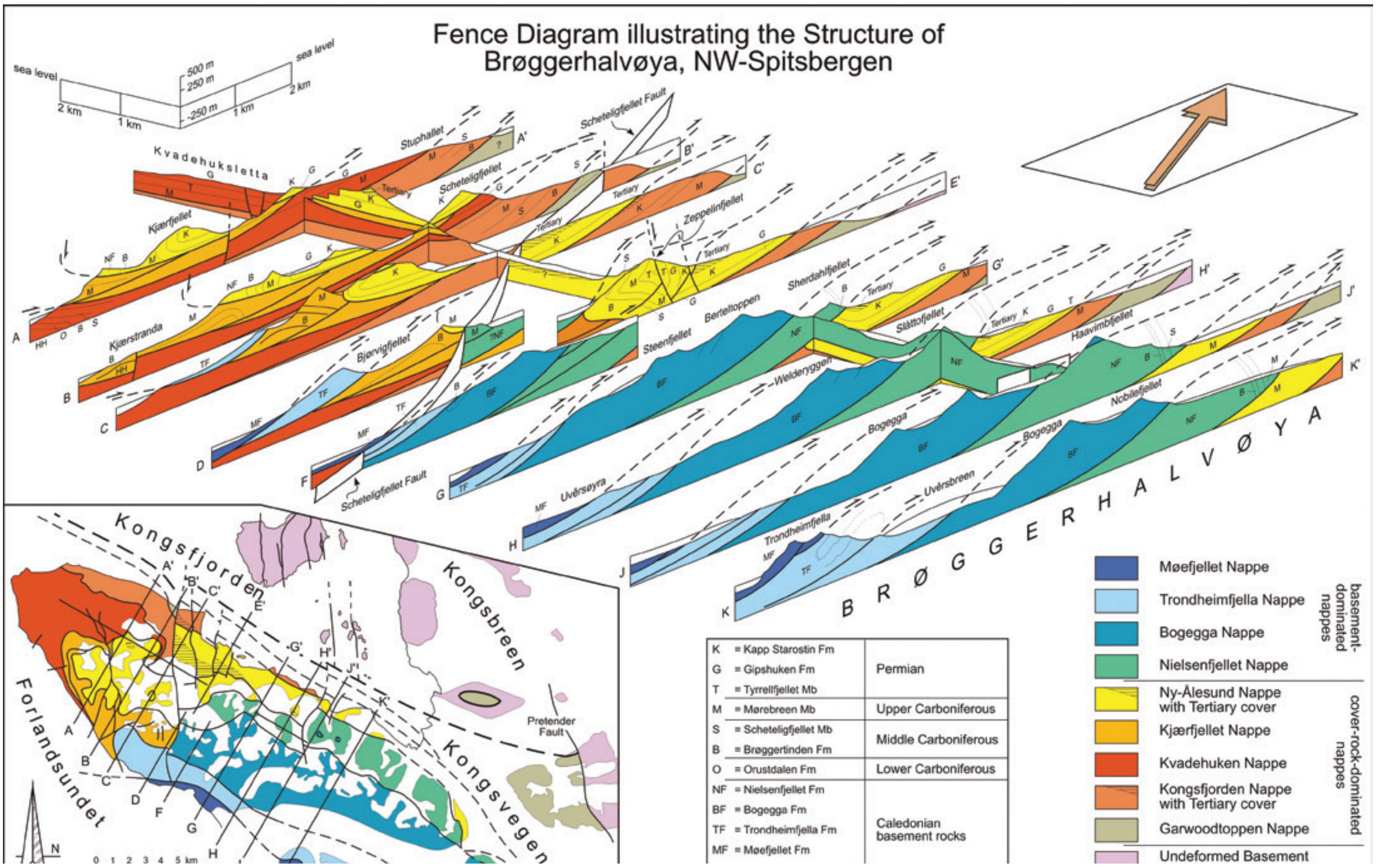

Fig. 2: Fence diagram illustrating the structure of the nappe stack of the West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya (Piepjohn et al. 2001).

Deciphering the tectonic evolution of the Prins Karls Forland – Oscar II Land Caledonide domain of Svalbard

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Understanding the tectonic evolution of the Prins Karls Forland and Oscar II Land Caledonide domain, including Brøgger-halvøya, has been hindered by the superimposition of the Late Cretaceous-Palaeogene West Spitsbergen Fold Belt (WSFB) generated deformation. It is clear that the D1 large scale folding and development of the main penetrative foliation accompanied the Caledonide metamorphism. Whether subsequent folds and associated foliations belong to the Caledonian or the WSFB events is often uncertain largely because they are not associated with any significant thermal resetting of mineral isotopic systems and elude, therefore, determination of their ages. The lack of Late Palaeozoic to Mesozoic rocks throughout most of the area, to aid discrimination of structural relations, adds to these difficulties. The broad lithostratigraphic divisions represented in this domain are summarised in Fig. 1 which also shows the locations of the two cross sections illustrated in Fig. 2. In the northern part of Oscar II Land (OIIL) to Brøggerhalvøya/Kongsvegen it is evident that the WSFB northeast directed folding and thrust faulting has driven the Caledonide metasediments over post-Caledonian rocks. In this area the order of Caledonian thrust nappe stacking has been reversed where the low grade, Comfortlessbreen to Moefjel-let rock slices are thrust over the higher grade Kongsvegen Group (Fig 2 & Fig 3) rocks suggesting significant involvement of the Caledonide rocks in the WSFB deformation. In St. Jonsfjorden the vergence of many structures is dominantly to the east (Figs. 4A & B). The intensity of deformation observable is, however, strongly dependent on rock type and a range of late extensional faults are often seen superimposed on the contractional structures in the less competetent rocks. Significantly, this area contains rem-nants of a subduction zone complex (Motalafjellet blueschists and eclogite pods) as well as other continental margin magmatic rocks.

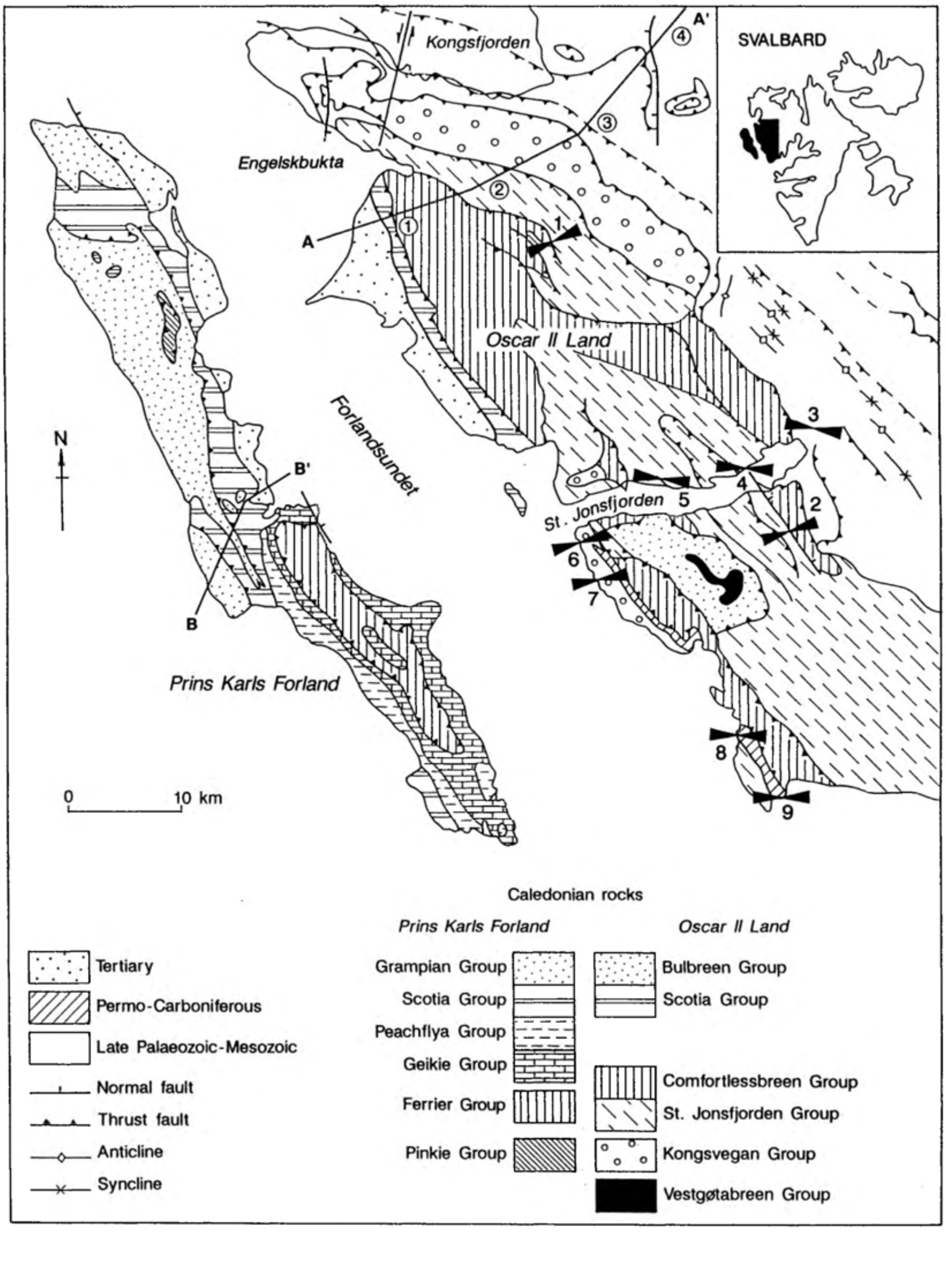

Fig. 1: Simplified geological map of the Prins Karls Forland – Oscar II Land domain showing location of two cross sections in Fig. 2.

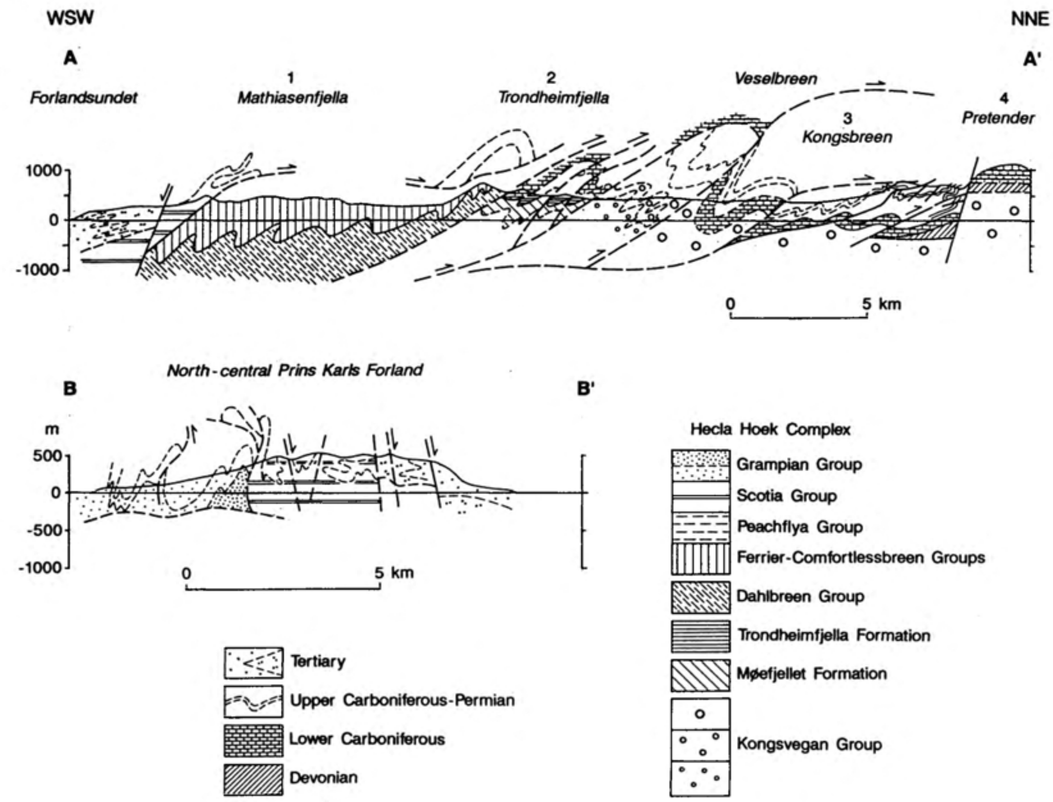

Fig. 2: Cross sections of Prins Karls Forland and northern Oscar II Land to show vergence directions of Caledonian structures involved in the West Spitsbergen Fold Belt deformation.

From outer St. Jonsfjorden southward along the western margin of southern OIIL the vergence of the major Caledonide structural features is, in contrast, to the west. In Prins Karls Forland (PKF) it appears that the Caledonide tectonic transport direction is also to the west (see Manby 1986 & Figs. 2 & 5). Later F2 folds here also have a westerly vergence (Fig. 6). In northern PKF the low-grade (biotite) Grampian and Scotia Groups are overthrust by narrow slices of higher grade epidote-amphibolite facies rocks with metadolerites and scapolite bearing metasediments (Figs. 6A & B: Manby 1983a). South and North Central PKF are separated by a late brittle dextral shear zone (Morris 1979) probably related to the opening of the Eurasian Basin.

Southern PKF like OIIL contains tillites that have been correlated with others in Nordenskiöld Land and Wedel Jarlsberg Land (Harland et al. 1979) that are interpreted to differ from those of Ny-Friesland – Nordaustlandet. It has been on this basis that the two regions are interpreted to have belonged to widely disparate terranes in Pre-Early Caledonian time (Harland & Wright 1979). The PKF-OIIL domain is commonly considered to represent a discrete terrane, separated from its neighbours by a fault zone roughly corresponding to the main thrust zone carrying the Caledonide rocks over the post-Caledonian rocks to the east. The presence of amphibolite facies rocks with blocks of migmatite in the Kongsvegen thrust nappe on Brøggerhalvøya as well as the epidote amphibolite facies rocks of PKF (Pinkie Group, Manby 1986) compare with the biotite and garnet biotite bearing metapelites of the inner Kongsfjorden (Ossian Sarsfjellet) and northwards through the migmatized successions of Haakon VII land and Albert Land where the effects of the WSFB deformation not recognisable. The palaeomagnetic, magmatic and isotopic affinities of selected limestones and metadolerites from the PKF – OIIL, the Northwestern and Eastern (Nordaustlandet and Ny-Friesland) domains of Svalbard are currently under investigation in an attempt establish the relationships amongst these apparently diverse crustal blocks during Caledonian time.

Fig. 3: Biotite hornblende gneiss Steenfjellet, Engelskbukta, Oscar II Land.

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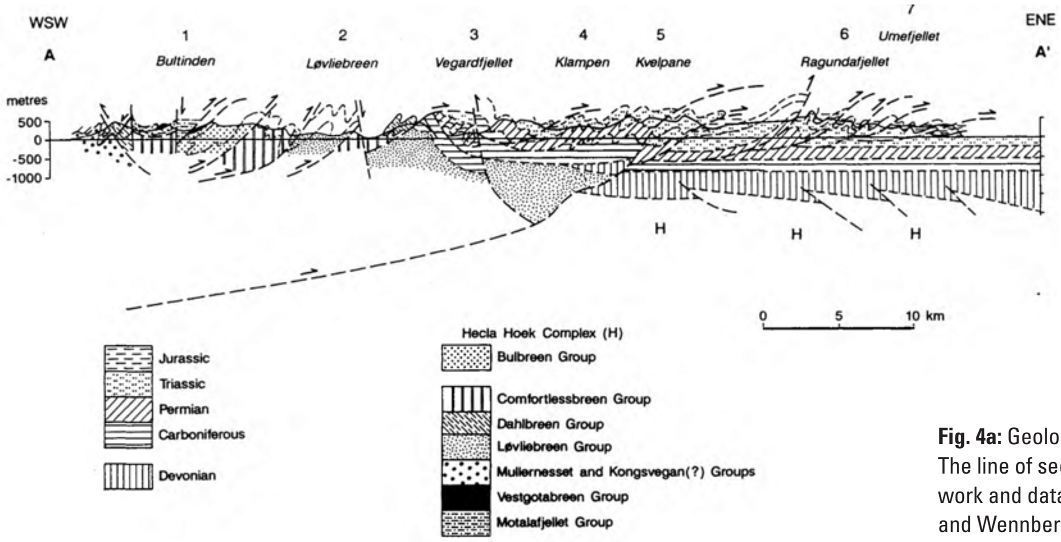

Fig. 4a: Geological cross section of Oscar II Land. The line of section is shown in Fig. 4b. Based on work and data from Morris (1988), Bergh (1990) and Wennberg et al. (1994).

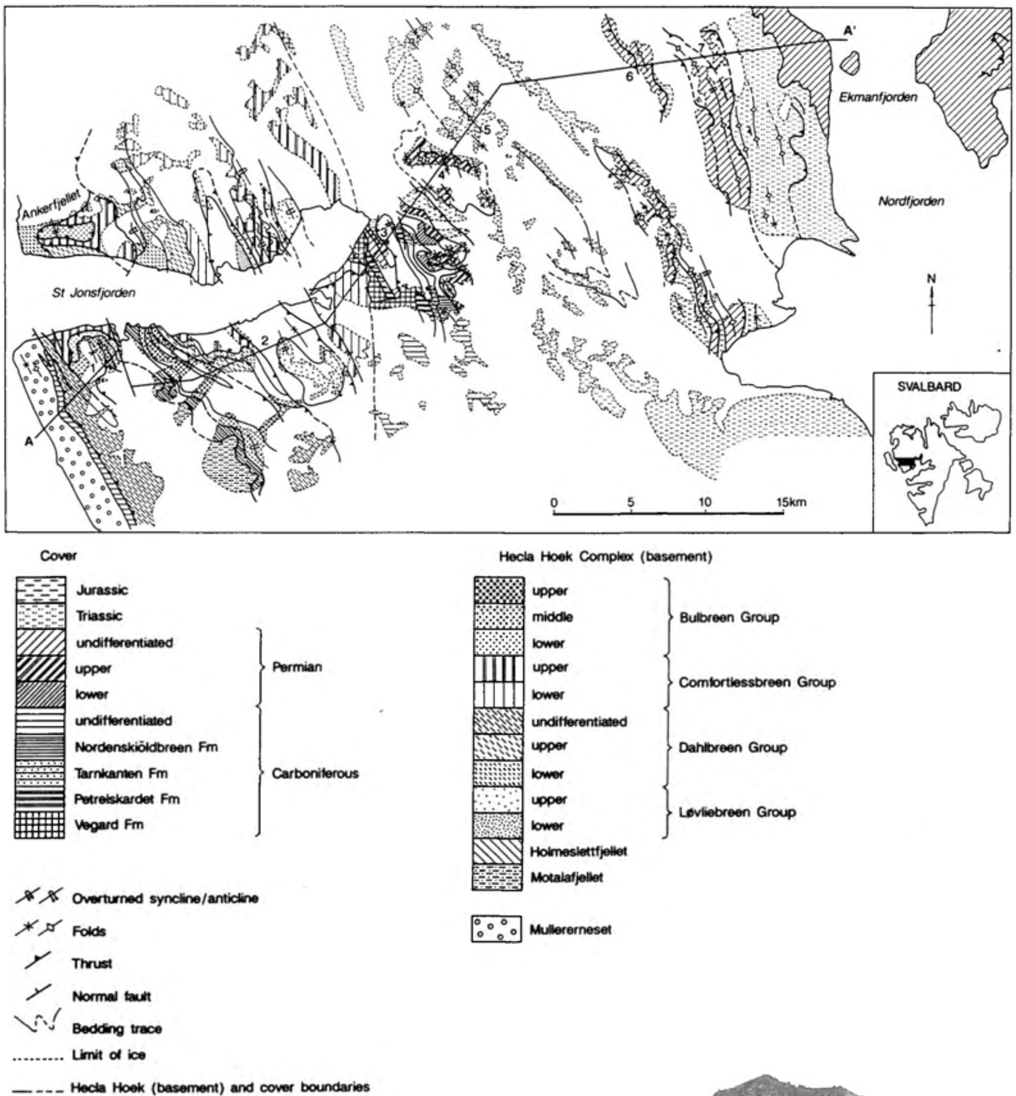

Fig. 4b: Simplified geological map of the St. Jonsfjorden area showing line of section in Fig 4a.

Fig. 5a: View of NW Tvihyrningen, Central Prins Karls Forland, to general westerly vergent main folds and thrusts and the development of a triangle zone in the centre of the field of view. From Manby 1986.

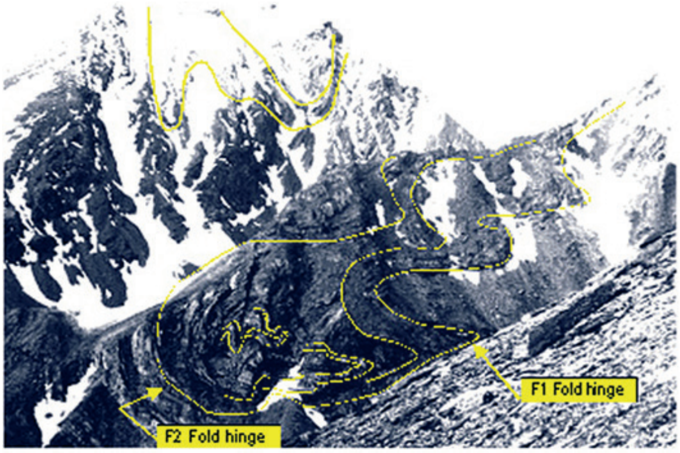

Fig. 5b: F1 – F2 folding of Grampian Group, western slopes of Jessiefjellet, PKF looking North

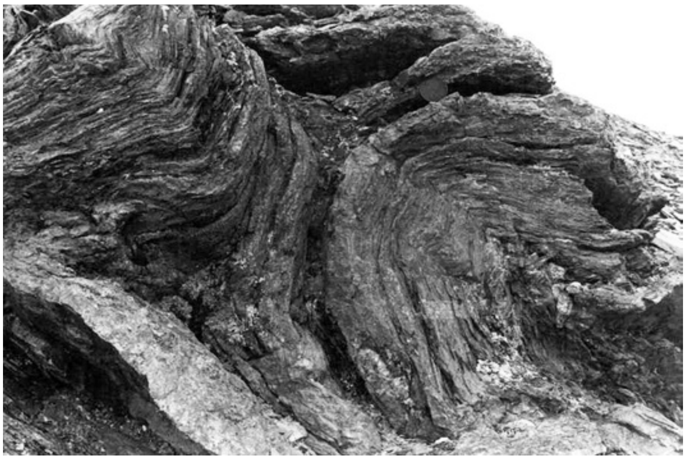

Fig. 6: West vergent F2 crenulation fold on the slopes of East Central PKF.

Integration of palaeomagnetic, isotopic and structural data to understand Svalbard Caledonian Terranes assemblage – PALMAG project 2012-2015

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Aim of the project

The main aim of the PALMAG project is to quantify time and place of the assembly of Caledonian terranes of Svalbard from integrated palaeomagnetic-isotopic-structural signatures. This will provide data to reconstruct the geotectonic events which led to formation of the northern branch of the Caledonides. Special attention is being paid to tracing the linkage between isotopic ages and secondary NRM (Natural Remanent Magnetisation) overprints of the terranes. PT-t paths for all terranes are being drawn and their exhumation/cooling rates are being estimated. The time of activity of the large scale faults bounding the terranes are being dated.

Methods

Both isotopic and palaeomagnetic records are based on the rule of 'closure process' – the critical Curie temperature below which the system become stable. The dated moment of the isotopic couple passing through the Curie point, during regional uplift can be related to recording of the NRM vector with defined unblocking temperatures. Using different isotopic systems we can achieve the rate of uplift of the crustal unit. By dating isotopically the acquisition of the secondary NRM components the rate of movements of the crustal unit relative to magnetic pole can be obtained. Published accounts of the palaeomagnetic and isotopic records of Caledonide rocks of Svalbard have concentrated largely on only a part of any particular terrane. This project proposes, for the first time, to establish the records for all of the Caledonian terranes of Svalbard (Fig. 1) from a variety of techniques using the improved methodologies currently available. This approach will allow consistent time constraints to be erected for comparing the thermal histories of the various terranes, assessing their plate settings and their possible spatial relations. In particular it is proposed to sample the major bounding fault zones of the terranes. These fault zones are frequently characterized by mylonites which, with the exception of some preliminary data for the Billefiorden Fault Zone, have yet to be robustly dated. Recent advances in UV laser ablation $^{40}Ar/^{39}Ar$ techniques for in situ mica crystals from mylonites have proven a reliable and powerful method for dating ancient fault zones.

A wide spectrum of analyses will being conducted including: the palaeomagnetic demagnetization procedures; the identification of ferromagnetic minerals by magnetic/microscopic/SEM/microprobe methods the PT-t conditions determinations in metamorphic rocks by Laser Ablation ICP Mass Spectrometry (LA-ICP-MS), Raman Spectrometry and U/Pb, Ar/Ar isotopic determinations.

Acknowledgements:

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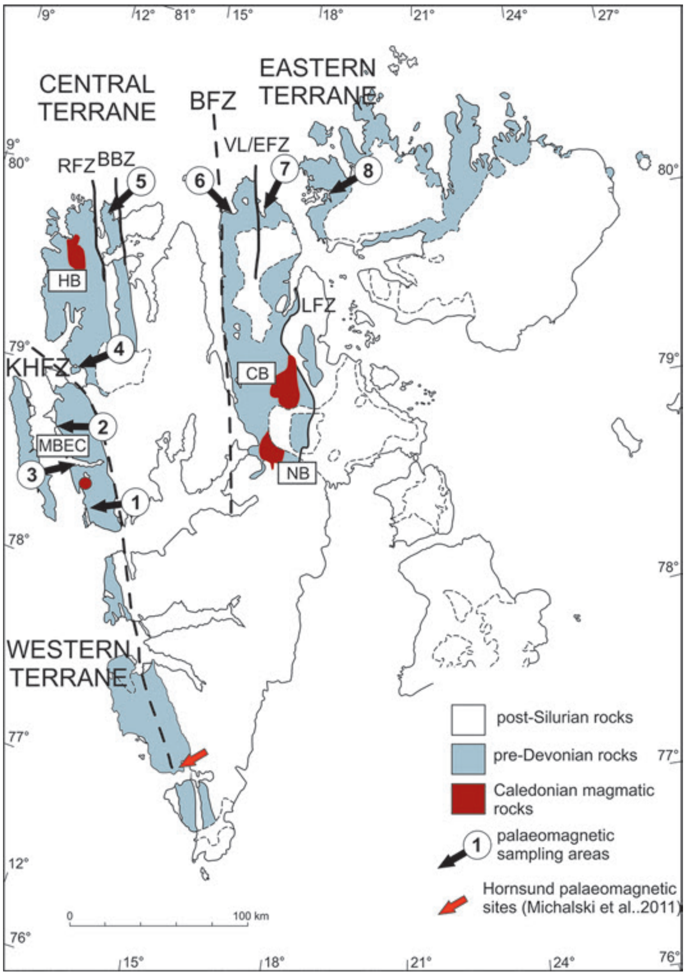

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Fig. 1: Location of PALMAG project sampling areas in Svalbard.
Western Terrane: 1 – Prins Karls Forland, 2 – St Jonsfjorden, 3 – western coast of Oscar II Land.
Central Terrane: 4 – Kongsfjorden, 5 – Krossfjorden, 6 - Raudfjorden.
Eastern Terrane: 7 – Mosselbukta, 8 – Sorgfjorden, 9 – Lomfjorden, 10 - Murchisonfjorden.
Fault zones : (KHFZ) Kongsfjorden – Hansbreen; (RFZ) Raud-fjorden; (BBZ) Breibogen; (BFZ) Billefjorden; (VL/EFZ) Veteranen Line /Eolussletta Fault Zone; (LFZ) Lomfjorden.
Magmatic Caledonian complexes: MBEC – Motalafjella blueschist – eclogite complex, HB - Hornemantoppen Batholith, NB - Nordenskiöldbreen Batholith, CB - Chydeniusbreen Batholith.

Palaeomagnetic method as the tool for reconstructing Proterozoic and Palaeozoic palaeogeography of Svalbard

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Despite the limitations of resolution and inherent analytical difficulties such as the determining the age of formation of the secondary carriers and formation of new magnetic carriers during the process of thermal demagnetisation, palaeomagnetism remains the only numerical method for quantifying the palaeoposition of the crustal units.

Palaeomagnetic studies in Svalbard have focused on defining final amalgamation of Svalbard with continental Europe/Baltica or reconstructing relative palaeopositions of the Caledonian terranes of Svalbard.

The present palaeomagnetic database of Svalbard confirms the lack of major movements (within limitations of resolution of the method) between Spitsbergen and continental Europe from Devonian time (*e.g.* Lovlie et al., 1984; Nawrocki, 1994) and amalgamation of the Central Caledonian Terrane (*sensu* Harland 1997) with Baltica from Silurian time onward (Michalski et al. 2012; Fig. 1). Maloof et a.l (2006) presented an interpretation of the Neoproterozoic palaeoposition of Svalbard based on palaeomagnetic directions from Akademikerbreen Group - Eastern Caledonian Terrane (*sensu* Harland 2007). The primary origin of some of their palaeomagnetic directions were questioned, however, by Michalski et al. (2012).

Actual priorities in palaeomagnetic investigations of Proterozoic and Palaeozoic successions of Svalbard can be defined as follows:

- Correlating Caledonian isotopic with palaeomagnetic records to establish the timing of pre-Devonian secondary magnetic overprints;
- Investigation of the primary Proterozoic to Lower Palaeozoic palaeomagnetic record of crustal units in Svalbard that appear to have escaped thermal or significant tectonic resetting during Caledonian time;
- Reconstruction of the relative pre–Devonian palaeopositions of the Caledonian terranes of Svalbard after the Baltica/Laurentia collision and the palaeogeography of the Iapetus Ocean system;
- Distinguishing relative roles of the Caledonian/Svalbardian/Eurekan tectonic events in modifying the geometry of tectonic structures of the pre-Carboniferous stratigraphic units of Svalbard (see applications of palaeomagnetic method to dating/recognition of tectonic events in Hornsund – Figs. 2,3).

Fig 1: The positions of palaeopoles obtained from the Cambrian Slaklidalen Fm. (Michalski et al., 2012) relative to the reference Apparent Polar Wander Paths of Baltica and Laurentia. The palaeopole, calculated from the most stable palaeomagnetic component of Slaklidalen Fm. (HORNMVGP), fits exactly the Silurian sector of the Baltica reference path suggesting lack of significant movements between the Central Svalbard Terrane (*sensu* Harland, 1997) and Baltica from Silurian time; palaeopoles of Baltica (grey ovals) and Laurentia (white ovals) are presented with their ovals of 95% confidence; the age of the sectors of reference paths is given.

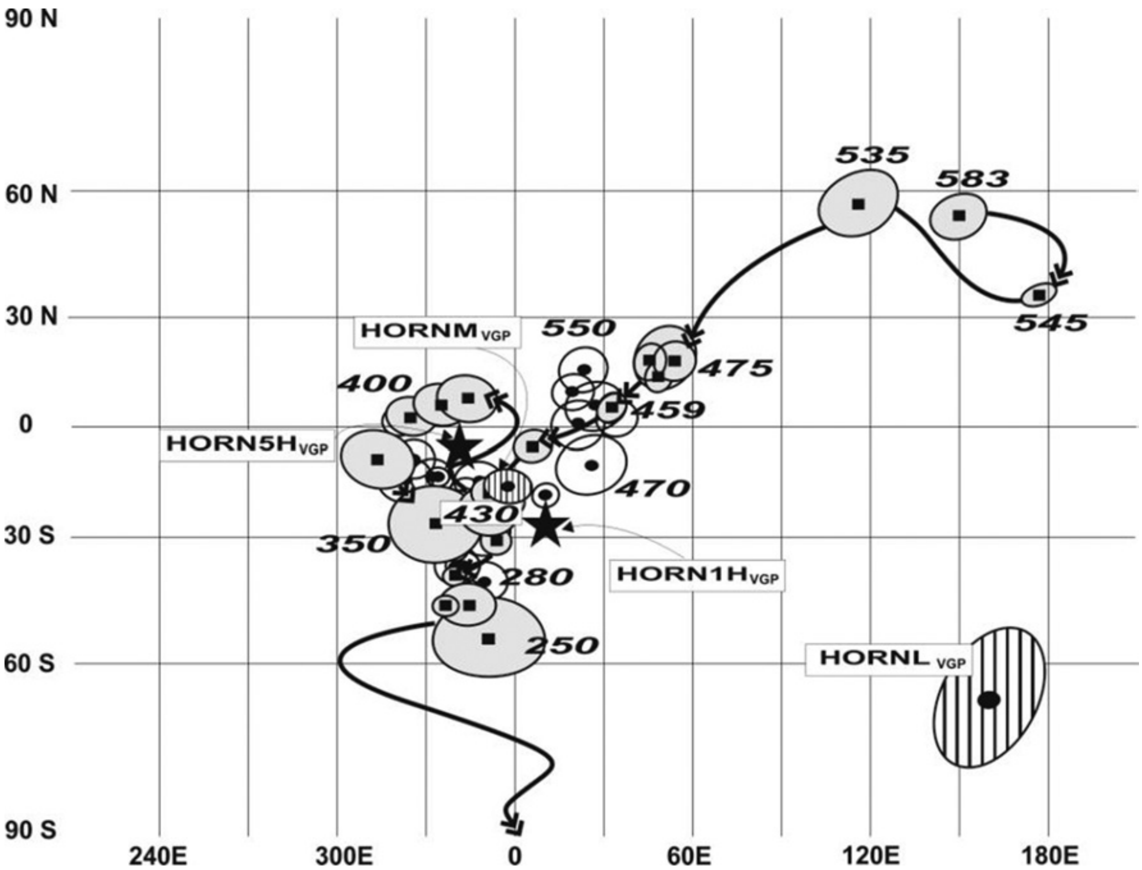
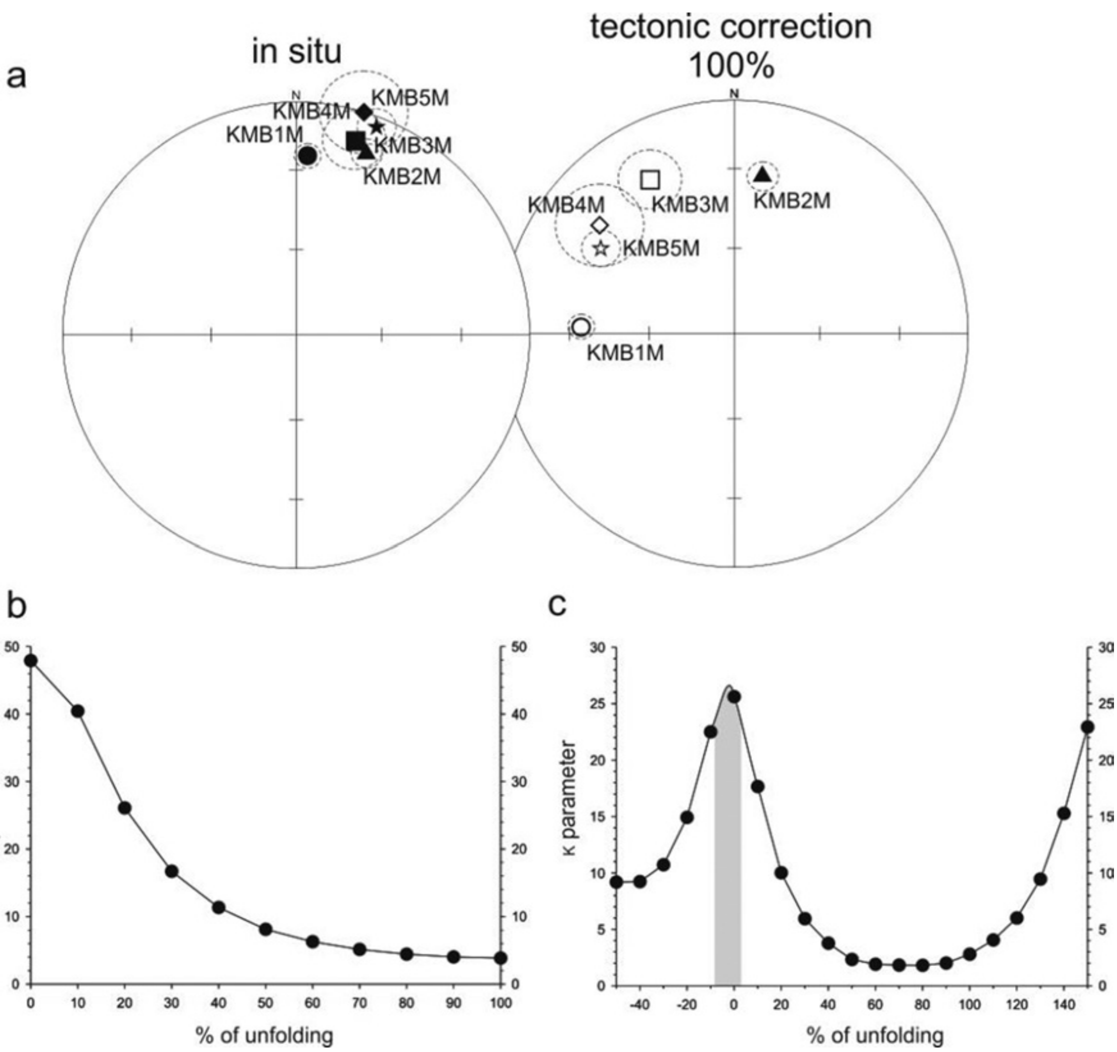


Fig 2: Results of the fold test conducted in Slaklidalen Fm. (Michalski et al. 2012). Post-folding origin of Silurian HORNM component implies that the geometry of Sofiekammen fold has not been significantly modified by the Svalbardian or Eurekan events. It is evident, therefore, that the Sofiekammen syncline, its S1 foliation and related shearing fabrics are entirely Caledonian in origin. (a) Equal area projections of HORNM site means in in situ and after 100 % tectonic correction positions. (b) Graph presenting changes of the κ precision parameter of the population of the HORNM site means in the course of the unfolding procedure. (c) Inclination only test for HORNM site means according to the procedure of Enkin & Watson (1996).



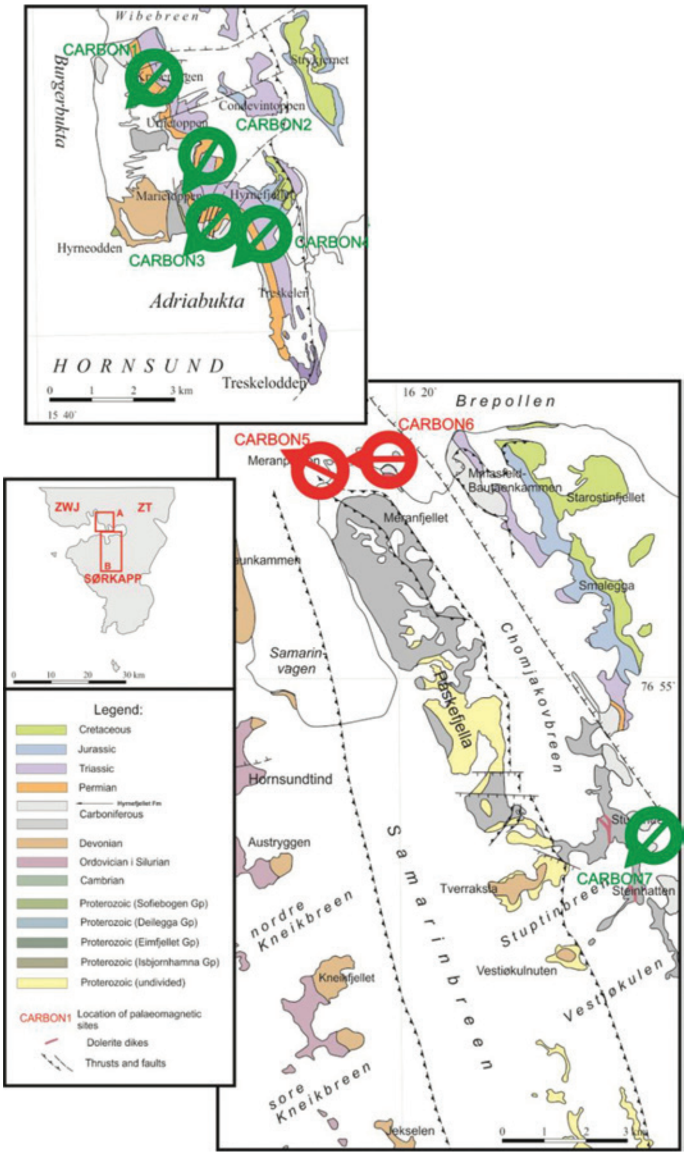


Fig 3: Change of the declination parameter of the HORNM/H early diagenetic component of the Carboniferous Hyrnefjellet Fm. in palaeomagnetic sites located in the area of Hornsund. Declination is clearly modified in the sites located within the axis of the Hornsund fjord (K. Michalski, unpublished data).

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Origin of ferromagnetic minerals from the St. Jonsfjorden metadolerite, Western Spitsbergen

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Metadolerites within the Precambran calcareous metapelites and marbles in the St. Jonsfjorden area were selected for mineralogical and palaeomagnetic study. The protoliths of the examined metadolerites were small Neoproterozoic dolerite sills/dykes intruded into the Precambrian successions which were subjected to greenschist facies metamorphism during the Caledonian Orogeny (Ohta 1985). This presentation examines the origin of the ferromagnetic phases in the metadolerites, which provide a palaeomagnetic record for these rocks.

Petrography of the metadolerites

The metadolerites from St. Jonsfjorden occur as lenses, up to 25 m in thickness, within marbles and calcareous metapelites, recrystallised during greenschist facies metamorphism. Their texture varied from medium to coarse-grained. Primary magmatic textures, ranging from doleritic to gabbroic, were well preserved. Only marginal parts of metadolerite bodies are schistose in texture (Ohta 1985). The examined metadolerites contain clinopyroxene, albite, biotite, apatite, pyrrhotite, and Fe-Ti oxides represented by ilmenite and titanite pseudomorphs after magnetite (Fig. 1A-B). The fine-grained groundmass was highly recrystallised during greenschist facies metamorphism and consists of fine-grained intergrowths of albite, actinolite, epidote, chlorite, titanite, anatase, biotite, quartz, Ca-Mg carbonates, and newly formed sulphides (Fig. 1B). The sulphide aggregates are commonly intergrown with the late metamorphic phases and consist of pyrrhotite, pentlandite, chalcopyrite, sphalerite, and pyrite. The enhanced H_2O activity is recorded by occurrences of covellite and goethite.

The primary magmatic assemblages were highly altered during the metamorphism, although primary igneous textures of the metadolerites are well-preserved. The clinopyroxenes with the composition Wo48.7-45.9En41.3-36.2Fs15.9-10.4 are partly replaced by actinolite and green hornblende. The plagioclase phenocrysts revealed composition close to the pure albite (An97.6Or0.14An0.26Cs0.03), despite of the fact that the An

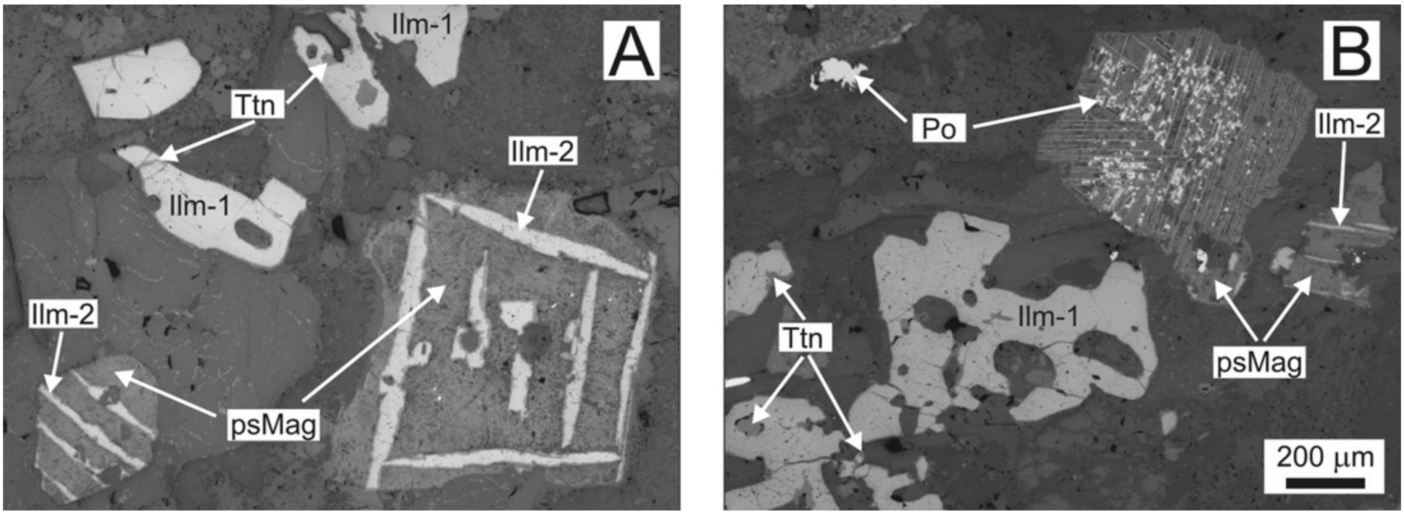

Fig. 1: Primary (magmatic stage) Fe-Ti oxide association from the St. Jonsfjorden metadolerite.
A) Two generations of ilmenite consist of anhedral grains of altered ilmenite (Ilm-1) and oxy-exsolved ilmenite (Ilm-2) occurred as thick trellis within titanite pseudomorph after magnetite (psMag). Sample G-3.
B) Magmatic ilmenite (Ilm-1) and titanite pseudomorph after primary magnetite (psMag) that containing fine intergrowths of the pyrrhotite (Po). Titanite (Ttn) partially replaces ilmenite. Sample G-1. Reflected light images, plane polarised light, the same magnification of both images.

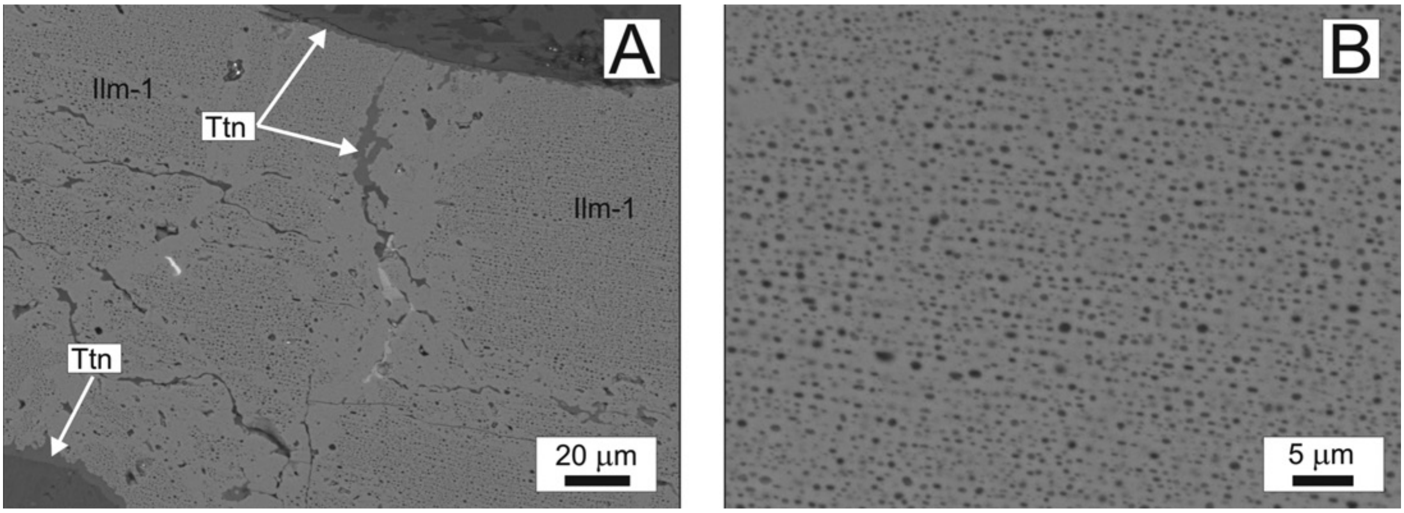

Fig. 2: Texture of altered ilmenite (Ilm-1) grain.
A) Ilmenite partly replaced by titanite (Ttn), and containing small intergrowths of Fe-sulphides and products of their oxidation to Fe-oxyhydroxides (bright intergrowths). Sample G-7.
B) Magnified fragment of ilmenite shows shape and distribution of small holes (black dots) probably developed after dissolution of hematite. Sample G-7. Backscattered electron image (BSE), 15 keV, 1nA.

content in unaltered dolerites is commonly greater than 50 mole %. The biotite grains, which in some samples are visible macroscopically, also belong to metamorphic assemblage, as indicated by occurrences of small biotite flakes of the same chemical composition within recrystallised groundmass. The biotite growth was probably the result of the breakdown of the Ti-magnetite into titanite and the recrystallisation of the K-bearing ternary feldspars from the dolerite groundmass.

The origin of oxide and sulphide ferromagnetic associations

The ferromagnetic mineral associations consist of ilmenite, usually overgrown by titanite, anatase(?), goethite, pyrrhotite, chalcopyrite, pentlandite, and pyrite (Fig. 1A-B). The ferromagnetic phases which evolved during the magmatic stage were recrystallised during greenschist facies metamorphism accompanied by a high activity of CO_2-rich aqueous fluids expelled from the host rocks. During these processes the whole Ti-rich magnetite and oxy-exsolved hematite in ilmenite have been transformed into titanite or have been dissolved (Fig. 2A-B). The textures of sulphide aggregates and their intergrowths with late silicates suggest that they have also recrystallised. The metamorphic processes have completely reset the Ti-rich magnetite and hematite phases within the metadolerite, so it should be expected that paleomagnetic data record the geotectonic history of the Western Svalbard from Late Silurian time onwards. The presented succession scheme summarises the evolution of the ferromagnetic associations observed in the St. Jonsfjorden metadolerite. This record starting from the time of their crystallisation (Neoproterozoic), through greenschist facies metamorphism (Late Silurian), to their transformation during tectonic deformation of the Western Spitsbergen (Paleocene-Eocene).

Acknowledgments:

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Torellian basement in south-west Svalbard: The missing piece between the Pearya Terrane and the Timanides?

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Svalbard's Caledonian crystalline basement contains several Meso- and Neoproterozoic metamorphic terranes of predominantly Svecofennian (1.9-1.75 Ga) and Grenvillian-Sveconorwegian (1000-850 Ma) age, respectively. Scarce 660-600 Ma ages, reflecting Late Neoproterozoic magmatic and metamorphic events, are known so far from NW Spitsbergen (Richarddalen Complex; Gromet & Gee 1998) and SW Spitsbergen (Isbjørnhamna and Eimfjellet groups; Majka et al. 2008). Current fieldwork and petrological investigations indicate that Late Neoproterozoic metamorphic rocks are much more widespread in Wedel Jarlsberg Land (SW Spitsbergen).

The southern part of Wedel Jarlsberg Land is composed of two metamorphic terranes (SW and NE) juxtaposed by the NW-SE trending regional, Caledonian Vimsodden-Kosibapasset Shear Zone (Mazur et al. 2009). The SW terrane contains the amphibolite facies Isbjørnhamna Group and the greenschist-amphibolite facies Eimfjellet Group (Czerny et al. 1993; Majka et al. 2010). The age of their metamorphism is 643±9 Ma (U-Th-Pb monazite dating; Majka et al. 2008), additionally supported by 616-575 Ma Ar-Ar cooling ages (Manecki et al. 1998) for hornblende (Eimfjellet Group) and muscovite (Isbjørnhamna Gr.), respectively. Dating of zircons and monazites from the pegmatite occurring within the Isbjørnhamna Group revealed ages in the range of 660-650 Ma (Majka et al. 2012). Recent ion microprobe U-Pb zircon dating of gabbros and rhyolites from the Eimfjellet Group confirmed their ca. 1.2 Ga protolith age (Larionov, unpublished). However, detrital zircon laser abalation U-Pb dating from the underlying Isbjørnhamna Group revealed ages ranging from 695 to 2789 Ma (<10% discordant results; Tebenkov unpublished). These results combined with the age of metamorphism and the fact that both units were metamorphosed together lead to the conclusion that the Eimfjellet Group is thrust onto the Isbjørnhamna Group. It is also supported by the field evidence, *i.e.* the occurrence of phyllonitic schist at the boundary of the two groups. Both units were subsequently subjected to the low grade Caledonian metamorphism.

The regional scale Torellian unconformity was recognised in the lithostratigraphic profile of the NW domain of Wedel Jarlsberg Land (Fig.1; Bjørnerud 1990; Czerny et al 1993). The unconformity occurs at the bottom of the Sofiebogen Group and cuts the underlying Deilegga Group rocks. U-Th-Pb dating of detrital and metamorphic monazites occurring in the clastic rocks on both sides of the unconformity revealed that the Torellian unconformity post-dates the c. 640 Ma event. The Sofiebogen Group lies structurally below the Kapp Lyell conglomerate of glacio-marine origin that is believed to be of Cryogenian age (850-635 Ma). Consequently, the likely interpretation is that Kapp Lyell tilloids were tectonically emplaced on top of the Sofiebogen Group.

Fieldwork in the north-easternermost part of Wedel Jarlsberg Land revealed that the Magnethøgda Group, known so far as a complex of augen gneisses, arkosic quartzites, phyllites and marbles, is actually built of mostly meta-igneous rocks. These meta-igneous rocks (here Berzeliuseggene Igneous Suite) are thrust over the lower-grade metasediments belonging to both the Deilegga and Sofiebogen groups. Ion microprobe U-Pb dating of zircons from augen gneisses revealed 950±5 Ma igneous and 635±10 Ma metamorphic ages, respectively. Moreover, SIMS U-Pb dating of zircons from the pegmatite cutting the gneisses revealed ca. 660 Ma age. In terms of metamorphism, this unit was subjected to the amphibolite facies event (at 635 Ma?) prior to the Caledonian high-pressure-low-temperature event (see Kośmińska et al., this volume).

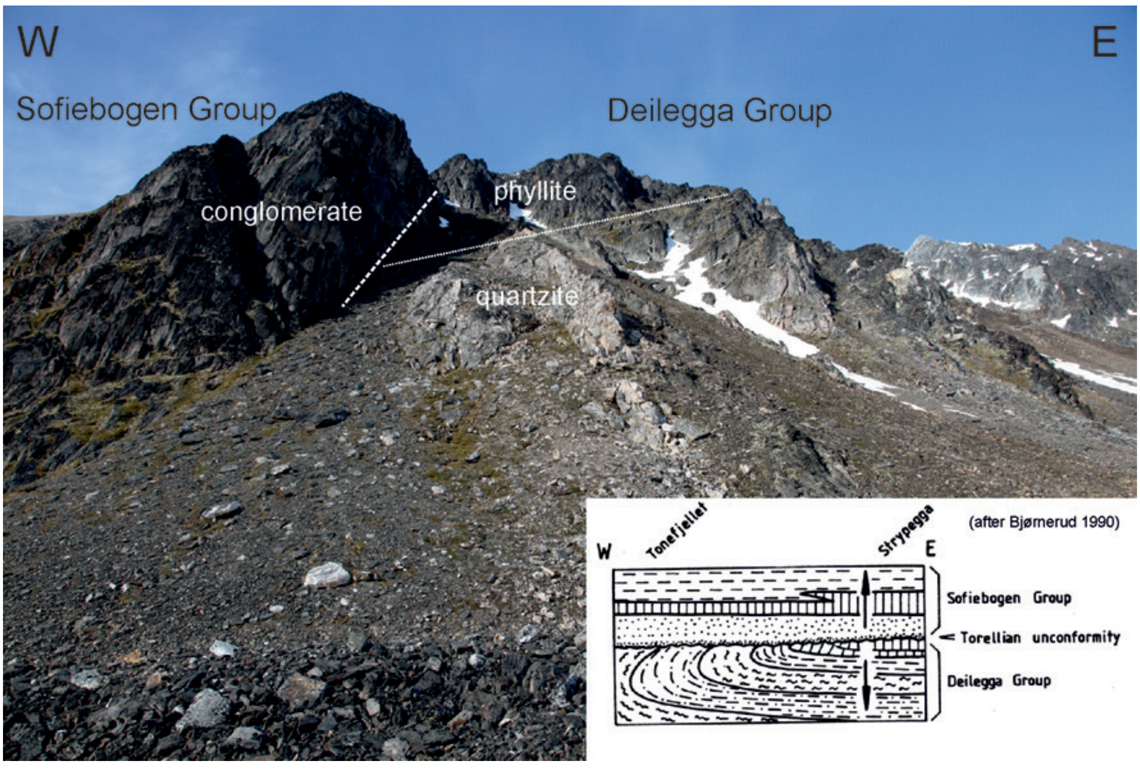

Fig. 1: View on the southern slopes of Solheimfjellet. Dashed line marks the Torellian unconformity. Inset sketch shows simplified relationships between the Deilegga and Sofiebogen groups (after Bjørnerud 1990).

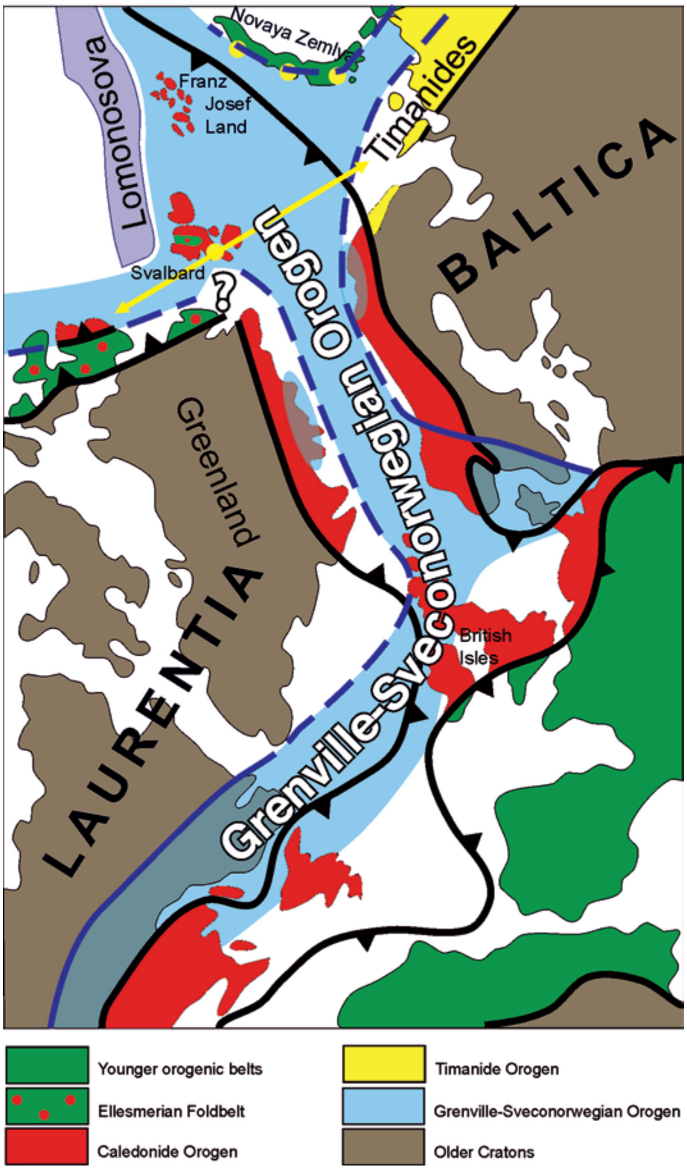

Fig. 2: Reconstruction of the late Mesozoic North Atlantic Caledonides (after Lorenz et al. 2012, modified). Yellow arrow shows possible Pearya – western Svalbard – Timanides connection.

The widespread occurrence of ca. 640 Ma metamorphic rocks in Wedel Jarlsberg Land as well as the presence of the unconformity of slightly younger age indicate a significant role of this Late Neoproterozoic, tectonometamorphic event in the geological history of SW Svalbard. We propose to call this event the Torellian Orogeny originating from the name of the unconformity, which is recognised in the metamorphic basement of not only Wedel Jarlsberg Land, but also in Sørkapp Land and Nordenskiöld Land. Evidence of the Torellian Orogeny in southwestern Svalbard calls for the revision of Neoproterozoic plate tectonic reconstructions for the circum-Arctic region. The most straight-forward explanation of tectonic setting for the Torellian event is the linkage with the Timanide belt of northeastern Europe. This interpretation has two important implications. Firstly, the Torellian orogeny must have occurred before the opening of Iapetus Ocean, since Svalbard is separated from Europe by the Caledonian suture (*e.g.* Gee & Tebenkov 2004). Secondly, such a linkage between southwestern Svalbard and the Timanides excludes the possibility of the large-scale early Palaeozoic rotation of Baltica, as has been proposed by some authors.

For many years (Gee & Tebenkov 2004), the tectonostratigraphy of southwestern Svalbard has been related to the Pearya Terrane of northern Ellesmere Island, where Mesoproterozoic basement is overlain by Neoproterozoic successions. The latter are divided into two units, perhaps separated by an unconformity, and covered by early Palaeozoic strata. The correlation of southwestern Svalbard with both the Timanides and the Pearya Terrane implies that the late Neoproterozoic orogenic belt could have continued from northeastern Europe via northern Greenland to the Canadian Arctic (current coordinates) and westwards beneath the Sverdrup Basin (Fig.2.).

Acknowledgements:

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New occurrences of high-pressure metamorphic rocks in the Caledonian basement of south-west Svalbard

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Until recently, only two occurrences of clearly high-pressure (HP) lithologies were known within the Svalbard's Caledonides (Fig. 1). The Richarddalen Complex (Biskayerhalvøya area) comprises high-pressure/low-temperature (HP/HT) eclogites, while high-pressure/low-temperature (HP/LT) blueschists and eclogites occur within the Vestgötabreen Complex (Motalafjella area). The subjects of this study are previously unrecognized HP rocks in the Caledonian basement of Nordenskiöld Land and Wedel Jarlsberg Land (Antoniabreen area).

In Nordenskiöld Land, recent investigations established the presence of blueschists. They form isolated bodies, enclosed within metasediments. These blueschists are strongly retrogressed. However, remnants of ferroglaucophane and phengite survived the retrogression. Blueschists consist mainly of garnet and amphibole. Garnet shows gradual, chemical zonation. Its composition varies from $Alm_{62}Prp_{0}Grs_{36}Sps_{2}$ in the rims to $Alm_{49}Prp_{1}Grs_{33}Sps_{17}$ in the cores. The pressure-temperature (P-T) conditions were estimated using the Perple_X software in the NCKFMMnASHTO system, assuming water and silicon saturated conditions. P-T estimates based on garnet and phengite compositional isopleths indicate peak metamorphic conditions at ca. 480°C and 20 kbar. The calculated pseudosection constrains the stability field of the mineral assemblage chlorite + phengite + actinolite + ferroglaucophane + garnet + sphene at HP/LT conditions.

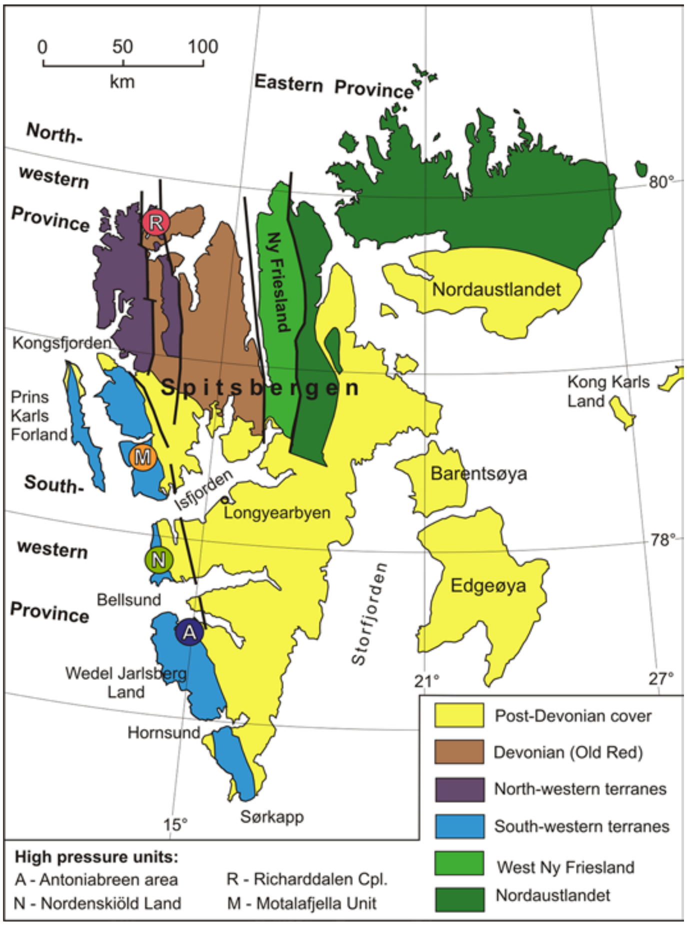

Fig 1: Geological map of Svalbard with high pressure rocks occurrences marked (modified, after Gee et al. 2008).

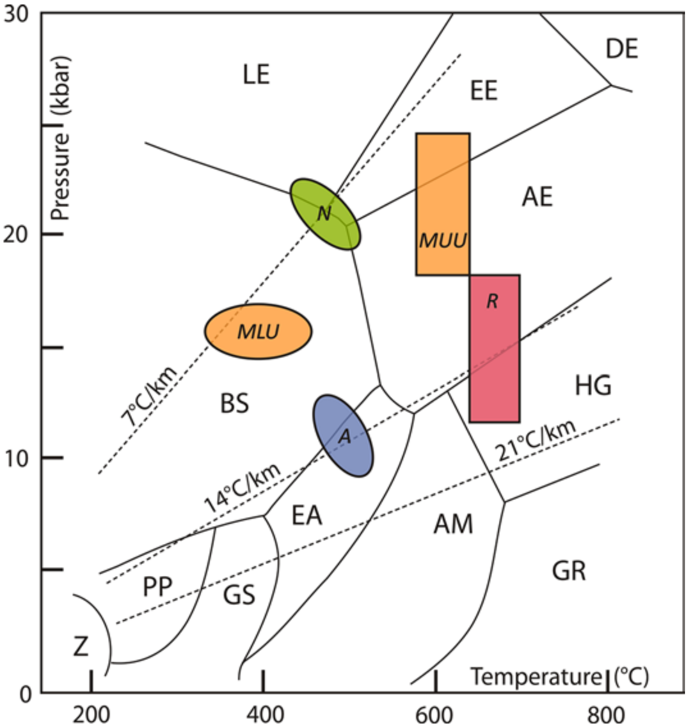

Fig 2: P-T conditions for HP rocks of Svalbard: AA-Antoniabreen Area, MLU-Motalafjella Lower Unit (Agard et al. 2005), MUU-Motalafjella Upper Unit (Hirajama et al. 1989), N-Nordenskiöld Land, RC-Richarddalen Complex (Ohta et al. 1989). Metamorphic facies after Oh (1992), with subdivision of the eclogite facies based on Okamoto & Maruyama (1999): AE - amphibole eclogite, AM - amphibolite, BS - blueschist, DE - dry eclogite, EA - epidote amphibolites, EE - epidote eclogite, GR - granulite, GS -greenschist, HG - high granulite, LE - lawsonite eclogite, PP - prechnite pumpellyite, Z -zeolite.

Farther south, in the Antoniabreen area of northern Wedel Jarlsberg Land, a sequence of augen gneisses and schists occurs, thrust onto low-grade Neoproterozoic metasediments. The schists content mainly garnet, muscovite, biotite, chlorite and quartz. In these rocks, most of the garnet porphyroblasts show two growth zones. Garnet-I ($Alm_{68}Prp_{8}Grs_{9}Sps_{9}$) forms cores which contain voluminous inclusions. Garnet-II ($Alm_{49}Prp_{2}Grs_{31}Sps_{18}$) builds either rims on garnet-I cores or separate euhedral crystals. Preliminary P-T estimates indicate the growth of garnet-I at ca. 550°C and ca. 5 kbar, whereas garnet-II has been growing under blueschist facies conditions (ca. 500°C and 12 kbar), most probably during Caledonian Orogeny.

Blueschists from Nordenskiöld Land indicate a geothermal gradient of 7°C/km (Fig. 2). It is in agreement with the P-T estimates for the Motalafjella Lower Unit (Agard et al., 2005) in the Vestgötabreen Complex. New evidence for HP metamorphism within the south-west Svalbard province indicates that the extent of the HP/LT metamorphism on Svalbard is substantially larger than previously supposed.

Acknowledgments:

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Phengite-bearing eclogites from NW Spitsbergen, Svalbard Caledonides

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Eclogites occur in the Richarddalen Complex on Biscayarhalvøya, NW Spitsbergen. The eclogitic rocks, which are found in orthogneisses, have been variably overprinted by amphibolite facies assemblages. Fortunately, the best preserved eclogites contain sufficient K_2O for the additional presence of phengite, the high-pressure white mica. The original high-pressure, plagioclase-free assemblages are composed of garnet, omphacitic clinopyroxene, phengite, clinozoisite, with quartz, dolomite and rutile as accessory phases (Fig. 1a). Original matrix omphacite is locally entirely replaced by fine-grained symplectites composed of clinopyroxene + plagioclase ± amphibole ± clinozoisite (Fig. 1b). The lower variance assemblage garnet-omphacite-phengite-quartz enables calculation of both pressures and temperatures of the eclogite facies metamorphism. Conventional geothermobarometry constrains the peak P-T conditions to 2.4-2.5 GPa and 720-740°C (Fig. 2). In addition to conventional geothermobarometry, we have utilized pseudosection modelling in order to constrain the evolution in P-T-X space. Pseudosection modelling calculated from bulk composition shows good agreement with the observed natural assemblages. A P-T pseudosection calculated for the formation of the post-eclogitic symplectites indicates that they formed at T ≈ 650°C and 1.2 GPa pressure (Fig. 3).

The reconstructed P-T evolution of eclogites of the Richarddalen Complex is shown in Fig. 4. The medium-T eclogite facies is consistent with formation in a continental collision zone. The retrograde post-eclogite stages comprise amphibolite facies associations formed along a steep, near-isothermal decompression type P-T path. The exact age of the eclogite facies metamorphism is not known yet. Metamorphic titanite from amphibolite and felsic gneiss of the Richarddalen Complex yields U-Pb ages of ca. 455 Ma (Gromet & Gee 1998). The titanite is in textural equilibrium with an amphibolite facies assemblage which apparently post-dates the high-pressure event. This suggests that the eclogite facies metamorphism occurred earlier in the Ordovician.

The eclogite-bearing Richarddalen Complex constitutes the uppermost unit of a simple stack of thrust sheets where the metamorphic grade is increasing structurally upward in the pile (Labrousse et al. 2008). The nappe stacking and formation of the inverse metamorphic tectonostratigraphy took place in a collisional wedge during the Silurian. Syn-collisional exhumation of the Richarddalen complex was achieved before the deposition of late Silurian/early Devonian conglomerates (Lilljeborgfjellet Conglomerate).

Additional geochronology is necessary in order to compare the high-pressure metamorphism in Svalbard to eclogite formation in other parts of the Arctic Caledonides, and thus to better understand the timing of collision between Laurentia and Baltica. Large parts of northeastern and northwestern Svalbard are thought to be derived from the East Greenland margin (Gee & Page 1994; Johansson et al. 2005) or comprise a northern continuity of the northeastern Greenland Caledonides (Gee & Tebenkov 2004). On the other hand, the Biscayarhalvøya eclogites show considerable similarities with eclogites from the Uppermost Allochthon in the Scandinavian Caledonides.

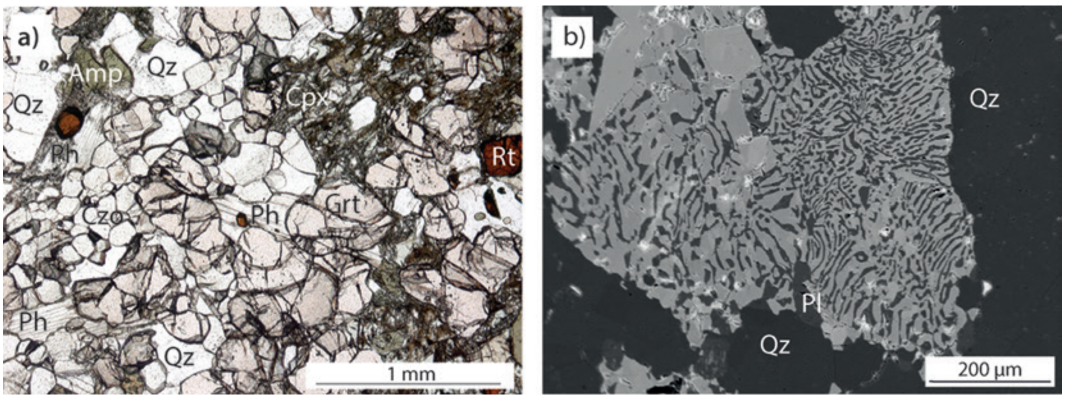

Fig. 1: a) The eclogite-facies assemblage comprises garnet, omphacite, phengite, rutile, quartz and clinozoisite. b) Primary omphacite is replaced by symplectites of diopside + plagioclase ± amphibole.

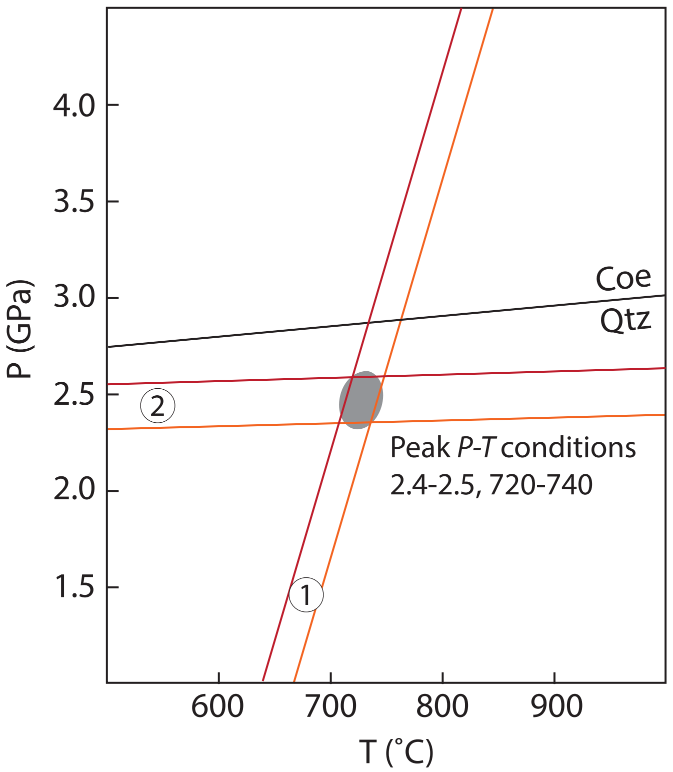

Fig. 2: Calculated P-T conditions for the phengite-eclogites from Biscayarhalvøya using the geothermobarometry of Ravna & Terry (2004). The numbers label the garnet-clinopyroxene exchange reaction (1) and the net-transfer reaction diopside + muscovite = grossular + pyrope + celadonite (2).

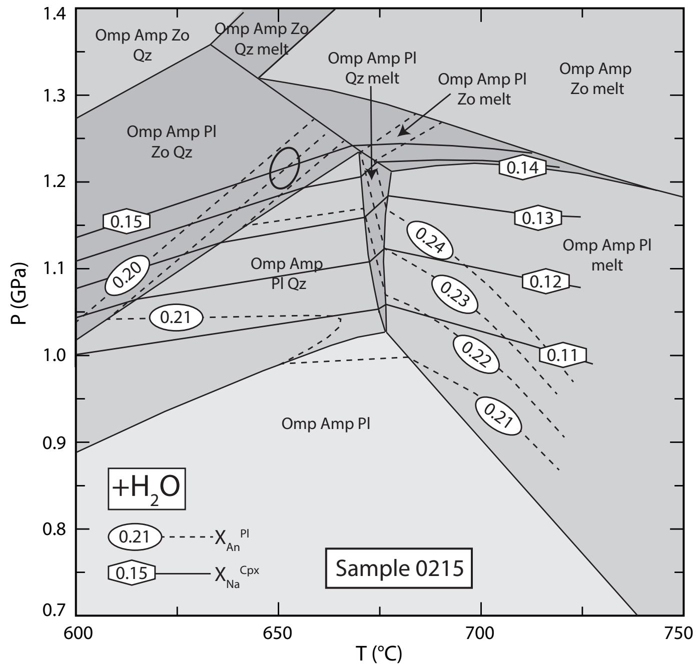

Fig. 3: P-T pseudosection calculated for the retrograde assemblage clinopyroxene + plagioclase + amphibole + clinozoisite. The retrograde assemblage appears to be stable at temperatures < 670°C and pressures < 1.35 GPa. The pseudosection is contoured with isopleths of X_{An} in plagioclase and X_{Na} in clinopyroxene for the relevant mineral assemblage. The isopleth for X_{Na}=0.15 intersects the isopleths for X_{An}=0.21 within the Omp-Pl-Amp-Zo-Qz stability field and constrain the P-T conditions to 650°C and 1.2 GPa.

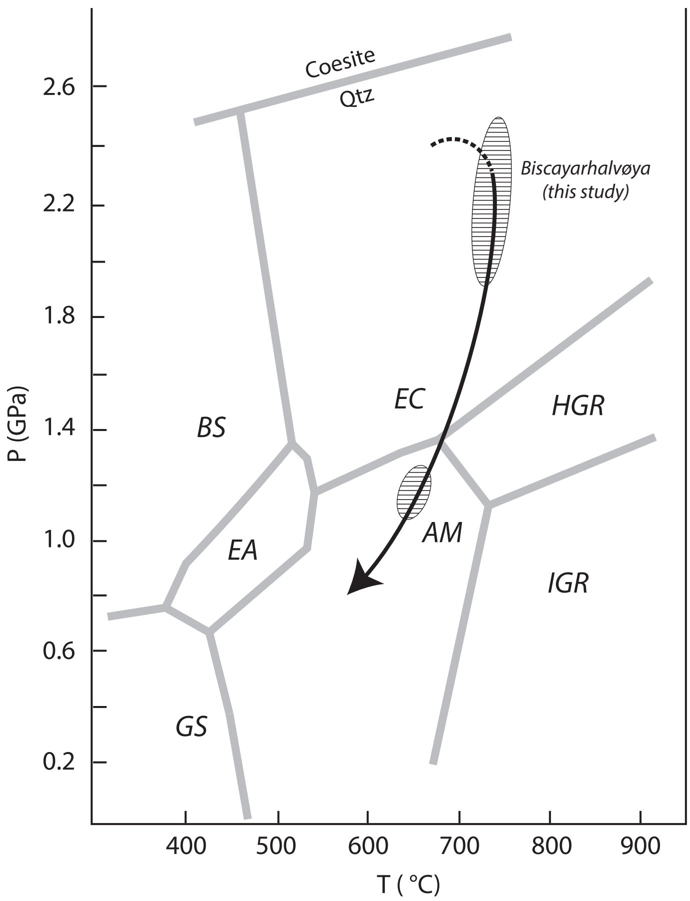

Fig. 4: P-T path for the Biscayarhalvøya eclogites. Abbreviations are: GS – greenschist facies; BS – blueschist facies; EC – eclogite facies; AM – amphibolite facies; EA – epidote-amphibolite facies; HGR – high-pressure granulite facies; IGR – intermediate pressure granulite facies.

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Photogrammetrical 3D-mapping of Kilen – a complex corner of eastern North Greenland

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The Carboniferous – Paleocene Wandel Sea Basin is exposed in easternmost North Greenland (Håkansson & Stemmerik 1989). In the southern part of the basin a structurally complex succession of Mesozoic sediments is exposed on Kilen, a 300 km^2 semi-nunatak (Fig. 1). Kilen was previously mapped during expeditions in 1980 and 1985 (Pedersen 1989; Håkansson et al. 1993) but further mapping was needed to gain a new and more accurate understanding of the complex geology. The oblique photogrammetry method (Dueholm 1993; Vosgerau et al. 2010; Sørensen 2012) is an ideal way to obtain high quality 3D data in remote areas with difficult logistic conditions and short field seasons, such as in North Greenland. Here, for the first time, oblique photogrammetry has been combined with 3D structural modeling to better understand the complex geological evolution of the area.

During the field seasons of 2012 and 2013 a total of 1293 overlapping photos covering areas of Kilen with exposed bedrock were taken from a helicopter by a hand-held digital SLR camera (Fig. 2). These photos have been triangulated and georeferenced at the Photogrammetry Lab at the Geological Survey of Denmark and Greenland (GEUS) using IMU-data also collected on flight. After the images were georeferenced they could be viewed as stereo pairs on a 3D-workstation and the visible geological features were drawn, annotated and exported as 3D-polylines (Fig. 3). Structural measurements are then extracted from the digitised polylines following Pedersen (1981) and Svennevig and Guarnieri (2012). 3D-polylines, structural measurements, raster maps (old maps, orthophotos) and a DEM produced form aerials were then imported into a 3D modeling software, in this case MOVE from Midland Valley. Finally a 3D-model was constructed and various structural hypotheses could be tested and quantified through 3D-modeling. The results from this modeling will be presented elsewhere.

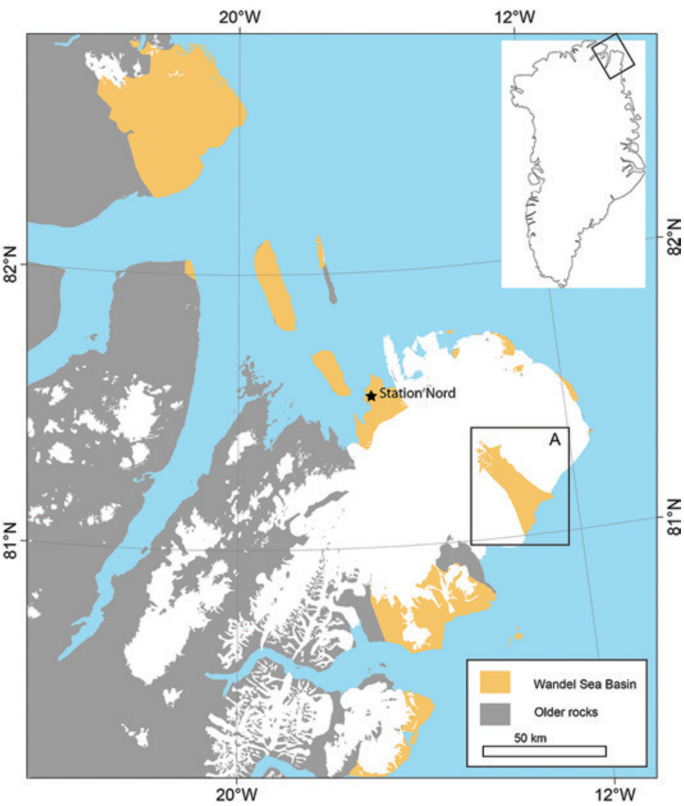

Fig. 1: Overview map of eastern North Greenland showing the extent of the Wandel Sea Basin along with Kilen and the area of Figs. 2 and 3 (marked with A).

The workflow presented here is ideal for fieldwork in remote and inaccessible areas, a large amount of high quality outcrop data being obtained in a short time; either as a supplement to classic mapping or as a stand-alone dataset. Another advantage of the method is that you can discuss the 3D-outcrop in plenum with your colleagues at home in the lab instead of discussing only the derived data one usually brings home from the field (field maps, structural measurements, profiles, 2D pictures). Furthermore, as proved by this study, the quality and quantity of the data compared to the previous mapping effort makes the method ideal for use as the basis for 3D-modelling.

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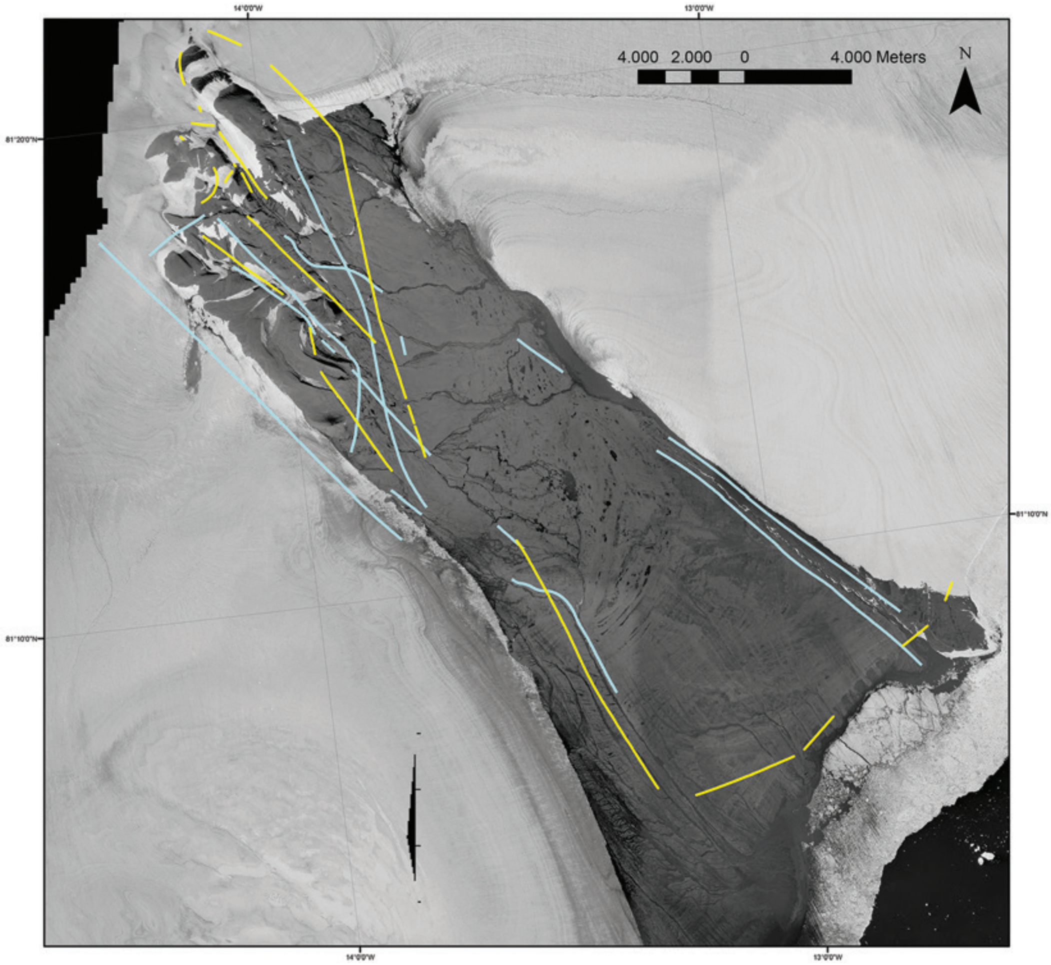

Fig. 2: Flight lines used for oblique photogrammetric mapping of Kilen. Light blue: 2012 field season, yellow: 2013 field season.

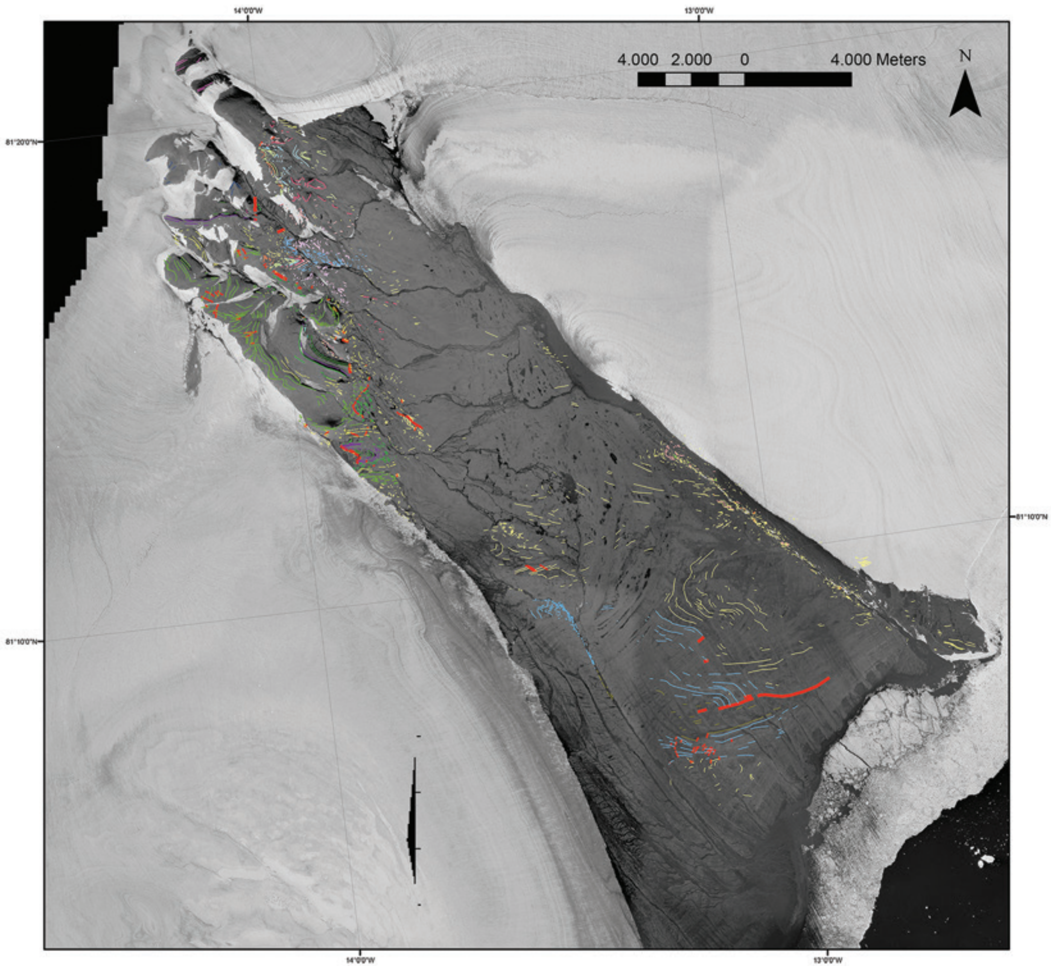

Fig. 3: Geological features (bedding and faults) mapped from oblique- and ordinary aerial photographs. The polylines are all in 3D. The colors reflect the different formations recognised.

Comparing the Svalbard and Northeast Greenland Caledonides

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Major high-angle N-trending faults subdivide the Svalbard Caledonides (Harland 1997) into blocks, or provinces, or so-called terranes, some separated by Old Red Sandstone (ORS) graben. Vertical movements, normal and reverse, have been variously estimated to several kilometers. Horizontal movements on these faults have been claimed to be in the order of hundreds to thousands of kilometers; by some as much as 4000 km. Interpretations of the regional Caledonian structure on Svalbard, depend greatly on how much lateral movement is accredited to these faults. It is proposed here that the transcurrent movements are subordinate and that, as in northeastern Greenland, the Caledonian structure in Svalbard is dominated by major allochthons, emplaced westwards onto the Laurentian margin and platform.

In northeastern Greenland (Higgins et al. 2008 and references therein), the Caledonides are exposed over a length of c 1300 km and a width of up to 300 km (Fig. 1), a far larger area than the fragmented Svalbard archipelago. The regional structure is dominated by thrusting and the subordinate influence of late-orogenic faulting is mainly extensional, being related to the development of ORS and younger basins. Major strike-slip faults have been identified; their displacement distances can be better controlled than on Svalbard and probably do not exceed a few tens of kilometers. The Caledonian thrust system of eastern Greenland, with displacement of the highest nappes of at least three hundred kilometers westwards over the Laurentian platform, is dominated by three major complexes, referred to here as the Upper, Middle and Lower allochthons. The Upper Allochthon, is dominated by the high grade metamorphosed Hager Berg complex with overlying low grade Neoproterozoic to Ordovician sedimentary rocks of the so-called Franz Josef allochthon. The Middle Allochthon, in southern parts (south of 78° N) is made up of the Niggli Spids complex, comprising Archean and Paleoproterozoic crystalline rocks and overlying, generally amphibolite facies metasedimentary rocks. Farther north, the Middle Allochthon comprises a higher grade, eclogite-bearing province, the Nørreland complex and underlying, amphibolite facies ”Western Thrust Belt”. The Lower Allochthon, in southern latitudes, outcrops in foreland windows and comprises imbricated basement crystalline rocks and greenschist facies latest Neoproterozoic and Cambro-Ordovician sedimentary cover successions. Only in the northeasternmost part of the mountain belt are thin-skinned thrust sheets well preserved, where the stratigraphy reaches from Neoproterozoic sedimentary successions up through the Cambrian and Ordovician into Silurian turbidites. An underlying Caledonian sole thrust separates the Lower Allochthon from an autochthonous cover of Meso- to Neoproterozoic and Cambro-Ordovician platform successions, resting on the crystalline basement.

The Upper Allochthon in the Greenland Caledonides differs from the underlying units in providing evidence of both late Grenville-age (Tonian) and Caledonian (Silurian) HT/LP metamorphism, migmatization and granite intrusion. The Tonian deformation and metamorphism of the Hager Berg complex, referred to as Renlandian orogeny, involved both syn- and post-tectonic 930-940 Ma granites, intruded into a latest Mesoproterozoic to earliest Neoproterozoic siliciclastic succession (the Krummedal and Smallefjord groups). These characteristics of the Hager Berg complex contrast markedly with the overlying low grade Franz Josef successions of the Eleonore Bay Supergroup, comprising thick Cryogenian (perhaps also late Tonian), mainly shallow marine sandstones, overlain by carbonates and tillites, passing up into typical Laurentian margin sandstones and a carbonate platform succession in the Cambrian to mid Ordovician. The contact between the Renlandian orogenic complex, and the overlying low grade sedimentary succession is highly deformed, but probably a major unconformity, and the Caledonian granites (ca. 435-420 Ma) intrude both these units of the Upper Allochthon.

The underlying Niggli Spids complex of the Middle Allochthon, is apparently not influenced by late-Grenvillian orogeny. These basement-derived crystalline rocks, overlain by latest Mesoproterozoic to earliest Tonian meta-sandstones (Krummedal Group), either overlie, or pass northwards into the eclogite-bearing Nørreland complex (HP/HT metamorphism at 415-390 Ma), which dominates the coastal areas of northeasternmost Greenland from 76° to 80° N. This HP and, locally, UHP complex (ca. 365-350 Ma), was thrust westwards over the Western Thrust Belt, comprising an amphibolite facies imbricated stack of Paleoproterozoic gneisses intercalated with late Paleoproterozoic to Mesoproterozoic quartzites (the Independence Fjord Group), all intruded by ca. 1350 Ma dolerite dykes.

The rock units in the Svalbard Caledonides (Fig. 2), with the exception of those exposed in westernmost areas within the Cenozoic fold-and- thrust belt, are remarkably similar to the components of the major allochthons in northeastern Greenland in terms of lithologies, stratigraphy, structure and metamorphism (Gee and Teben'kov, 2004 and references therein). It would be very surprising indeed if they were not dominated by Greenland-type allochthoneity.

The correlatives, in Svalbard, of the Upper Allochthon in eastern Greenland are best exposed in the Nordaustlandet “terrane” of Svalbard´s Northeastern Basement Province. The lower part (correlative of the Hager Berg complex) comprises the meta-sedimentary Brennevinsfjorden (including Helvetesflya) Group, which was syn- to post-tectonically intruded by 950 Ma granites during Nordaustlandet Orogeny. This late-Grenvillian, “basement”, influenced at least locally by Tonian-age migmatization, was unconformably overlain by calc-alkaline volcanics (also, ca. 950 Ma) and then by the Murchisonfjorden Supergroup sedimentary succession (Eleonore Bay Supergroup correlatives), passing up through Marinoan tillites into Cambro-Ordovician sandstone to carbonate formations. The highest stratigraphic units are preserved in a major syncline (Hinlopenstretet) separating Nordaustlandet from Ny-Friesland, and Murchisonfjorden Supergroup correlatives, the Lomfjorden Supergroup, dominate eastern Ny-Friesland. This E-dipping succession is in fault contact with underlying semi-pelitic schists and paragneisses of the Planetfjella Group, which have been inferred to be thrust westwards over the Atomfjella complex of western Ny-Friesland, the contact-zone being marked by a string of ultramafic lenses. The Nordaustlandet Allochthon was influenced by Caledonian migmatization and granite intrusion prior to emplacement onto the underlying metamorphic complex, outcropping in western Ny-Friesland.

The West Ny-Friesland Allochthon (previously terrane) comprises late Paleoproterozoic granites (ca. 1740 Ma), intruded, at least locally, into Late Archean gneisses, unconformably overlain by Mesoproterozoic meta-sandstones; nearly all units are intruded by dolerites (ca. 1300 Ma). This correlative of the Western Thrust Belt of northeastern Greenland was subject to high amphibolite facies metamorphism and was apparently not influenced by Grenville-age orogeny. The structure in western Ny-Friesland is dominated by a stack of thrust sheets, each comprising Paleoproterozoic basement and Mesoproterozoic cover, folded by a major antiform (Atomfjella) and subject to intense axial elongation, typical of the hinterlands of major orogens (e.g. the Scandinavian Caledonides and the Himalaya-Tibet Orogen) where axial extrusion (tectonic escape), dominates the late stages of orogeny.

Relationships between the West Ny-Friesland allochthon and the metamorphic complexes of northwestern Svalbard are hidden beneath the Andreeland-Dicksonland, ORS graben, the basement of which is not exposed, but may include a tectonic window. Northwestern Svalbard is also disrupted by a N-trending ORS graben, but the Caledonian complex is readily divisible into two parts. The one is an eclogite-bearing complex (Richarddalen) of metasedimentary rocks, including marbles and paragneisses, intruded by garnetiferous augen granites and coronitic gabbros (both ca. 960 Ma) and younger dolerites (ca. 660 Ma), all subject to mid to late Ordovician HP/HT metamorphism; the other is a lower pressure, higher temperature metasedimentary succession of schists and subordinate marbles (Krossfjorden Group), also intruded by 960 Ma granites and influenced by both late-Grenvillian and Caledonian migmatization. The former is a possible correlative of the Nørreland complex in northeastern Greenland and the latter is closely comparable to the Tonian “basement” in the Nordaustlandet Allochthon of theNortheastern Basement Pro-

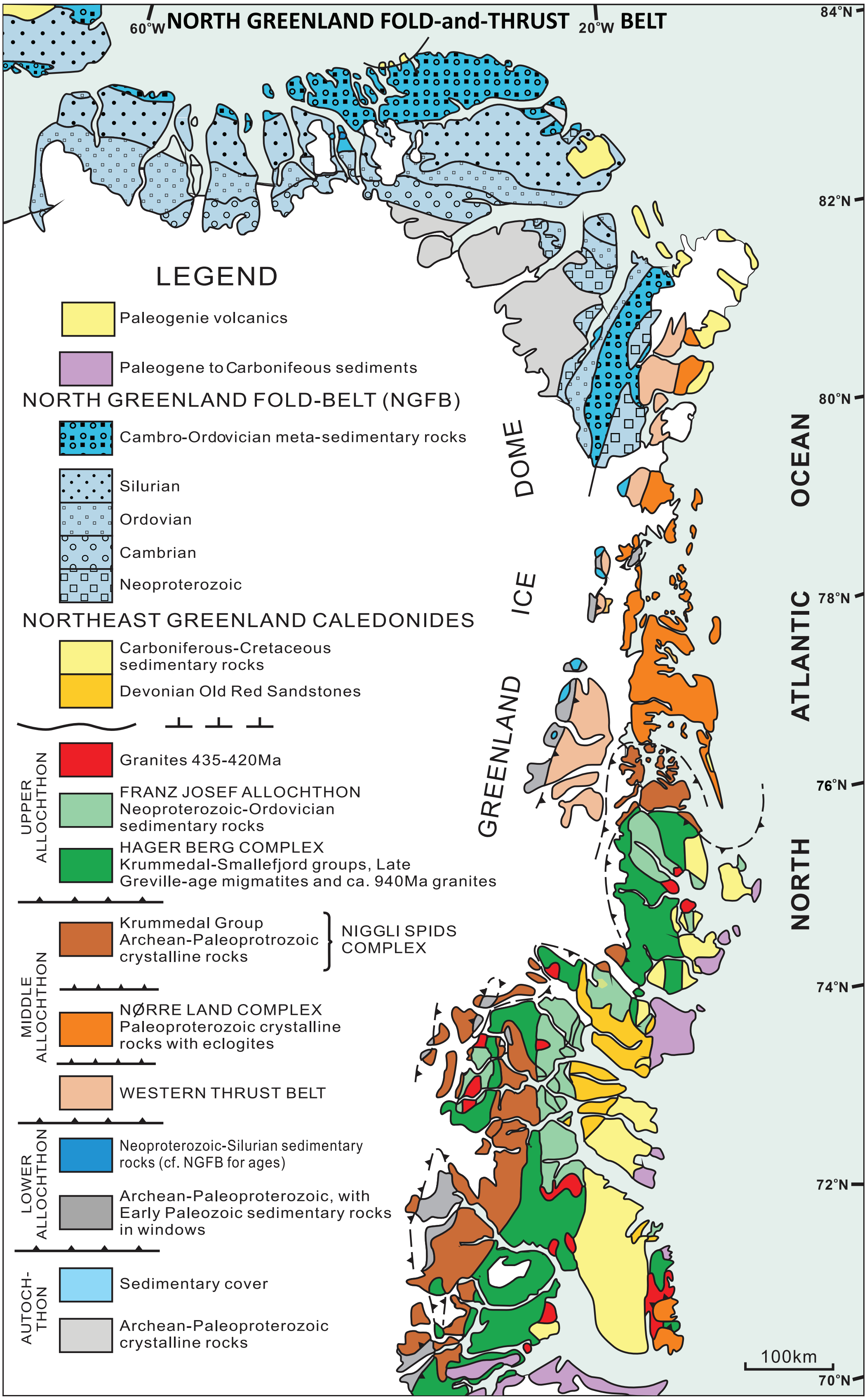

Fig. 1: Tectonostratigraphic map of northeastern Greenland, based on Henriksen (2003) and Gee et al. (2008).

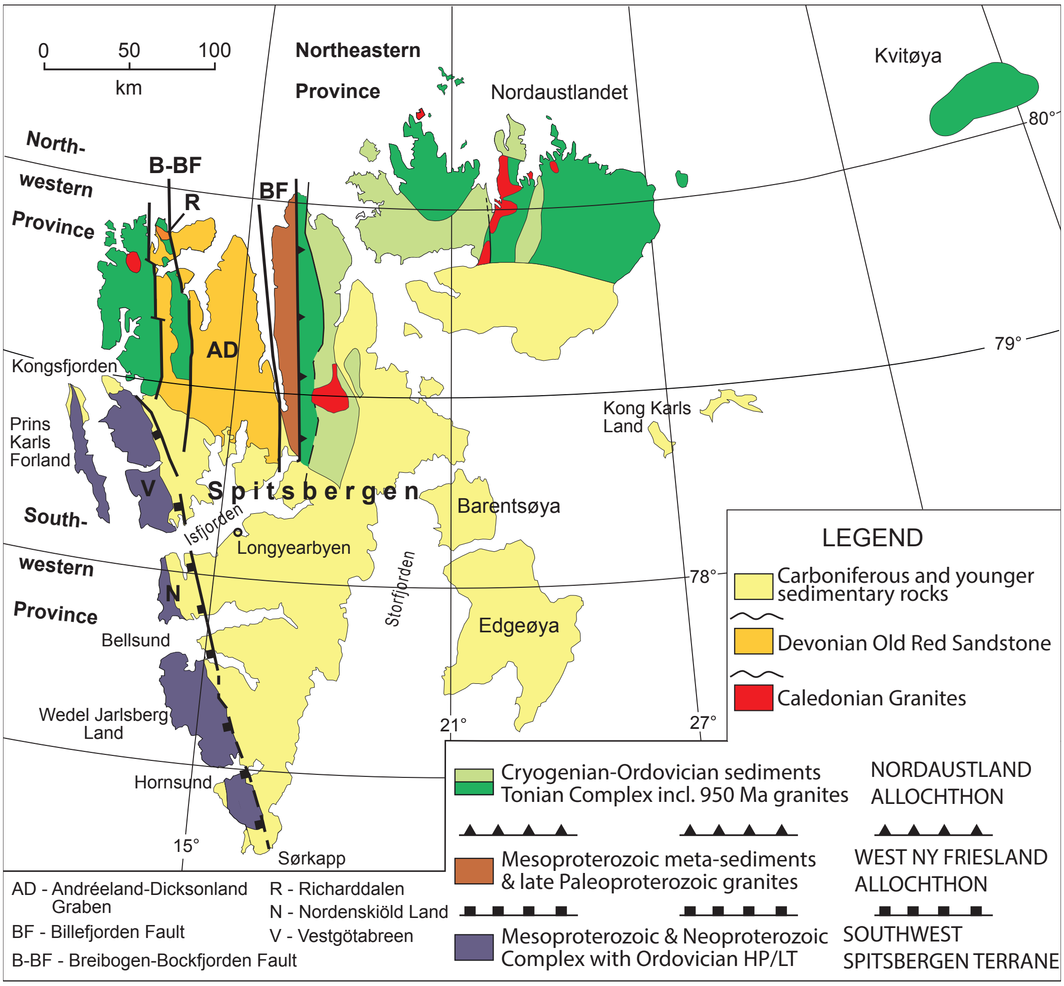

Fig. 2: Tectonostratigraphic map of Svalbard, based on Dallmann et al. (2002) and Gee &Teben'kov (2004).

vince. It is proposed here, based on the Greenlandian analogue, that the Tonian complexes on Nordaustlandet and correlatives in northwestern Svalbard, are both part of the same major, long-transported Caledonian allochthon.

The Caledonian bedrock (Southwestern Basement Province) preserved within the Cenozoic fold-and-thrust belt of western Svalbard, provides evidence of a 1200 Ma "basement" igneous complex and overlying Neoproterozoic to Ordovician sedimentary succession interrupted by Torellian unconformity and ca. 640 Ma orogeny; locally, there is evidence of Early Ordovician subduction (blue schists and eclogites). This terrane differs fundamentally from the bedrock further to the north and east in Svalbard. Affinity to the Pearya terrane of northern Canada has been proposed. This interpretation implies that the Caledonian thrust-sheets of northeastern Greenland continue northwards off-shore, via the continental shelf, to Svalbard, where they are disrupted by the N-trending fault-zones. Strike-slip displacements are inferred to be of subordinate importance, except in connection with the axial extrusion of the hinterland and juxtaposition of the northeastern Greenland allochthons with Svalbard´s Pearya correlatives.

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Post-Caledonian tectonic overprint of Svalbard's basement

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When working with the structural evolution of the Caledonian basement of Svalbard, it is essential to be aware of subsequent events that have affected the region.

During Early Devonian time faulting events, mainly of strike-slip nature, affected the Devonian Basin of northern Svalbard (Piepjohn 2000) and the adjacent Northwestern Basement Province.

The Ellesmerian Orogeny of the Canadian Arctic Archipelago and Northern Greenland appears to have affected Svalbard also as the Svalbardian Event (Vogt 1928; Piepjohn 2000) in Early Carboniferous time. The basement of eastern Svalbard was uplifted and thrust over the late-orogenic Devonian molasse sediments. The main uplift occurred along the N-S striking Billefjorden Fault Zone (Harland et al. 1974; Manby et al. 1994; McCann & Dallmann 1996), which has since then, been repeatedly reactivated. Other subparallel fault zones (e.g. Lomfjorden Fault Zone) to the east developed – or were reactivated – during this time (Dallmann and Piepjohn, unpubl).

During Mid-Carboniferous time several sedimentary basins developed along the major N-S striking fault zones, and extensional fault block tectonism affected much of the area (Gjelberg & Steel 1981; Steel & Worsley 1984).

While Svalbard was a stable platform during most of the Mesozoic (Steel & Worsley 1984), the intrusion of dolerite and sills and dykes into Early Cretaceous and older rocks heralded the break-up of the Greenland and European platforms (Burov et al. 1977; Nejbert et al. 2011).

Sea-floor spreading in the Labrador Sea from Late Cretaceous time led to continental transform fault movement and associated faulting in Northern Greenland. Northward propagation of the spreading zone in the early Palaeogene and the onset of spreading in the North Atlantic caused an oblique northward movement of Greenland along the Wegener Fault Zone against the Barents Shelf. This motion led to the formation of the Eurekan Foldbelt in Arctic Canada, Northern Greenland and Svalbard – in the latter place referred to as the West Spitsbergen Fold Belt. Thrusting and faulting heavily affected the basement of western Svalbard (Kristoffersen & Talwani 1977; Talwani & Eldholm 1977; Srivastava 1978; Srivastava & Tapscott 1986; Tessensohn & Piepjohn 2000; Saalmann et al. 2005).

In the Late Eocene, Svalbard moved southeast along the Hornsund Fault Complex, a transform fault system, past the Greenland Shelf. During later stages of transform movement (Early Oligocene), when the continental connection between Northern Greenland and Svalbard was broken, the direction of rifting changed (Kristoffersen & Talwani 1977; Talwani & Eldholm 1977, Tessensohn & Piepjohn 2000). A new, extensional tectonic regime developed at the Hornsund Fault Complex, leading to the formation of minor sedimentary basins (especially the Forlandsundet Basin) off the western coast of Svalbard (Eiken & Austegaard 1987; Gabrielsen et al. 1992; von Gosen et al. 2001).

The latest tectonic overprint was an overall E-W extension that affected more or less all favourably oriented earlier faults and also generated significant new faults in the basement western Svalbard. These fault movements must be seen in the context with the post-Eocene development of a passive continental margin.

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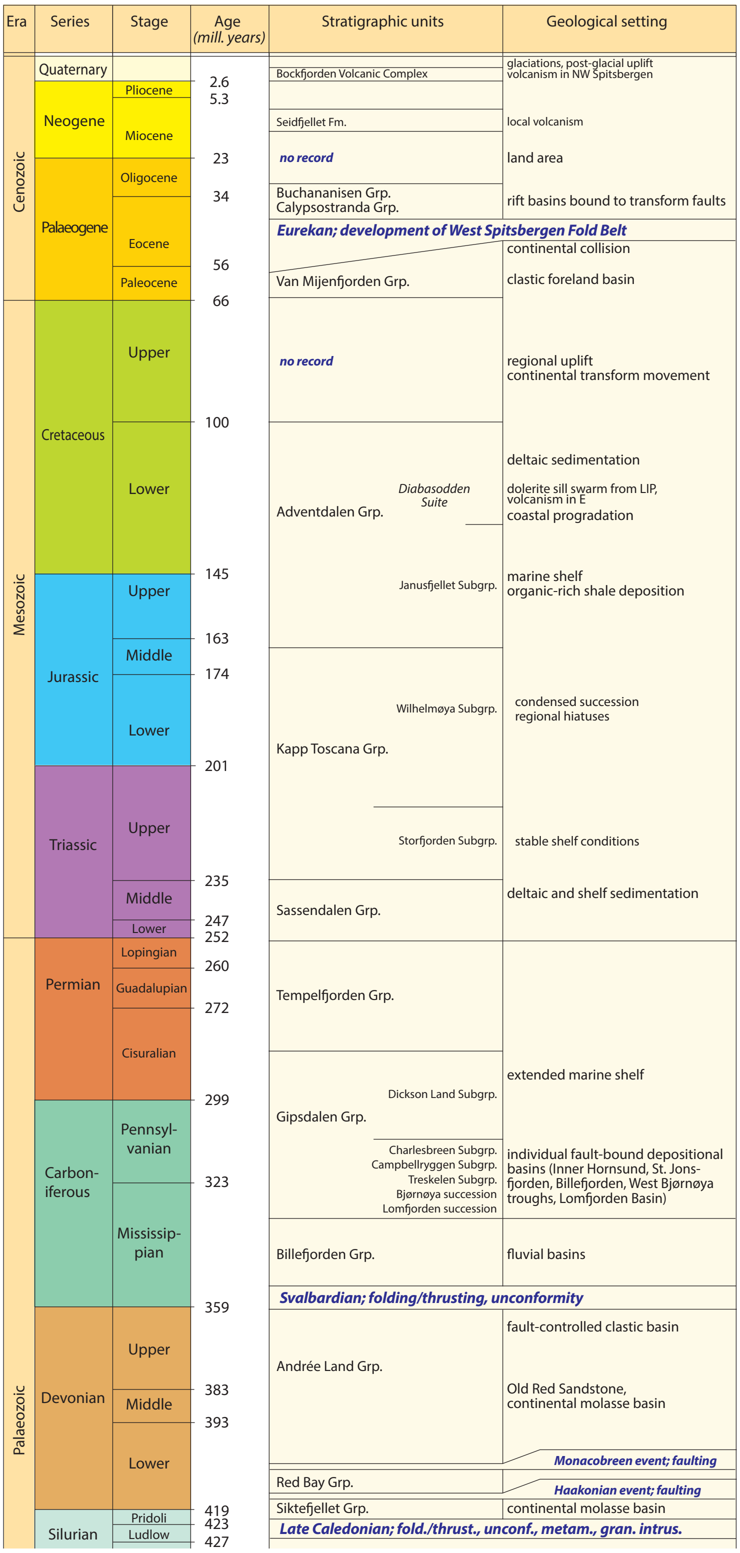

Fig. 1: Simplified table of the post-Caledonian geological development of Svalbard

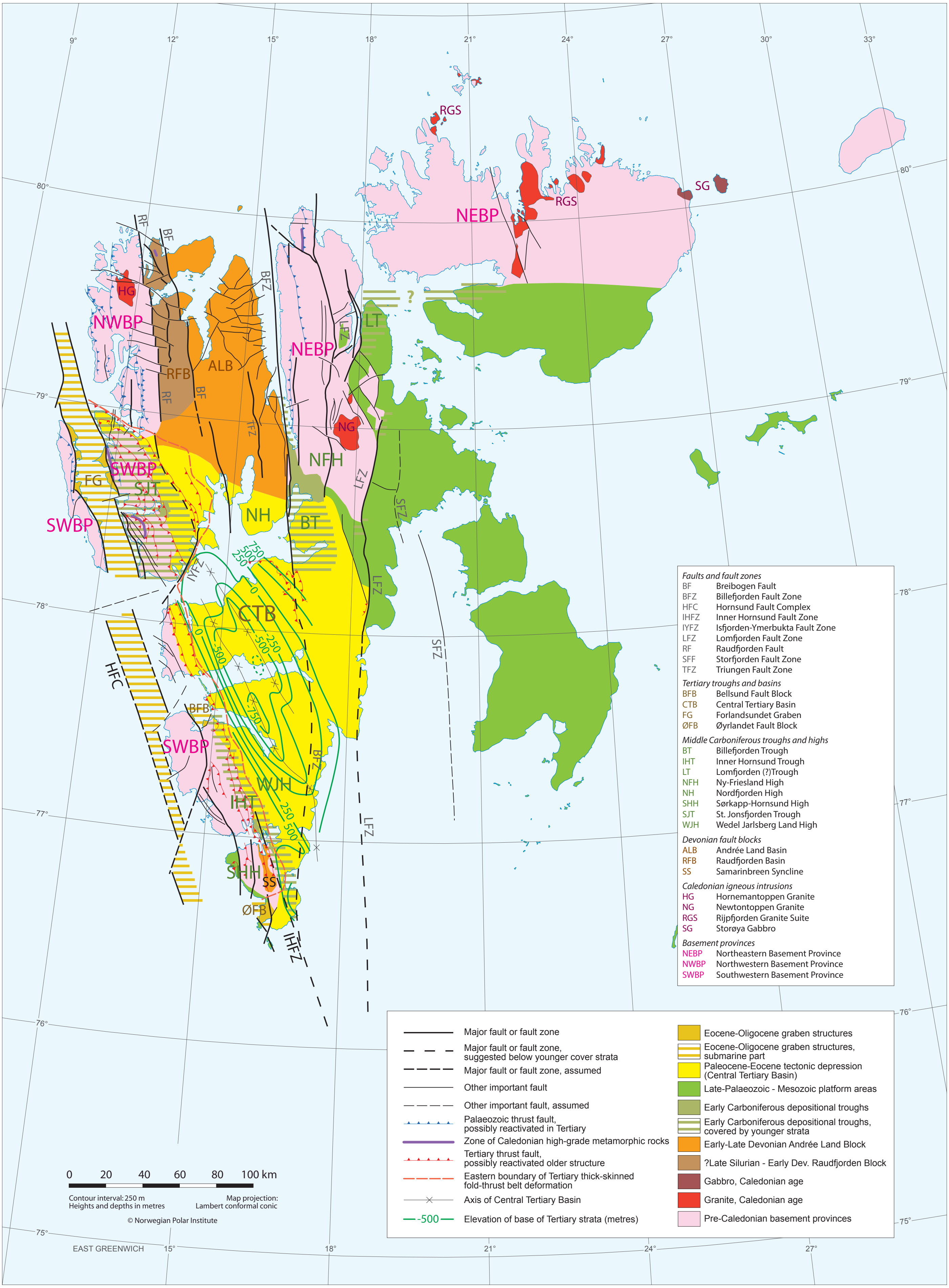

Fig. 2: Tectonic overview map of Svalbard showing the structural elements discussed in the text.

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Late Cretaceous-Paleocene tectonics of the East Greenland margin

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The East Greenland margin is a long stretch starting from 60°N up to 81°N in a distance of more than 3000 km. It represents the counterpart of the European margin now separated by the Northeast Atlantic (Fig. 1). Separation between Greenland and Europe began at 55 Ma after a long period of E-W extension and almost N-S oriented rift basins formed during the Late Jurassic-Early Cretaceous. In the Early Eocene the line of breakup followed NE-SW oriented trends together with the emplacement of the North Atlantic Igneous Province. Post-breakup thermal subsidence followed in the Eocene, while the Oligocene initiated a period of plate re-organisation with the initial separation of the Jan Mayen microcontinent. At this time a complex tectonic history with inversion structures and uplifts along both the East Greenland and European margins initiated. Along the East Greenland margin the effects of this tectono-magmatic history are documented by exhumed sedimentary basins, dyke swarms, fault systems, intrusive centers, shield volcanoes and plateau lavas constituting, in some cases, the highest mountains of Greenland with peaks up to 3700 m.

During fieldwork in East Greenland four areas were visited to collect new geological and structural data describing brittle deformation related to the Northeast Atlantic tectonics: Skjoldungen, 63°N, Kangerlussuaq, 68°N, Traill Ø, 72°N and Wollaston Forland, 75°N (Fig. 1). More than 1000 fault-slip data for structural analysis along major faults together with hundreds of kilometres of helicopter flights and thousands of oblique pictures for 3D-photogeology and 3D-mapping were collected.

Kinematic analysis of brittle deformation associated with a Late Cretaceous-Paleocene rift shows strike-slip movements (Guarnieri 2011). Paleostress tensors reconstructed from fault-slip data highlight a NE-SW maximum horizontal stress in a strike-slip tectonic setting along the entire East Greenland margin pre-dating the breakup of the Northeast Atlantic (Guarnieri et al. 2012; Fig. 2). Structural data allow to interpret a two-stage evolution for the Kangerlussuaq Basin from a pull-apart setting in the Campanian-Danian to an oblique rift in the Selandian-Thanetian associated with volcanism, magmatic segmentation of macro-dyke complexes and activation of the ENE-WSW trending Kangerlussuaq Fault Zone. The latter are represented by former Proterozoic lineaments (2,0 Ga) reactivated during the Northeast Atlantic rifting.

Strike-slip deformation evidenced by the structural data collected along the East Greenland margin shows as the rift-to-drift transition of the Northeast Atlantic opening. It is not related to a classic pure shear event stretching the lithosphere, but to more complex simple shear (Fig. 2). From a plate tectonic point of view separation between Greenland and Europe is characterized by two main events of rifting: The first stage, documented in North-East Greenland, is of Late Jurassic-Early Cretaceous age with a N-S trending rift in a general E-W extensional regime. The second initiated in the Late Cretaceous, leading to the opening of the Northeast Atlantic in the early Eocene following a NW-SE extension. During this shifting extension from E-W to NW-SE, which

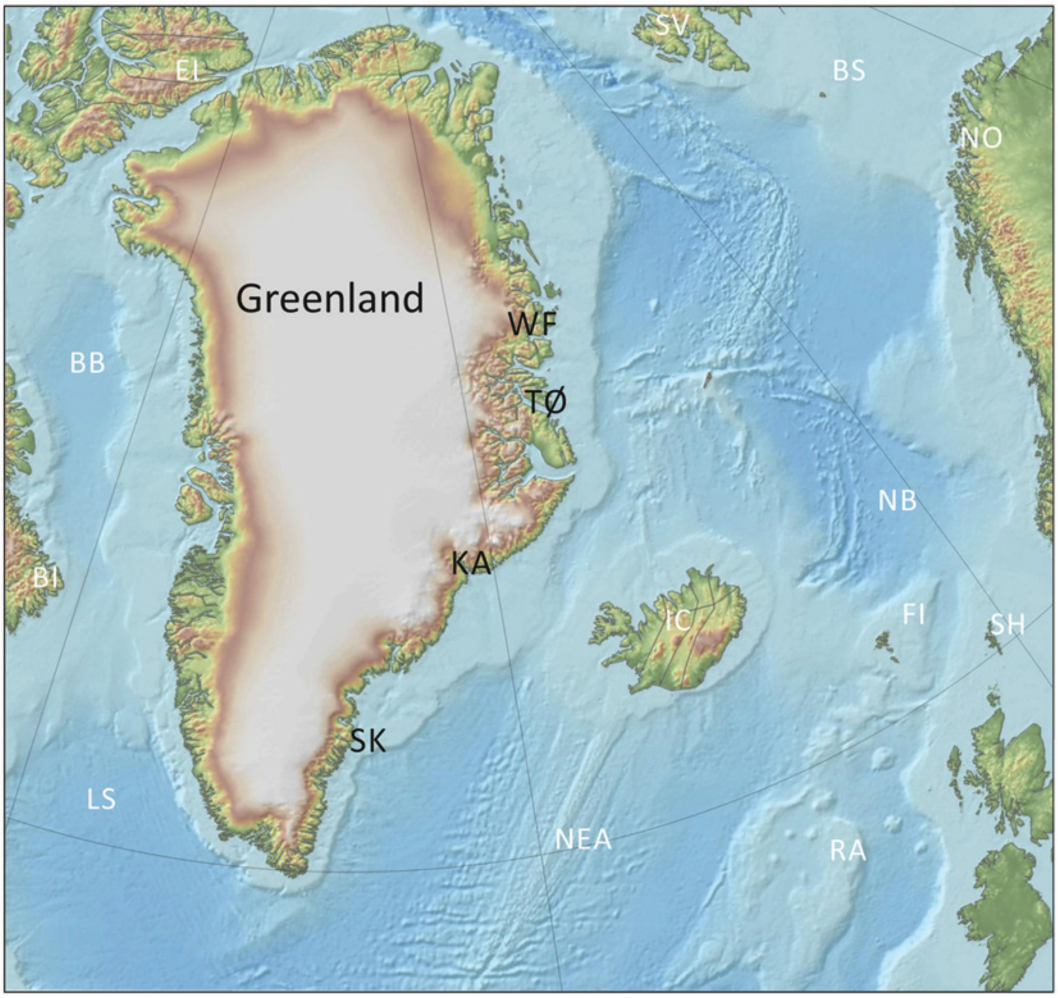

Fig. 1: Location map of the areas investigated during fieldwork in South-East and East Greenland. SK Skjoldungen; KA Kangerlussuaq; TØ Traill Ø; WF Wollaston Forland. SV Svalbard; BS Barents Sea; NO Norway; NB Norwegian Basin; FI Faroe Islands; SH Shetland; RA Rockall Plateau; IC Iceland; NEA North East Atlantic; LS Labrador Sea; BI Baffin Island; BB Baffin Bay; EI Ellesmere Island.

was contemporaneous with the rift-to-drift of the Labrador Sea, the East Greenland margin was deformed by strike-slip tectonics. The data collected show a coherent palaeostress along the margin with NE-SW compression and NW-SE extension in a strike-slip tectonic regime that can be interpreted in a context of oblique rifting (Fig. 2), which arises when the bulk extension direction is not perpendicular to the boundary faults.

Pull-apart basins, oblique rifting and strike-slip deformation along the East Greenland margin reflect the pre-breakup counterclockwise rotation of Greenland in response to the rifting and opening of the Labrador Sea (Guarnieri 2012) (Fig. 2).

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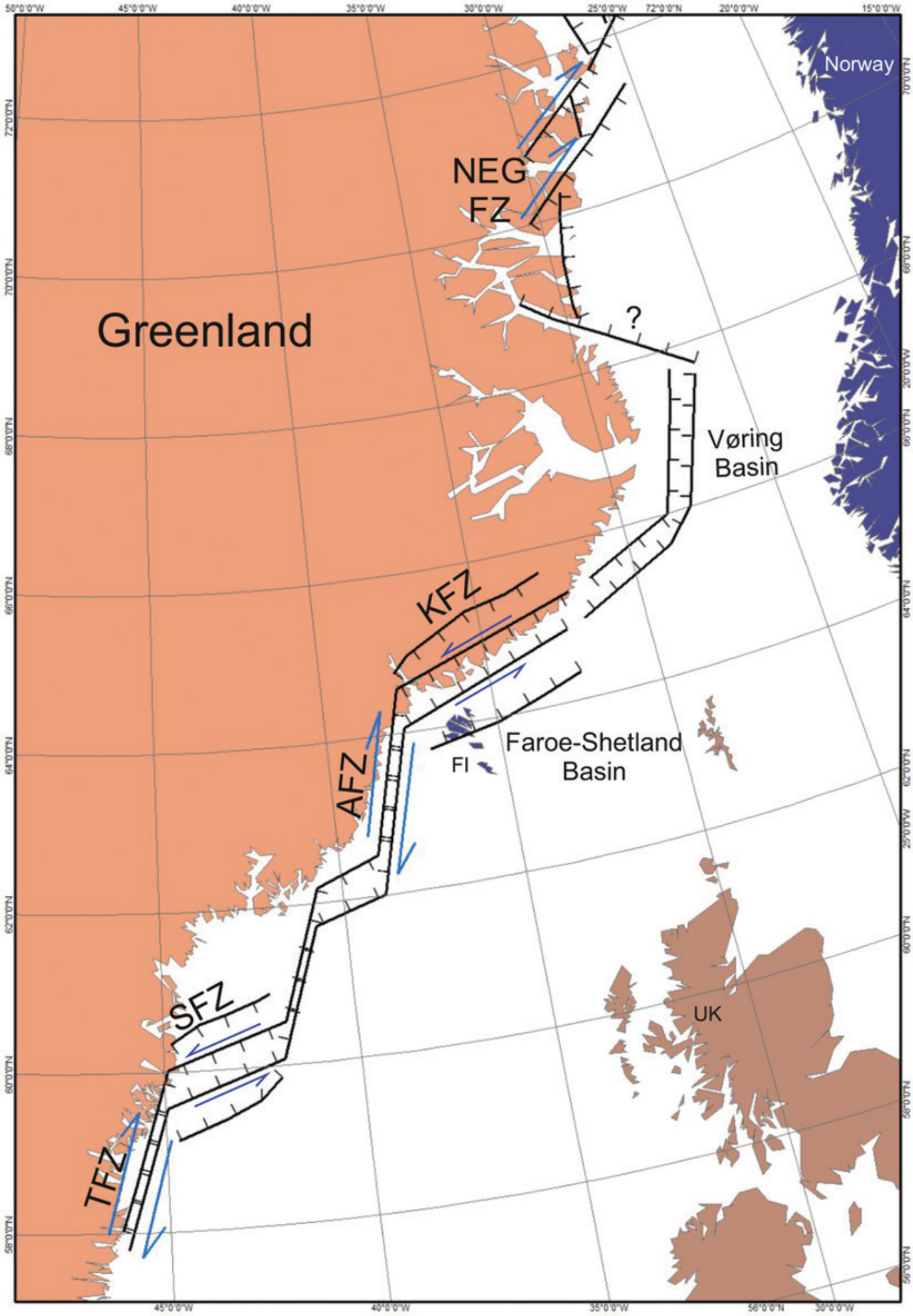

Fig. 2: Plate reconstruction of Greenland in Paleocene time showing the geometry and kinematics characterising the NE Atlantic rift before breakup, around 55 Ma. TFZ Timmiarmiit Fault Zone; SFZ Skjoldungen Fault Zone; AFZ Agtertia Fault Zone; KFZ Kangerlussuaq Fault Zone and the North East Greenland Fault Zone.

Eurekan fault tectonics along the northern margin of Ellesmere Island (Canadian High Arctic)

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In the northern part of Ellesmere Island, a number of major NE-striking fault zones are exposed parallel to the passive continental margin of the Canadian Arctic Archipelago (Fig. 1a). Some of the fault zones were already initiated during the Early Carboniferous Ellesmerian Orogeny, or even earlier (Trettin 1987, 1989), when the allochthonous Pearya Terrane approached and docked against the Franklinian Basin along the northern margin of Laurentia (Klaper 1992; Piepjohn et al. 2013). After the evolution of the post-Ellesmerian Sverdrup Basin from Carboniferous through Palaeogene times, new fault zones were initiated and the Ellesmerian faults were reactivated as thrust or strike-slip faults during the Palaeogene Eurekan deformation. The age of the strike-slip movements along the northern margin of the Canadian Arctic Islands indicates that the evolution of the large brittle fault zones is more likely related to the opening of the Eurasia Basin than to the formation of the Amerasia Basin (Piepjohn et al. 2013).

The fault zones on Ellesmere Island are characterised by different kinematics and successions of tectonic episodes. Although the existence of a major fault between Greenland and Ellesmere Island (Wegener Fault) has been questioned by, e.g., Hansen et al. (2011) and Pulvertaft & Dawes (2011), geological mapping and onshore structural observations north of Cape Lawrence clearly indicate that there are onshore portions of an important fault zone within Nares Strait which can be traced from Judge Daly Promontory (Gosen et al. 2008; Saalmann et al. 2008; Tessensohn et al. 2008) towards Hall Basin and Robeson Channel (Damaske & Oakey 2006). The more or less NE trending fault zones parallel to Nares Strait, are characterized by sinistral strike-slip movements (Fig. 1a) followed by SE-directed compression (von Gosen et al. 2008), or by oblique sinistral NW-SE compression (Saalmann et al. 2008). ENE striking fault zones in the centre of Ellesmere Island are dominated by SSE-NNW compression and subordinate dextral strike-slip movements (Piepjohn et al. 2007). Fault zones parallel to the continental margin in the northern part of Ellesmere Island are characterised by intense strike-slip tectonics which mostly show both sinistral and dextral displacements (Fig. 1a)(Piepjohn et al. 2013). Until now, it has not been possible to estimate amounts of displacement along the fault zones by, for example, the offset of rock units. And the change from sinistral to dextral movements and, possibly, back to sinistral movements makes estimations much more difficult.

The brittle, dextral and sinistral strike-slip displacements in the northern part of Ellesmere Island took place after the intrusion of the Hansen Point Volcanic Complex at 82 Ma and the deposition of the Maastrichtian to Paleocene Eureka Sound Group along the northern coast of Ellesmere Island, near Yelverton Inlet (Fig. 1a) (Piepjohn et al. 2013). As the assumed sea-floor spreading in the Amerasia Basin was already terminated between 120 and 95 Ma (Embry & Dixon 1992; Grantz el al. 1998; Müller et al. 2008), the movements are most probably not related to the evolution of the Amerasia Basin. Therefore, the driving forces for the extended lateral movements and the formation of large strike-slip fault zones along the North American margin are most likely related to the plate-tectonic development of the Eurasia Basin since 55 Ma, when Greenland was a separate plate between the large continental plates of Eurasia and North America (Fig. 1c,d). However, the superposition of both sinistral and dextral displacements parallel to the North American continental margin during the Eurekan deformation in the Eocene is still unclear.

Tessensohn & Piepjohn (2000) proposed a three-step-model, which was controlled by tectonic activity especially along the continental margin transform faults, northwest (Wegener Fault) and northeast (De Geer Fracture Zone) of Greenland and the different development of the spreading centres in the west (Labrador Sea and Baffin Bay) and east (Norwegian and Greenland seas). Saalmann et al. (2005) separated the Eurekan deformation along Nares Strait into two stages, but a four-step-model is preferred here:

Step 1 represents the pre-Eurekan situation at anomaly 31 (68 Ma) (Fig. 1b). The boundary between North America on the one hand and Greenland/Eurasia on the other hand was situated west of Greenland and was characterised by sea-floor spreading in Labrador Sea, rifting in Baffin Bay, sinistral strike-slip tectonics along Nares Strait and rifting in the Eurasia Basin (e.g. Kristoffersen & Talwani 1977; Srivastava 1978; Hinz et al. 1979; Srivastava & Tapscott 1986).

Step 2, the first stage of the Eurekan deformation, occurred between anomalies 24 (55 Ma) and 21 (49 Ma)(Fig. 1c), when Greenland was a separate plate (Tessensohn & Piepjohn 2000) with contemporaneous spreading on both sides of Greenland (Greenland and Norwegian seas in the east, Labrador Sea and Baffin Bay in the west) and in the Eurasia Basin (e.g. Kristoffersen & Talwani 1977; Talwani & Eldholm 1977; Menzies 1982; Srivastava & Tapscott 1986). During this time span, Greenland moved towards the NE, and sinistral strike-slip movements took place along Nares Strait, whereas the western margin of the Spitsbergen was affected by intense compressive movements within the West Spitsbergen Fold-and-Thrust Belt.

At the beginning of *Step 3*, at anomaly 21 (49 Ma), which represents the second stage of the Eurekan deformation (Fig. 1d), the plate-tectonic situation changed, and Greenland moved more towards the NW resulting in compression-dominated tectonics along Nares Strait and dextral transpression along the boundary between Greenland and Svalbard. Greenland was still a separate plate, and sea-floor spreading went on in the Eurasia Basin, in the Greenland and Norwegian seas, the Labrador Sea and the Baffin Bay (e.g. Kristoffersen & Talwani 1977; Talwani & Eldholm 1977; Menzies 1982; Srivastava & Tapscott 1986).

Step 4 rrepresents the post-Eurekan stage, from anomaly 13 (36 Ma) to recent times (Fig. 1e). The sea-floor spreading terminated in Labrador Sea and Baffin Bay (Kristoffersen & Talwani 1977), but continued in the Eurasia Basin and Greenland-Norwegian seas (Talwani & Eldholm 1977). In the Miocene, the deep-water connection between the North Atlantic and the Eurasia Basin opened along Fram Strait. Greenland was now part of the North American plate again (Tessensohn & Piepjohn 2000), and there were no further strike-slip motions in the northern part of the Canadian Arctic Archipelago.

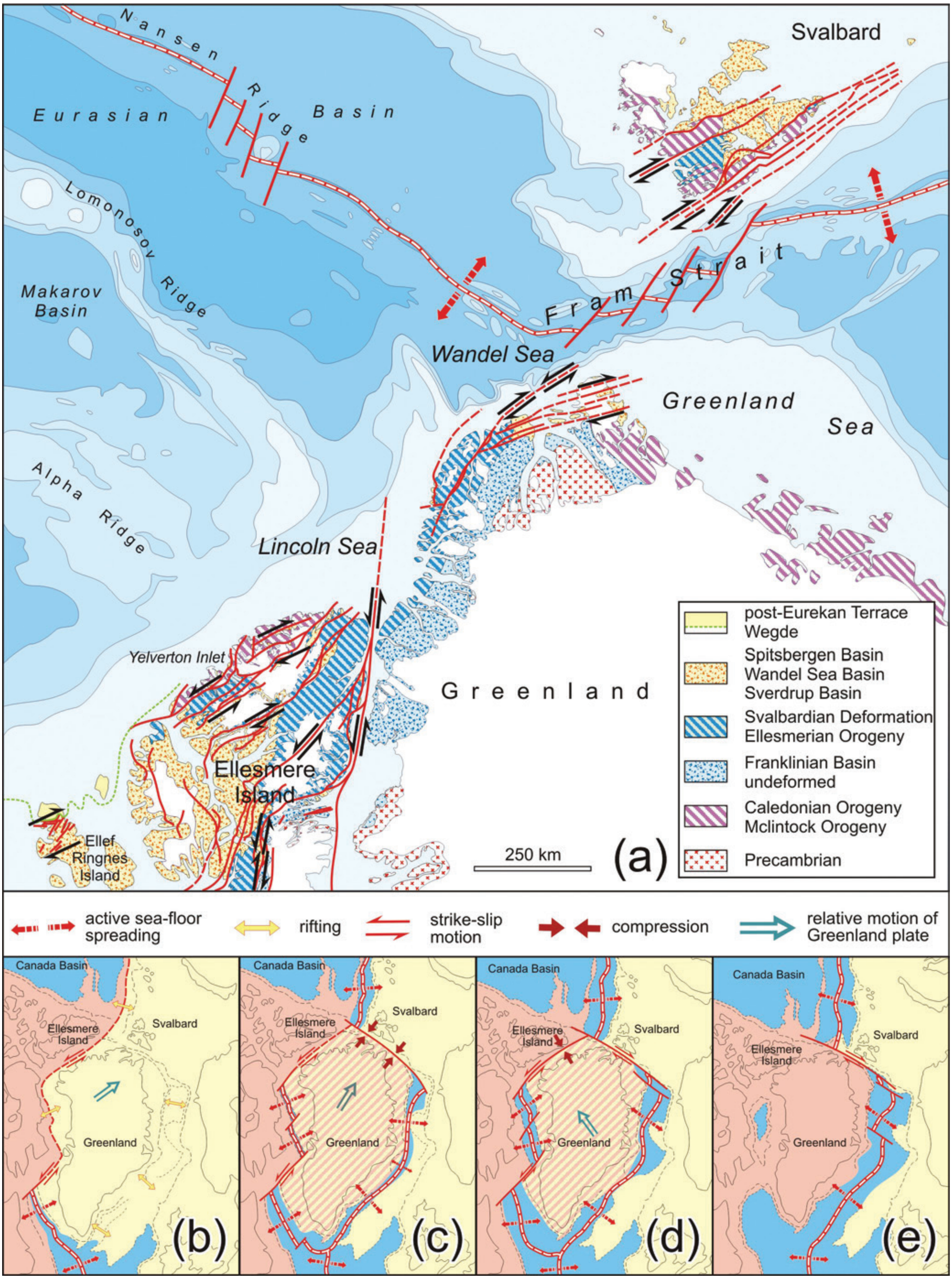

Fig. 1: (a) Tectonic map of Svalbard, North Greenland and the northern Canadian Arctic Archipelago showing the major fault zones along the northern margin of North America and the margin of the Barents Shelf (von Gosen et al. 2012; Piepjohn et al. 2013). (b) – (e) Sketch maps of the reconstruction of the different plate tectonic stages (modified from Tessensohn & Piepjohn (2000) and Piepjohn et al. (2013)): (b) (Step 1) pre-Eurekan situation at anomaly 31 (68 Ma), (c) (Step 2) first stage of Eurekan deformation at anomaly 24 (55 Ma), (d) (Step 3) second Eurekan stage at anomaly 21 (49 Ma), (e) (Step 4), post-Eurekan situation at anomaly 13 (36 Ma), followed by opening of the deep-water connection between the North Atlantic and the Eurasia Basin along Fram Strait in the Miocene.

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Added value through cooperation. News and information from Svalbard Science Forum (SSF) and the Research in Svalbard (RiS) database

Svalbard Science Forum

Svalbard Science Forum, Longyearbyen, Norway

The Svalbard Science Forum (SSF) is a part of the Research Council of Norway (RCN) and promotes coordination and collaborative efforts in research activities in Svalbard. Our objective is to contribute to the development of Svalbard as a platform for international research cooperation in the Arctic.

SSF Strategic Objectives:

- Increased cooperation within Svalbard research
- Increased coordination of activities
- Open sharing of data
- Reduced environmental impact

The SSF organises workshops and administers three funding schemes targeted towards the Svalbard research community. The deadlines for all the funding programs is October every year.

SSFs tasks include managing the database 'Research in Svalbard' (RiS) which contains information relating to more than 2200 Svalbard related projects. RiS is established in cooperation with the Norwegian Polar Institute and is a valuable source for information on previous, current and future research activities in the region. SSF is always working towards helping researchers and management and hopes to simplify and combine the RiS registration, Kings Bay registration and booking and application to the Governor of Svalbard in the new and improved RiS Portal which will be launched in 2014.

Data from the RiS data base reveals that despite the strong historical links to geological exploration in Svalbard's history and the establishment and location of the current settlements only about 10% of the current research projects are classified as 'solid earth'. However most of the current day mineral exploration done by Store Norske and other commercial companies is not included in the database. Also many geological projects do not require a permit from the governor and are therefore not forced to register in RiS. However RiS can still be a powerful tool for geologists to find cooperation partners, on-going projects or contacts within the scientific community. There are currently 81 active projects classified as solid earth, almost half of which focus on sedimentary rocks, and bedrock lithology.

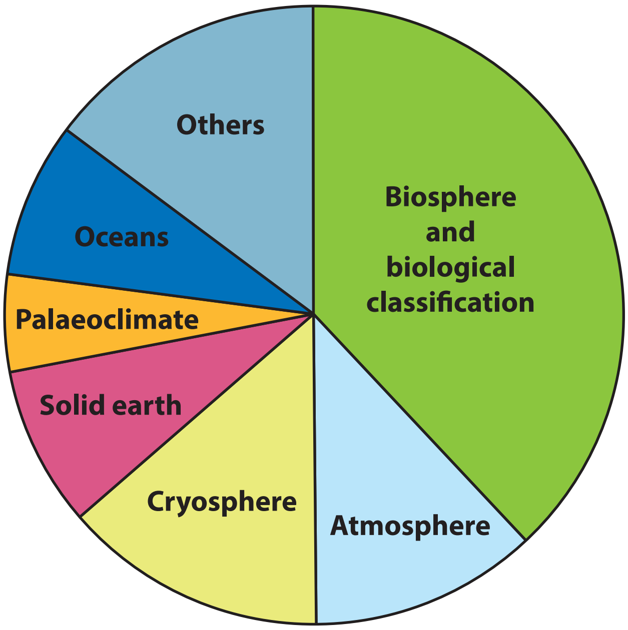


Fig. 1: Projects by topic for the RiS database, 2013

Appendix 1: 'Basements' in Svalbard

In the context of the present workshop title, as in many other contexts in Svalbard, the term 'basement' refers to the Caledonian deformed rocks of pre-Devonian age. This composite basement to the Old Red Sandstone on Svalbard has been referred to, in general, as the 'Hecla Hoek Complex'. One major aspect of the workshop, however, was to discuss the evidence for the various orogenic phases *within* this general 'basement', a significant number of which have been identified in the different provinces. These form the framework of the tectonostratigraphic subdivision, which still is not clear in many areas. In addition, angular unconformities with basement-cover relationships also exist within the Devonian succession – the products of erosion of the Caledonian mountains, deposited during the late Caledonian tectonic phases in intramontane basins. The following summary has been compiled by David Gee.

1. Archaean
Northeastern Basement Province

In northern Ny-Friesland, late Archaean orthogneisses (ca 2700 Ma), inferred to have underlain Palaeoproterozoic sandstones (the latter occurring now as xenoliths in ca. 1740 Ma old granites), comprise the oldest basement yet recognised in Svalbard.

2. Palaeoproterozoic
Northeastern Basement Province

The late Palaeoproterozoic granites (ca. 1740 Ma) intruded into (1.) above, together comprise the basement for the early-mid Mesoproterozoic quartzites of the Polhem unit (youngest detrital zircons ca. 1400 Ma) and related metasedimentary rocks that are all intruded by ca. 1300 old Ma dolerites.

3. Early Neoproterozoic, Tonian I (Nordaustlandet Orogeny)
Northeastern Basement Province (also Northwestern Province)

The late Mesoproterozoic (to earliest Neoproterozoic?) metasedimentary succession of the Smutsbreen Group (siliciclastics and carbonates) in Ny-Friesland, overlying and also overthrust by (2) above, are not intruded by the 1300 Ma old mafic dykes, and have yielded detrital zircons down to ca. 1100 Ma. These metasediments may well be of approximately the same age as the Brennevinsfjorden Group (including their correlatives on Helvetesflya) of siliciclastic, metasedimentary rocks on Nordaustlandet (detrital zircons reach down to ca. 1050 Ma).

On Nordaustlandet, the Brennevinsfjorden Group is deformed, metamorphosed (partly migmatised) and intruded by syn- and post-tectonic 950 Ma old granites. Together, these comprise the essential components of mid Tonian basement, the result of late Grenville-age Nordaustlandet Orogeny. This basement is unconformably overlain by the Kapp Hansteen (and Svartrabbene) calc-alkaline volcanics, also middle Tonian in age.

4. Early Neoproterozoic, Tonian II
Northeastern Basement Province

The Tonian volcanics and underlying late Grenville-age complex on Nordaustlandet together comprise the basement for the unconformably overlying Murchisonfjorden Supergroup. This Cryogenian (and perhaps late Tonian) sedimentary succession of sandstones passing up into dolomites and limestones is conformably overlain by the Hinlopenstretet Supergroup, comprising Marinoan tillites (with Archaean clasts) and then a Cambro-Ordovician sandstone to carbonate succession.

In Ny-Friesland, the relationships between the Lomfjorden Supergroup (Murchisonfjorden Supergroup correlative) and the underlying, more metamorphosed Planetfjella Group (also called Mosselhalvøya Group) remain to be clearly defined, but the Planetfjella siliciclastic metasedimentary rocks have detrital zircon populations as young as 950 Ma, as in the Murchisonfjorden Supergroup. (Clearly, more work on these relationships is needed).

5.Late Mesoproterozoic to Early Neoproterozoic (possible Grenville-age orogeny)
Southwestern Basement Province

In Svalbard´s Southwestern Basement Province, northwest of Hornsund, there is a late Mesoproterozoic (ca. 1200 Ma) igneous suite of both intrusive and volcanic rocks and associated metasediments, comprising the Eimfjellet Complex. This complex may be part of a Grenville-age basement to the Neoproterozoic sedimentary successions of southwestern Spitsbergen. However, their dominating amphibolite facies metamorphism has been dated to ca. 640 Ma (Torellian) and Grenvillian metamorphism has not been recognised.

6. Late Cryogenian (Torellian Orogeny)
Southwestern Basement Province

The Cryogenian sedimentary succession of the Southwestern Basement Province is interrupted by a major unconformity (Torellian), separating a younger succession, including tillites and reaching up into the Ordovician, from isoclinally folded and greenschist facies metamorphosed (ca. 640 Ma) older Neoproterozoic sedimentary rocks (see above).

7. Early/Middle Ordovician (early Caledonian Orogeny)
Southwestern Basement Province

Locally, within the Southwestern Basement Province (in areas south of St. Jonsfjorden), a high pressure, subduction-related, blueschist-eclogite association, the Vestgötabreen Complex, occurs thrust over Neoproterozoic formations. The high-pressure/low-temperature metamorphism has yielded ca. 470 Ma ages and the complex is unconformably overlain by late Ordovician limestones, conglomerates and Silurian shales and greywackes.

8. Latest Silurian to Early Devonian (main Caledonian Orogeny)
All basement provinces

In Svalbard´s Northwestern Basement Province, the overlying Old Red Sandstones of Devonian and probably latest Silurian age rest unconformably on metamorphosed successions that provide evidence of both the late Grenville-age orogeny and Caledonian migmatisation and granite intrusion of late Ordovician to Silurian age (as on Nordaustlandet, 3. above). The oldest components of the Old Red Sandstone succession comprise conglomerates and sandstones of the Siktefjellet Group, resting, locally, on Caledonian metamorphosed (probably late Ordovician), eclogite-bearing ortho- and paragneisses of the Richarddalen Complex, the latter including ca. 960 Ma old granites and gabbros.

A significant angular unconformity separates the Siktefjellet Group and underlying Richarddalen Complex from the overlying Red Bay Group of early Devonian fluvial conglomerates and sandstones. Deformation of the Siktefjellet Group prior to Red Bay deposition has been referred to as the Haakonian event.

9. Earliest Carboniferous (Svalbardian/Ellesmerian Orogeny)
Northwestern and Southwestern basement provinces

The Red Bay succession continues up into younger Devonian fluvial to shallow marine successions without significant discontinuities. Towards the end of the Devonian, the entire Old Red Sandstone succession and underlying basement was influenced by so-called Svalbardian (Ellesmerian) folding and faulting, followed by erosion; early Carboniferous shallow marine successions transgressed the entire archipelago.

Appendix 2: Recommendations from the workshop

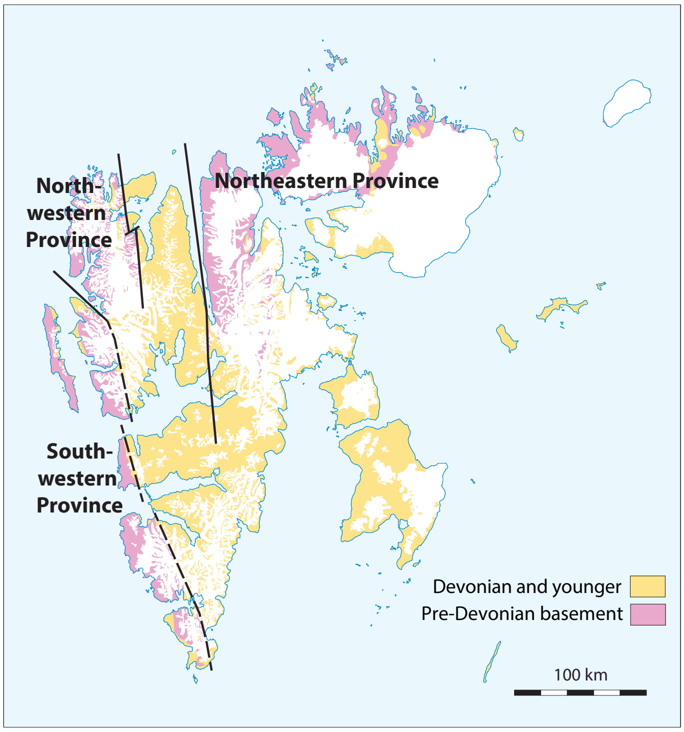
During the closing discussions, on the last day on board of Horyzont II, a number of recommendations were proposed to address the most outstanding problems relating to Svalbard's basement geology.

The collected recommendations refer to regional research topics in Svalbard, correlative studies between Svalbard and Greenland/Canada, enhanced collaboration with other disciplines, as well as the application of new scientific methods.

Regional research in Svalbard

In the context of large-scale tectonic reconstructions and the possible assemblage of crustal units from different terranes during the Caledonian Orogeny, all three basement provinces of Svalbard must be considered to be of equal importance. Studies of stratigraphy, structure and metamorphic history should be complemented with other investigations such as geochemical modeling of magma sources and detection of palaeomagnetic signals, and applied across the entire basement of Svalbard.

The Southwestern Basement Province exhibits an especially complicated tectonic history with the overprint of Palaeogene deformation, which is weak or absent in the other provinces. Correlations within and between various parts of the Southwestern Basement Province are controversial. This has resulted in a number of recommendations for research topics, which aim to unravel their internal tectonostratigraphy and sequences of events.



Recommendation No. 1:
Deciphering events in the Southwestern Basement Province affected by the West-Spitsbergen Fold Belt

Problems with interpretation of the Southwestern Basement Province are the result of a complicated sequence of deformation events prior to and during the Caledonian Orogeny, which were overprinted by the West Spitsbergen Fold Belt tectonics in the Palaeogene. Severe segmentation and tectonic juxtaposition of pre-Caledonian terranes, has made the evolution of the region difficult to unravel.

Recommendation No. 2:
Correlation and unification of nomenclature of basement stratigraphy in the Southwestern Basement Province

The Southwestern Basement Province extends over a large distance from north to south and various research groups have worked in different subareas. Consequently, unified stratigraphic and tectonostratigraphic nomenclatures have rarely been applied and meaningful correlations are difficult.

Recommendation No. 3:
Provinciality of igneous rocks of the Southwestern Basement Province

Geochemical investigations of the meta-igneous rocks of the Southwestern Basement Province are expected to provide important data on their geotectonic settings, which will further an understanding of the geotectonic history of the basement province and of the fold belt.

Recommendation No. 4:
Discrimination of Caledonian and older deformation events in the Southwestern Basement Province

In recent years, studies have identified deformation events that took place prior to the Caledonian Orogeny, such as the ca. 640 Ma old Torellian event. This discovery confirmed the importance of a Cryogenian-age unconformity, which had previously been thought to have been of Grenvillian age. Discrimination and timing of other Precambrian deformational episodes in the region are critical to further understanding of the geotectonic history of this basement province.

Recommendation No. 5:
Fault reactivation and basin evolution

Post-Caledonian sedimentary basins of Svalbard and elsewhere on the Barents Shelf have in many cases been controlled by the reactivation of pre-existing faults or shear zones within the basement. A better understanding of such basement structures will undoubtedly provide information on how they have contributed to the evolution of the sedimentary basins.

Recommendation No. 6:
Basement sources of younger clastics and thermochronology

A more detailed knowledge of basement lithologies is required to enable identification of the provenance of younger sedimentary basin fills throughout Svalbard. Such studies have been scant and few if any have been combined with thermochronological studies to understand basin evolution from inception to inversion and uplift. On-shore based studies of this type can act as proxies to help understand, in particular, hydrocarbon evolution in adjacent offshore basins.

Recommendation No. 7:
Defining the origin of Caledonian granites

Late Caledonian granitic intrusions of NW Spitsbergen (Albert I Land, Oscar V Land) and N Nordaustlandet, while being well known from an age and compositional point of view, are poorly understood geochemically. Geochemical modeling of the magma source generation would help to define the tectonic setting of Svalbard during Caledonian Orogeny. Identification of sources and evolution of granitic melt and associated migmatites will help to determine the range of interactions between mantle and crust in the convergent environment. Results from different Late Caledonian igneous provinces of Svalbard should be compared and correlated with adjacent Caledonian crustal units. These studies will provide new data to develop models for reconstructing the Arctic Caledonides.

Recommendation No. 8:
Composition of the lower crust and mantle beneath Svalbard

Of fundamental importance for our understanding of the Caledonian structure on Svalbard is the composition of the lower crust and upper mantle. Unique evidence has been obtained from xenoliths in recent volcanic vents located on both sides of the Breibogen Fault Zone in Svalbard´s Northwestern Province. More work is needed, in particular on the crustal xenoliths from both sides of this fault, to define the Caledonian structure.

Arctic correlation

Investigations of the Circum-Arctic tectonic evolution are a relative recent field of research, as significant data have become increasingly available during the last two decades.

Recommendation No. 9:
The extent of the Grenville-Sveconorwegian Orogen in the Arctic

Evidence for the presence of late Grenville-age Orogeny in eastern Greenland (Renlandian Orogeny) and on Svalbard (Nordaustlandet Orogeny) has been available since the mid 1990s. Sedimentary successions involved in this mid Tonian tectonothermal event host detrital zircon populations that were derived from source terrains similar to those in the type areas of the Grenville and Sveconorwegian orogens. The Grenville-Sveconorwegian Orogen may well have continued northwards into the high Arctic. This hypothesis needs further investigation; it influences not only reconstructions of the 1.0 Ga Rodinia super-continent, but also an understanding of the sgnificance of lithospheric inheritance for Caledonian Orogeny.

Recommendation No. 10:
Svalbard – NE Greenland/Pearya correlation

The Pearya Terrane of northern Ellesmere Island, like the basement of Svalbard, is interpreted to have been assembled during Caledonian Orogeny. The need for unravelling the tectonothermal history of Pearya is critical. Given the evidence that both areas, as well as northeast Greenland, were only a few hundred kilometres apart during the late Palaeozoic and Mesozoic, integrated stratigraphic, petrographic, including geochemical and isotopic studies are now needed to investigate any commonality in their respective evolutionary pathways.

Recommendation No. 11:
Reconstruction of the northern Iapetus Ocean development

The basement of Northeastern and Northwestern Svalbard is very similar to correlatives in the Caledonides of northeastern Greenland and the latter are well established parts of the Laurentian margin. Sedimentary and volcanic sequences intruded by magmatic rocks in Svalbard should be reinvestigated to see if they can be related to stages in the development of the Iapetus Ocean. Geochronology and stratigraphy of these rocks still need improvements and redefinitions.

Recommendation No. 12:
Torellian orogen and unconformity

The relatively recent unveiling of the 640 Ma old Torellian event in southwestern Svalbard, an approximate correlative of Timanian Orogeny along the northeastern margin of Baltica, raises the question of how significant this event was in terms of geotectonic origin and regional distribution. It would be important to know if it can be identified, not only in other areas in Svalbard, but also in northern Greenland and perhaps farther west in Pearya and beyond.

Collaboration/events

Recommendation No. 13:
Integration of geological and geophysical methods

Workshop participants unanimously expressed the need of better collaboration between geologists and geophysicists. Collaboration with geoscientific institutes that already have experience with Svalbard research, like Institute of Geophysics - Polish Academy of Sciences (IGF PAS), Fed. Inst. of Geosciences and Natural Resources (BGR, Germany), should be encouraged.

Recommendation No. 14:
Joint meeting at EGU in Vienna

The next General Assembly of the European Geosciences Union, held in Vienna, 27 April – 2 May, 2014, will be a convenient occasion to gather relevant researchers to continue discussions on the various aspects of Svalbard basement research. It is recommended, therefore, to arrange a special session on this topic.

Application of remote sensing/geophysical methods

Recommendation No. 15:
Broadening of application of remote sensing techniques

Remote sensing techniques such as SAR (Synthetic Aperture Radar), hyperspectral and ETM (Enhanced Thematic Mapper) data combined with ground-truthing are capable of providing a powerful array of new approaches to exploring the structure and composition of Svalbard's bedrock. To date these techniques have rarely been employed for bedrock investigations. They have, however, provided valuable new data for the investigation of glacial processes in Svalbard and other regions.

Recommendation No. 16:
New seismic profiling along the northern coast

Although seismic reflection profiling across the northern offshore area of Svalbard was carried out in the 1970s the results were not fully released and some reprocessing of the data could help to improve understanding of the tectonic architecture of the adjacent onshore regions. It is important to better define the continuation of the major faults onto the offshore platform and what kind of basement underlies, for example, the Devonian Basin of northern Svalbard. To better understand the entire Caledonian structure of this northwestern part of the Barents Shelf, a new wide angle and CMP reflection profile will be necessary. The results would be of importance for all other seismic studies of the region.

Recommendation No. 17:
Application of 3D-photogeology and 3D-structural modeling

3D-photogeology (photogrammetry) and 3D structural modeling (Svennevig, abstract, this volume) is a suitable method to obtain a large quantity of high-quality structural data in remote areas, where logistics are difficult. The application of the method to structural problems on various scales in Svalbard has the potential to solve long-standing geological questions – and rise many new ones – as recent results from eastern North Greenland have shown. The method could be applied using satellite or aerial images from previous surveys, or from oblique photos taken from ships, helicopters, snow mobiles or drones.

Recommendation No. 18:
Recognition of the palaeomagnetic record of Svalbard

Palaeomagnetism is the only method which can quantify the former position of the crustal units. Pre-Devonian palaeomagnetic records of the various terranes is still poorly recognized. Priorities: defining primary magnetic directions from the rocks which has not been subjected to Caledonian metamorphism, dating of secondary magnetic Caledonian overprints, integration of structural and palaeomagnetic studies in the West Spitsbergen Fold Belt, reconstruction of the basement geometry during the subsequent stages of deformation.

Recommendation No. 19:
Promoting young carriers in Svalbard geological basement topics

It is suggested to strengthen efforts to promote topics related to Arctic basement geology in universities. In particular, young scientists who conduct scientific investigations involved in SvalGeoBase topics should be encouraged and supported.

Short term goals

- Recommendations for the forthcoming years, based on already established cooperation and work plans:
- Promote collaboration of geoscientists working on the bedrock geology of Svalbard, northeastern and northern Greenland and northernmost Canada. Encourage interaction and exchange, both in the field and laboratories.
- Extend the previous studies of high-grade metamorphic rocks by the universities of Uppsala and AGH Kraków to other areas and more details, in collaboration with the Norwegian Polar Institute's mapping programme.
- Unwinding the Southwestern Basement Province in the West-Spitsbergen foldbelt as a collaborative effort between the Norwegian Polar Institute's mapping programme and the universities of Uppsala and AGH Kraków.
- Quantify positions of Svalbard's basement provinces using palaeomagnetism (in cooperation with PALMAG group – Inst. of Geophysics, Polish Acad. of Sciences /Geology Department, Univ. of Warsaw / Museum of Natural History, London).
- Define the origin of Svalbard's Caledonian granites – re-investigation of already collected material, resampling of Svalbard granitic bodies during the following field seasons (cooperation between NPI and Geology Department, Univ. of Warsaw).
- Reconstruct Early Palaeozoic palaeogeography of the NW part of the Barents Shelf based on palaeomagnetic and paleontological investigations of the Cambrian and Ordovician rocks of Svalbard (cooperation between Polish and Russian Academies of Sciences and Uppsala University).
- Structural and geological cross section through the northern part of Ny-Friesland between Mosselbukta and Sorgfjorden possibly in summer 2015 (cooperation between BGR, NPI and Yukon Geological Survey).

Appendix 3: Evaluation of the workshop

Scientific outcome of the SvalGeoBase workshop

- Defining the most significant knowledge gaps concerning Svalbard's geological basement;
- Improvement of dialogue and interaction between scientific groups working in different areas of Svalbard and on different topics;
- Systematization of knowledge concerning correlation of Svalbard's geology with adjacent Arctic regions (Northern Scandinavia, Greenland, Arctic Canada);
- Improvement of dialogue and interaction between research teams working in Svalbard with those from adjacent Arctic regions (GEUS, BGR, Russian Academy of Sciences);
- Defining nearest future priorities (see 'Recommendations');
- Defining possibilities of shared logistics in Svalbard and adjacent Arctic regions to reduce the environmental impact of field work;
- Presentation of funding possibilities for planned geological field investigations in Svalbard and adjacent Arctic regions, e.g. presentation of Svalbard Science Forum's Arctic Field Grants.
- Initiation of nearest future conferences/workshops straightly related to priorities of SvalGeoBase. Following meetings will constitute the core of SvalGeoBase community interactions and excellent platform for exchanging ideas, redefinition of actual priorities, initiation of new projects e.g. dedicated session on European Geophysical Union meeting in Vienna 2014: Basement – cover relationships in orogenic belts from Greenland to Svalbard: The Arctic gateway (co – organized) – conveners: Pierpaolo Guarnieri (GEUS), Jarek Majka (Uppsala University) – participants of SvalGeoBase.
- Initiation of cooperative projects – some projects have already been started as a direct effect of the workshop, e.g. 'Reconstruction of the Lower Palaeozoic palaeogeography of NW part of Barents Plat¬form based on palaeomagnetic and palaeontological investigations of the Cambrian and Ordovician rocks of Svalbard' - a cooperative project between the Polish and Russian Academy of Sciences.
- Exchange of ideas and experience between senior and young geologists participating in SvalGeoBase.

Experiences concerning organisation and logistics of the workshop

Participants of the workshop were selected and invited to represent important stakeholder institutions and most took up the challenge. Importantly, it provided an opportunity for a number of young scientists to become involved and bring new perspectives to the current state knowledge thus safeguarding future endeavour and innovation. The workshop also brought together, for the first time, participants with contrasting views and different experiences generating, as a consequence much discussion thoughout its progress.

The combination of field excursions and scientific presentations was unanimously considered to be worthwhile drawing as they did on the wide range of experiences represented by the participants. The event was an opportunity for scientists to become better acquainted and thus provide a more profound basis for future collaboration.

Appendix 4: Workshop participants

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Visit in Ny-Ålesund, view from the roof of NPI's Sverdrup Station. The vessel R/V Horyzont II in the background. Photo: W.K. Dallmann.

Visit at the Polish Polar Station in Hornsund. Photo: W.K. Dallmann.