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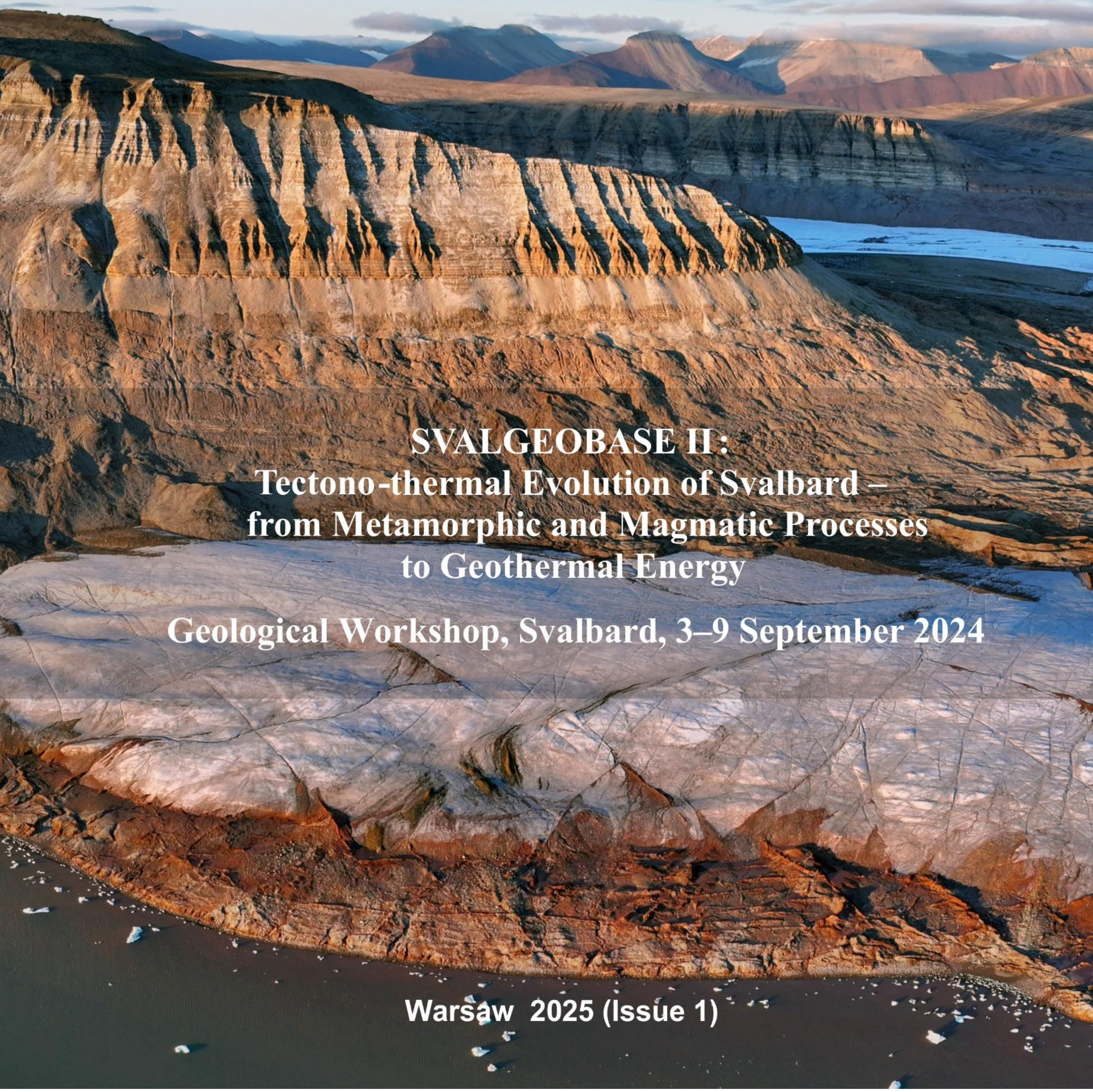

SVALGEOBASE II : Tectono-thermal Evolution of Svalbard – from Metamorphic and Magmatic Processes to Geothermal Energy

Geological Workshop, Svalbard, 3–9 September 2024

Warsaw 2025 (Issue 1)

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Editors:
Krzysztof Michalski, Jarosław Majka, Piotr Głowacki,
Lars Eivind Augland, Geoffrey Martin Manby,
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The University Centre in Svalbard, Department of Arctic Geology

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The University Centre in Svalbard

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Acknowledgements

The organizers would like to express their sincere gratitude to the Chief National Geologist, Prof. Krzysztof Galos, and the Ministry of Climate and Environment of the Republic of Poland for their support of the SvalGeoBase II workshop initiative.

We also extend our heartfelt thanks to all participants for taking part in SvalGeoBase II. It was our honor to have you on board.

Preface

We are pleased to present the report from the second edition of the geological workshop SvalGeoBase II, titled "Tectono-thermal evolution of Svalbard – from metamorphic and magmatic processes to geothermal energy". Held from September 3 to 9, 2024, in Svalbard, this event continued the legacy of the first edition, SvalGeoBase I, organized in 2013 under the theme "Proterozoic and Lower Palaeozoic basement of Svalbard – state of knowledge and new research perspectives".

Once again, this ambitious project aimed to host an Arctic scientific conference aboard an expedition vessel. Through multiple landings in the northern Spitsbergen region and Nordaustlandet, participants had the rare opportunity to engage in field discussions and closely examine rock outcrops that are at the forefront of ongoing scientific debates within the Arctic geology community.

The Svalbard Archipelago once again provided the backdrop for the activities of SvalGeoBase II. Svalbard's exceptional geological profile spans rocks ranging from the Early Proterozoic to the Neogene, offering a detailed record of this Arctic region's paleogeographic and tectono-thermal evolution. It reflects key processes such as the formation and breakup of the Proterozoic supercontinent Rodinia, the opening of the Iapetus Ocean, the Caledonian collision, and the more recent history tied to the expansion of young oceanic basins in the North Atlantic and the Eurasian Basin.

However, this edition of the workshop's objectives differed from those set 11 years ago. In addition to topics related to the evolution of Svalbard's Caledonian basement, the workshop agenda also included issues concerning the post-Caledonian tectono-thermal history of the archipelago and contemporary geothermal processes. Furthermore, while the first edition primarily served as a discussion platform for geologists with prior experience working in the European Arctic, SvalGeoBase II was designed to bring together specialists who had never conducted research in the Arctic before but offered unique expertise and innovative research approaches.

The scientists invited to the workshop represented a wide range of geosciences: large geotectonic reconstructions, palaeogeography, metamorphic petrology, mineralogy and mineral resources, structural geology, geochemistry, palaeomagnetism, digital geology, glaciology.

Participants included representatives from prominent institutions actively engaged in recent geological research on Svalbard: The University Centre in Svalbard – UNIS (Norway), University of Oslo – UiO (Norway), Institute of Geophysics, Polish Academy of Sciences – IG PAS (Poland), Uppsala University – UU (Sweden), AGH University of Krakow – AGH (Poland), Natural History Museum of London – NHM (Great Britain), and University of Warsaw – UW (Poland).

We were also honoured to host representatives from the following institutions on board: Ministry of Climate and Environment (Poland), Geological Survey of Denmark and Greenland – GEUS (Denmark), Curtin University (Australia), Stockholm University – SU (Sweden), University of Gothenburg – GU (Sweden), and Museum of Natural History (Sweden).

The workshop was organized and coordinated by a consortium of two institutions: (1) IG PAS (Poland), led by Dr. hab. Krzysztof Michalski and Prof. Piotr Głowacki, and (2) UU (Sweden), represented by Prof. Jarosław Majka. IG PAS took responsibility for the organization and logistics of the workshop, including the cruise and landings, under the leadership of expedition coordinator Dr. hab. Krzysztof Michalski.

The official partners of SvalGeoBase II included: (1) UiO (Norway) and (2) UNIS (Norway).

The SvalGeoBase II workshop received financial support from the Svalbard Integrated Arctic Earth Observing System (SIOS). Additionally, the workshop was partly funded by the EEA and Norway Grants 2014–2021 through the project HarSval – A Bilateral Initiative Aiming at Harmonisation of the Svalbard Cooperation (UMO-2023/43/7/ST10/00001).

Once again, the workshop's transport platform was the R/V Horyzont II, operated by the Maritime University of Gdynia. The organizers would like to extend their heartfelt thanks to Captain Ryszard Durlik and the crew for an outstanding voyage and the fantastic atmosphere on board throughout the journey.

We hope that SvalGeoBase II will foster effective collaboration among Arctic geologists and that this report will serve as a foundation for innovative new scientific projects and publications.

Krzysztof Michalski (IG PAS, Poland)

Jarosław Majka (UU, Sweden; AGH, Poland)

Piotr Głowacki (IG PAS, Poland)

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

SvalGeoBase Geological Workshop in the Context of Polish Polar Policy

Geological research on the Svalbard Archipelago began in the first half of the 19th century and intensified in the second half. Polish researchers joined these studies in the 1930s. In 1934 the first Polish scientific expedition to southern Spitsbergen occurred, involving two outstanding Polish polar geologists—Stefan Różycki and Stanisław Siedlecki. One of the key outcomes of this pioneering expedition was the development of a geological map of the then-unexplored and scientifically unknown areas of northwestern Torell Land. To this day, this work remains a cornerstone of Svalbard's geological literature.

The intensification of Polish scientific research on Spitsbergen, including geological studies, took place during the International Geophysical Year (1957–1958) under the leadership of the legendary Polish polar geologist Stanisław Siedlecki. These studies were focused on the Hornsund fjord region. Subsequent Polish scientific expeditions, initiated in the early 1970s and including geological research, concentrated on the northern areas of the Hornsund fjord, particularly in Wedel Jarlsberg Land and Torell Land in the southern part of Spitsbergen. Since 1978, these studies have been conducted continuously, based at the Polish Polar Station named after Prof. Stanisław Siedlecki in Hornsund, which has been continuously modernised and expanded. For many years, the station has been managed by the Institute of Geophysics, Polish Academy of Sciences in Warsaw.

In the following decades, Polish geological research on the Svalbard Archipelago intensified, initially focusing on the southern part of Spitsbergen. The early 21st century saw the expansion of these studies into other areas of Svalbard, along with the progressive development of research collaboration with scientists from different countries. One example of such cooperation is the SvalGeoBase International Geological Workshops, coordinated by the Institute of Geophysics of the Polish Academy of Sciences. The first edition took place in 2013, followed by another in 2024. In both cases, the research and training vessel m/s Horyzont II, operated by the Maritime University of Gdynia, provided an excellent platform for theoretical lectures while serving as a safe and convenient means of transport for workshop participants.

Since 2020, Polish research in the Arctic and Antarctic has been conducted within the framework of the Polish Polar Policy, a document approved by the Council of Ministers of the Republic of Poland. The Polish Polar Policy Task Force, operating continuously under the Ministry of Foreign Affairs, oversees its implementation, while the Committee on Polar Research of the Polish Academy of Sciences defines the key directions for scientific work in this field. The primary objective of the Polish Polar Policy is to ensure Poland's sustained and active presence in global polar dialogue, cooperation, and policy-making. One of its specific goals is to strengthen Poland’s presence in polar regions, particularly by fostering the development of scientific research activities in a highly multidisciplinary and interdisciplinary manner.

The SvalGeoBase Workshop plays a crucial role in fulfilling these objectives, particularly in geological research. It is hoped that this format of international cooperation in geological research on the Svalbard Archipelago will continue and develop further.

Prof. Krzysztof Galos
Undersecretary of State
at the Ministry of Climate and Environment
Chief National Geologist

Participant of the SvalGeoBase II workshop

SvalGeoBase II Objectives

SvalGeoBase II served as a multidisciplinary, international platform for critically evaluating current geotectonic and paleogeographic models, facilitating discussions on Svalbard's tectonic-thermal evolution, and laying the groundwork for future scientific collaboration—encompassing joint projects, field campaigns, and publications.

Initially, the field-based workshop aboard the research vessel "Horyzont II" was structured into three distinct thematic packages:

A. The jigsaw puzzle of Svalbard's tectono-thermal provinces – spatial relationships, paleogeographic positions, and geotectonic context.

B. From magmatic processes to climate change.

C. At the edge of the continental platform – the geothermal potential of Svalbard.

The priorities of SvalGeoBase II were defined as follows:

Elevating the scientific quality of research in Svalbard – 11 years after the first edition of SvalGeoBase, the current state of knowledge about Svalbard's Caledonian basement was once again reviewed. Significant knowledge gaps in the tectono-thermal history of Proterozoic and Phanerozoic Svalbard were identified.

Improved coordination of research activities – a strategy for upcoming investigations in Svalbard and adjacent Arctic regions, including Greenland and Ellesmere Island, which share a common geological history, was thoroughly discussed.

Enhanced collaboration between researchers and institutions in Svalbard – SvalGeoBase II serves as an ideal multidisciplinary platform to strengthen the research network among leading European scientific institutions focused on the geological evolution of Svalbard and the High Arctic as a whole.

Positioning Svalbard research within a broader pan-Arctic and global context – discussions focused on the paleogeographic relationships of Svalbard with adjacent paleocontinents, including Baltica and Laurentia, as well as its role within the Rodinia supercontinent.

Open sharing of data collected in Svalbard – discussions are underway regarding the creation of a detailed data repository and the implementation of an open-access strategy for published articles.

Minimizing the environmental footprint of research activities – coordinated plans for future fieldwork are being developed to maximize the scientific outcomes of expeditions while minimizing their impact on the fragile Arctic ecosystems.

Recommendations
from the SvalGeoBase II Workshop

1. SVALGEOBASE AS THE MULTIDISCIPLINARY SCIENTIFIC PLATFORM

Participants of the SvalGeoBase II workshop emphasized the need for an open Arctic scientific platform to bring together specialists representing various disciplines in Earth Sciences. In the context of Svalbard, the platform should cover all aspects of the geological development of the archipelago, including research on the evolution and assembly of metamorphic terranes/provinces of Svalbard from the earliest preserved, Archean crustal seeds to Cenozoic tectonics. The need to implement new, state-of-the-art research methods in Svalbard was highlighted. Therefore, the discussed platform should enable scientists with no polar experience to participate in Arctic research, e.g. by creating joint scientific projects, sharing previously collected material and reinterpreting data. At the same time, the University of Oslo (UiO), The University Centre in Svalbard (UNIS), and the Norwegian Polar Institute (NPI) were identified as the key Norwegian partner institutions for the ongoing and future geoscience Svalbard projects.

The previous edition of the SvalGeoBase workshop took place eleven years ago, in 2013. It was noticed that the SvalGeoBase community should interact with each other more frequently. This contact should take place at various levels:

A Information about key events, projects, and publications should be provided on the website and mailing list.

B Through regular conference meetings. For this purpose, the infrastructure of regularly held recognized conferences, e.g. AGU, EGU, ICAM, NGWM, may be used. Meetings could also be held in dedicated sessions or the “town hall meeting” format.

C Through regular field workshops in the Arctic, which will be held, for example, every 3–4 years. Targets could include S-SE Svalbard, the Mesozoic outcrops of South Spitsbergen, Edgeøya and Barentsøya, Scoresby Sund area – East Greenland. The unique character and effectiveness of this type of scientific meeting were emphasised, during which research topics can be directly discussed in rock outcrops. The R/V Horyzont II vessel offers only 20 berths for this type of workshop participants. This is not enough if the workshops were to constitute a platform for communication between experienced scientists and young geoscientists (PhD, MSc students).

Creating and maintaining the described infrastructure requires financial support and human resources. The “SvalGeoBase team” should maintain the website, communicate with the geological community, and organise conference meetings and field workshops.

2. PLACING SVALBARD RESEARCH IN A LARGER PAN-ARCTIC AND GLOBAL PERSPECTIVE

The 2.7-billion-year-old geological sections of Svalbard record the history of the evolution of the supercontinents Nuna (?), Rodinia and Pangea, and palaeocontinents Laurentia and Baltica.

Svalbard was an integral part of large geotectonic structures, e.g. the Iapetus Ocean, Arctic Basin and High Arctic Large Igneous Province (HALIP), and it is a unique place for the study of key global geological phenomena, such as the Neoproterozoic Snowball Earth episodes, the end-Permian mass extinction or True Polar Wander (TPW) events.

Participants of SvalGeoBase II highlighted the unique potential of Svalbard's research to address large-scale issues in regional and global geology. The priority for future Svalbard research should be a broader approach – placing Svalbard geological research in a larger pan-Arctic and international perspective.

The absolute priority is constant, stable cooperation with the Geological Survey of Denmark and Greenland (GEUS) and the continuation of projects focused on paleogeographic reconstructions of the North Atlantic and the correlation between Svalbard and Greenland geological records.

3. APPLIED RESEARCH IN THE ARCTIC

The unique quality and extent of rock exposures in Arctic regions (due to the lack of chemical weathering and poor vegetation) allow for incomparably more precise measurements of the geometry of tectonic structures, analysis of the tectonic and thermal evolution of rock complexes, and analysis of mineral resources.

The Arctic is a natural laboratory for applied research. SvalGeoBase II highlighted the potential of cooperation with industrial partners, e.g. in training highly qualified staff or researching high Arctic mineral deposits (this knowledge can be used in exploration at lower latitudes).

Participating in the workshop, a representative of the Polish Ministry of Climate and Environment, the Chief National Geologist, Prof. Krzysztof Galos, expressed the willingness of Polish industrial partners to cooperate with the geological community in applied research in the Arctic.

"The unique quality and extent of rock exposures in Arctic regions allow for incomparably more precise measurements of the geometry of tectonic structures, analysis of the tectonic and thermal evolution of rock complexes, and analysis of mineral resources". The photograph depicts the southwestern slopes of Palatiumfjellet in Ekmanfjorden, composed of carbonates and evaporites of the Permian Wordiekammen, Gipshuken, and Kapp Starostin Formations (from base to top). The sedimentary sequence is overlain by a Cretaceous doleritic sill, which constitutes the summit of the massif (drone image taken with a Mavic 3 Pro by Anna Sartell and Rafael Kenji Horota; VR Svalbard, Svalbox).

4. RELATIONSHIPS BETWEEN THE GEOSPHERE AND OTHER SPHERES – INTEGRATION WITH SIOS ACTIVITIES

Svalbard Integrated Arctic Earth Observing System (SIOS) is a natural partner for SvalGeoBase, and a significant part of our priorities are parallel to the issues underlined in the latest State of Environmental Science in Svalbard (SESS) Report 2024; Chapter 2 (Senger et al. 2025).

Reference

Senger, K., F. Ammerlaan, P. Betlem, M.-A. Dumais, G. Eagles, W. Foster, W.H. Geissler, S.-A.Grundvåg, A. Hodson, R.K. Horota, J.H. Hurum., M. Jones, H.P. Kierulf, J. Majka, L. Marsden, K. Michalski, A. Minakov, K. Ogata, S. Olaussen, P.T. Osmundsen, S. Planke, A. Ruppel, A.M.R. Sartell, G. Shephard, K.K. Śliwińska, L. Smeraglia, A. Smyrak-Sikora, C. Spiegel-Behnke, and V. Zuchuat (2025), Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL). **In:** Runge et al. (eds.), *State of Environmental Science in Svalbard (SESS) Report 2024*, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, 52–83, DOI: 10.5281/zenodo.14425478.

5. PREPARATION FOR THE NEW EDITION OF THE INTERNATIONAL POLAR YEAR (2032–2033)

One of the priorities of the SvalGeoBase community should be preparation for the next edition of the Fifth International Polar Year – IPY (2032-33). Upcoming Arctic geoscience projects should take into account the priorities defined by the organisations currently involved in the IPY Planning Group:

- Allow researchers and knowledge holders to capitalise on the outcomes of previous IPYs by expanding integrated and coordinated observations of accelerating changes and long-term monitoring required to understand current conditions and inform predictions of future states;
- Provide a comprehensive assessment of the operation and evolution of polar ecosystems, enabling a more holistic understanding of the Earth's interconnected systems and climate change trajectory and supporting practical global and local adaptation solutions;
- Build on the methodological, technological, and epistemological advancements of the 4th IPY (2007–2008), including significant shifts toward working across knowledge systems;
- Achieve a step-change in transdisciplinary polar research through meaningful integration of natural sciences, social sciences, humanities research, and indigenous knowledge systems.

6. PROMOTING EARLY CAREERS OF ARCTIC GEOSCIENTISTS

Transferring knowledge between generations of Arctic geoscientists should be one of the main goals of SvalGeoBase. It was underlined that offering courses in Arctic geology, geophysics, and polar logistics as well as safety courses, The University Centre in Svalbard (UNIS) is an excellent educational platform for early career scientists, including the students who complete their diploma theses in research institutions outside Svalbard. The Arctic Field Grants (AFG) was indicated as an excellent source of funding for students and young researchers conducting fieldwork in Svalbard and Jan Mayen. At the same time, it was emphasized that during future SvalGeoBase workshops, the organizers should provide an appropriate number of places for young scientists and PhD/MSc students (min. 1/4 of the available places).

PhD students from UNIS, Anna Sartell and Rafael Kenji Horota, using drone technology in Ekmanfjorden (Photo: Krzysztof Michalski).

7. COOPERATION WITH SSF AND SIOS AS THE GUIDELINES FOR THE FUTURE ACTIVITIES

SvalGeoBase should cooperate closely with the Svalbard Science Forum (SSF) and implement its information policy regarding new initiatives and ongoing projects. At the same time, SvalGeoBase's goals should reflect the mission of SIOS in terms of: a) sharing technology, experience, and data; b) closing knowledge gaps; and c) decreasing the environmental footprint of science.

8. SCIENTIFIC PRIORITIES – SVALGEOBASE VER. 2024

Following scientific issues related to the tectono-thermal evolution of Svalbard were recognized as priorities:

- **A Tectono-thermal evolution of Svalbard Caledonian terranes/provinces –** Despite decades of structural and geochemical investigations, the tectono-thermal evolution of the Caledonian crustal units which constitute today's Svalbard is controversial. The complete assembly of the different Caledonian terranes in Svalbard is still poorly constrained. A new methodological approach and more precise age determination of the metamorphic and magmatic events, including detrital zircon geochronology, are needed to link particular parts of Svalbard with their initial provenance. Integration of recent detailed, tectonic-magmatic and – metamorphic results from several of the terranes with improved paleogeographic models have the potential of refining models for the Caledonian Svalbard amalgamation and test models for large-scale strike-slip displacements during continental collisions.
- **B Quantification of the Eastern Svalbard pre-Caledonian paleo position** – Most Svalbard provinces were subjected to Caledonian metamorphism, resetting the previous paleomagnetic directions. Locations around Hinlopenstretet within the Eastern Svalbard Terrane (EST)/ Northeastern Basement Terrane (NBT), which lies outside the main Caledonian orogen, are potentially the only places where pre-Caledonian paleomagnetic record could survive. This creates a unique opportunity to reconstruct

the Proterozoic – Lower Palaeozoic positions of EST/NBT, studying its spatial relations to the adjacent Baltica and Laurentia as well as within the supercontinent Rodinia and test the Neoproterozoic True Polar Wander (TPW) hypothesis.

C **Climate change recorded in the past** – a paleoclimatological approach to the research on the dynamics of climate change and the factors that influenced the Earth's climate and biosphere in past geological epochs is a priority and, simultaneously, a challenge to modern Earth Sciences. Svalbard geological sections contain records of key events for the evolution of our planet, such as the Cryogenian glaciation, Permian–Triassic mass extinction, Cretaceous High Arctic Large Igneous Magmatism (HALIP), and the Paleocene-Eocene thermal maximum (PETM).

D **Integration of offshore geophysical data with onshore multidisciplinary data:**

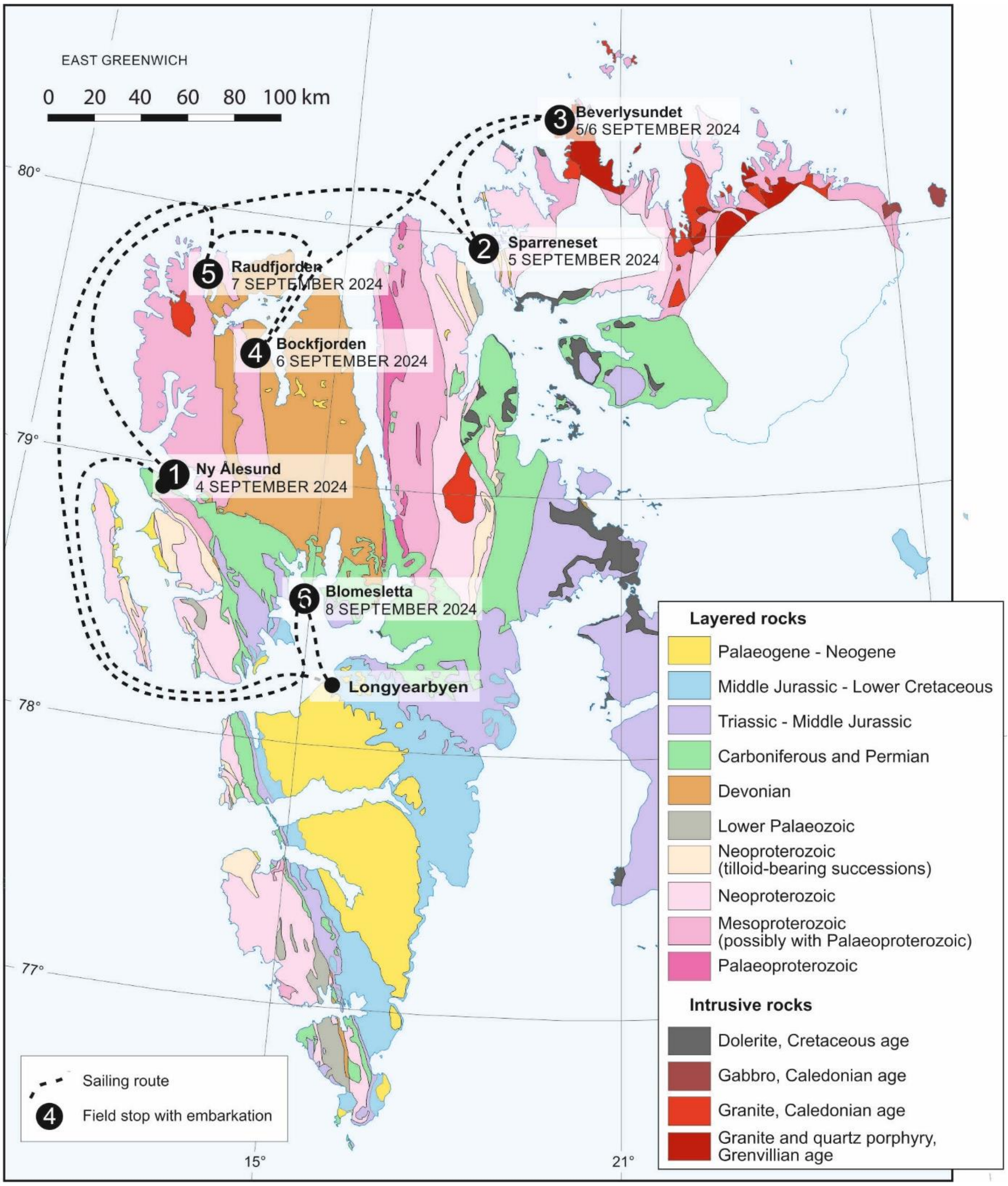
I. **Improving understanding of Svalbard post-Caledonian tectono-thermal evolution.** By Late Caledonian–Devonian time, Svalbard was adjacent to North Greenland. The Devonian–Permian tectono-thermal and sedimentary evolution of Svalbard and North Greenland, are linked to the assembly of supercontinent Pangea. Still, again, Svalbard's location needs better palaeogeographic control. During this interval, little consideration has been given to the thermo-tectonic controls on basin evolution, particularly the interaction between the crust and the mantle.

II. **The separation of Svalbard from North Greenland** and the formation of the West Spitsbergen fold and Thrust Belt are controversial. Better consideration of all the evidence is needed for a robust model. Svalbard's timing and changing location need a better definition. The North Atlantic Ocean opening together with the Nansen Basin, followed by the propagation of the Knipovich Ridge and related basaltic magmatism, have had tectonic-thermal consequences causing crustal thinning and uplift inducing widespread faulting on the western Barents Shelf, which is often overlooked on Svalbard. Given that offshore sedimentary basins host oil, gas, coal, and other mineral resources, there is a need for onshore geologists to collaborate more effectively with geophysicists.

E **Digital geology** – photogrammetry and drone technologies can undoubtedly aid enhanced reconstructions of Svalbard's primary extensional and contractional structural geometries and their kinematics. Paleomagnetic methods and Anisotropy of Magnetic Susceptibility (AMS) will help determine the age of successive tectonic stress fields and induced deformation stages

The list of selected projects conducted on Svalbard (since 2015) related to palaeogeography and the tectono-thermal evolution of the archipelago can be found in Appendix 4 of this report.

SAILING ROUTE



Geological map authored by the Norwegian Polar Institute, kindly provided by Dr. Winfried Dallmann.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Description of Field Excursions

Karsten PIEPJOHN, Geoffrey MANBY, Jarosław MAJKA, Krzysztof MICHALSKI,
Anna SARTELL, Szczepan BAL, and Rafael Kenji HOROTA

NY-ÅLESUND – BRØGGERHALVØYA (4 September 2024)

Objectives and geological background

On the 4 September, the SvalGeoBase II participants visited Ny-Ålesund to consider the effects of the Cenozoic Eurekan deformation on the Brøggerhalvøya (Fig. 1). The SvalGeoBase II workshop aimed to discuss the geological evolution of this arm of the West Spitsbergen Fold and Thrust Belt (WSFTB). The Eurekan structures have re-activated and/or overprinted earlier Ellesmerian, Caledonian, and Timanian structures. The West Spitsbergen Fold-and-Thrust Belt and the role of the offshore fault zones along the western continental margin of Spitsbergen have affected the Southwestern Basement Terrane of Svalbard and need further investigation (Fig. 2). In particular, the mapping, determination of the kinematics of the Eurekan structures and consequences of the resultant deformation are needed to recognize the effects of the Caledonian, Timanian, and/or possibly older orogenic events along the entire South West Basement Terrane.

The Eurekan deformation in Spitsbergen's central and southern parts is shown in Fig. 2 (after Piepjohn et al. 2016). Between Brøggerhalvøya and Sørkapp, the West Spitsbergen Fold-and-Thrust Belt can be divided into a basement-dominated domain 1 (brown) and a sediment-dominated domain 2 (green). Figure 2 shows that large parts of the West Spitsbergen Fold-and-Thrust Belt have affected the basement areas of Prins Karls Forland, Oscar II Land, Wedel Jarlsberg Land, and Sørkapp Land. The transport directions of the West Spitsbergen Fold-and-Thrust Belt are generally towards the ENE, with an exception at the northernmost end of the fold belt, where the transport directions turn into an NNE- to N-direction.

The kinematics and timing of the West Spitsbergen Fold-and-Thrust Belt is a matter of debate. Harland (1969), Birkenmajer (1972), Lowell (1972), Harland and Horsfield (1974), Kellogg (1975), and Steel et al. (1985) suggested that the fold belt was a transpressive strike-slip orogen developed at an intercontinental transform margin.

Later structural analyses led to the interpretation that convergent tectonics were predominantly responsible for most of the fold and thrust deformation (e.g. Craddock et al. 1985; Bergh

Fig. 1. Ny-Ålesund. From the left: Dr. Geoffrey Manby (NHM), Dr. Pierpaolo Guarnieri (GEUS), and Dr. Karsten Piepjohn (ex-BGR) discussing the geological structure of the Brøggerhalvøya Peninsula (photo: Szczepan Bal).

et al. 1988; Dallmann 1988, 1992; Maher 1988a,b; Maher and Craddock 1988; Nøttvedt et al.1988; Dallmann and Maher 1989; Maher et al. 1989; Bergh and Andresen 1990; Haremo et al. 1990; Welbon and Maher 1992). However, other authors (e.g. Lyberis and Manby 1993a,b; Manby and Lyberis 1996) consider the WSFTB to have been the result of Late Cretaceous – Palaeocene Svalbard-Greenland convergence following the opening of the Labrador Sea-Baffin Bay before the formation of the Central Tertiary Basin on Svalbard.

Tessensohn and Piepjohn (2000) and Piepjohn et al. (2016) proposed a succession of compressive and strike-slip events: the first tectonic phase of the Eurekan deformation on Svalbard was dominated by WSW–ENE compression with large-scale folding, detachment-faulting, and reverse faulting (Piepjohn et al. 2016). The Eurekan stage 1 was followed by major dextral strike-slip movements along NNW-SSE trending major faults (Hornsund Fracture Zone, Billefjorden Fault Zone, Lomfjorden Fault Zone; Fig. 2) of the Eurekan stage 2 (Piepjohn et al. 2016) and post-Eurekan extensional re-activation of the strike-slip faults. In contrast, Lamar et al. (1986); Manby and Lyberis (1992); and later Manby et al. (1994) using stress tensor (cf. also Lisle and Srivastava 2004) analyses across the Devonian Basin, including the Billefjorden Fault Zone, interpreted the deformation as the result of orthogonal compression. These authors also noted that the Mid-Carboniferous Monchiquite dykes at Krosspynten on the east coast of Andree Land are deformed, suggesting some possible WSFTB deformation.

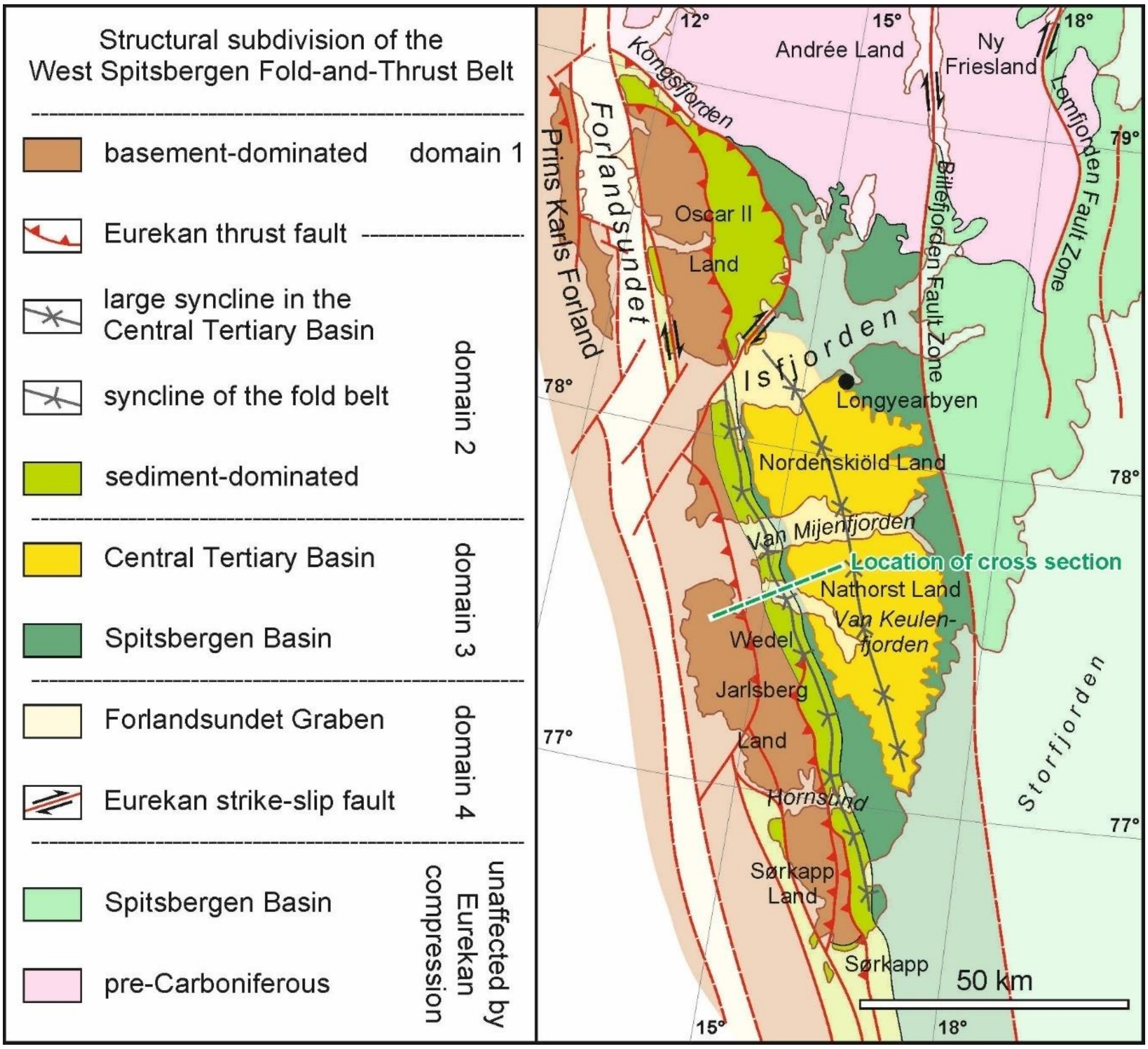

Fig. 2. Tectonic map of Spitsbergen showing the distribution of the Paleogene Eurekan deformation along the West Spitsbergen Fold-and-Thrust Belt – interpretation after Piepjohn et al. (2016).

Pressing scientific issues

- Better constrained field work that considers off-shore geophysical and further use of stress tensor analyses;
- Some reprocessing of the offshore geophysical data to greater depths across the Barents Shelf;
- A focus on obtaining isotopic ages of fault zones.

SPARRENESET – NEOPROTEROZOIC SUCCESSION (5 September 2024)

Objectives and geological background

One of Earth's most complete Neoproterozoic sequences is exposed in northeastern Svalbard. This unique region provides an exceptional opportunity to study climate fluctuations, including proposed global glaciation events and their impact on the evolution of life during this period. The Late Proterozoic was also marked by a major reconfiguration of lithospheric plates associated with the breakup of the Rodinia supercontinent. On the morning of 5 September, a field

Fig. 3. Landing on the Sparreneset Peninsula (Murchisonfjorden). Outcrop 1 (detailed description in the text). On the right side of the photo, red siltstones overlain by stromatolites – Backlundtoppen Formation(?)/Elbobreen Formation(?) (drone image taken with a Mavic 3 Pro by Anna Sartell and Rafael Kenji Horota; VR Svalbard, Svalbox).

trip was conducted to examine the geology and structures of the uppermost rock formations within the kilometre-thick Neoproterozoic sedimentary succession of western Nordaustlandet, northeast of Sparreneset (Fig. 3).

In the absence of radiometric dates, the local age models of the Neoproterozoic Murchisonfjorden sections are based primarily on lithostratigraphic and chemo-stratigraphic correlations (Hoffman et al. 2012; Halverson et al. 2018a,b), also correlated with other well-dated sections, located outside Svalbard, e.g. in Canada (Halverson et al. 2022). The stratigraphy of western Nordaustlandet is dominated by unmetamorphosed sedimentary rocks of the Tonian Murchisonfjorden Supergroup and the Cryogenian to Lower Palaeozoic Hinlopenstretet Supergroup (Fig. 4; e.g. Harland 1997; Halverson et al. 2022; Millikin et al. 2022). The Murchisonfjorden Supergroup primarily consists of clastic siltstones, sandstones, and quartzites, with some redbeds, which are exposed in the inner and eastern parts of Murchisonfjorden (Veteranen Group). The upper unit consists of limestones, dolomites, and stromatolites of the Akademikerbreen Group (Roaldtoppen Group). These rocks are overlain by limestones, dolomites, and diamictites of the Cryogenian Elbobreen Formation of the Polarisbreen Group (Gothiahalvøya Group), followed by post-glacial siltstones of the Ediacaran Dracoisen Formation and quartzitic sandstones and dolomites of the Lower Paleozoic Sparreneset Formation. The workshop participants visited outcrops representing the upper part of the Tonian Akademikerbreen Group, as well as exposures of the Cryogenian Polarisbreen Group.

In Outcrop 1, limestones of the Backlundtoppen Formation are exposed east of the landing site (Figs. 3 and 4). In the cliffs west of the landing site, a 10 to 20 m thick unit of red siltstones is exposed overlain by stromatholites. In the Neoproterozoic succession, similar red-beds are mainly exposed in the underlying clastic Tonian rock units, e.g., Raudstuped Formation, but there are also thin units of siltstones present in the uppermost Backlundtoppen Formation (Kinnvika Member) and in the upper Russøya Member of the Elbobreen Formation (Fig. 1b SPAR). The geological situation suggests that the red siltstones in Outcrop 1 are part of the Kinnvika Member between the limestones of the Backlundtoppen Formation below and the Elbobreen Formation above.

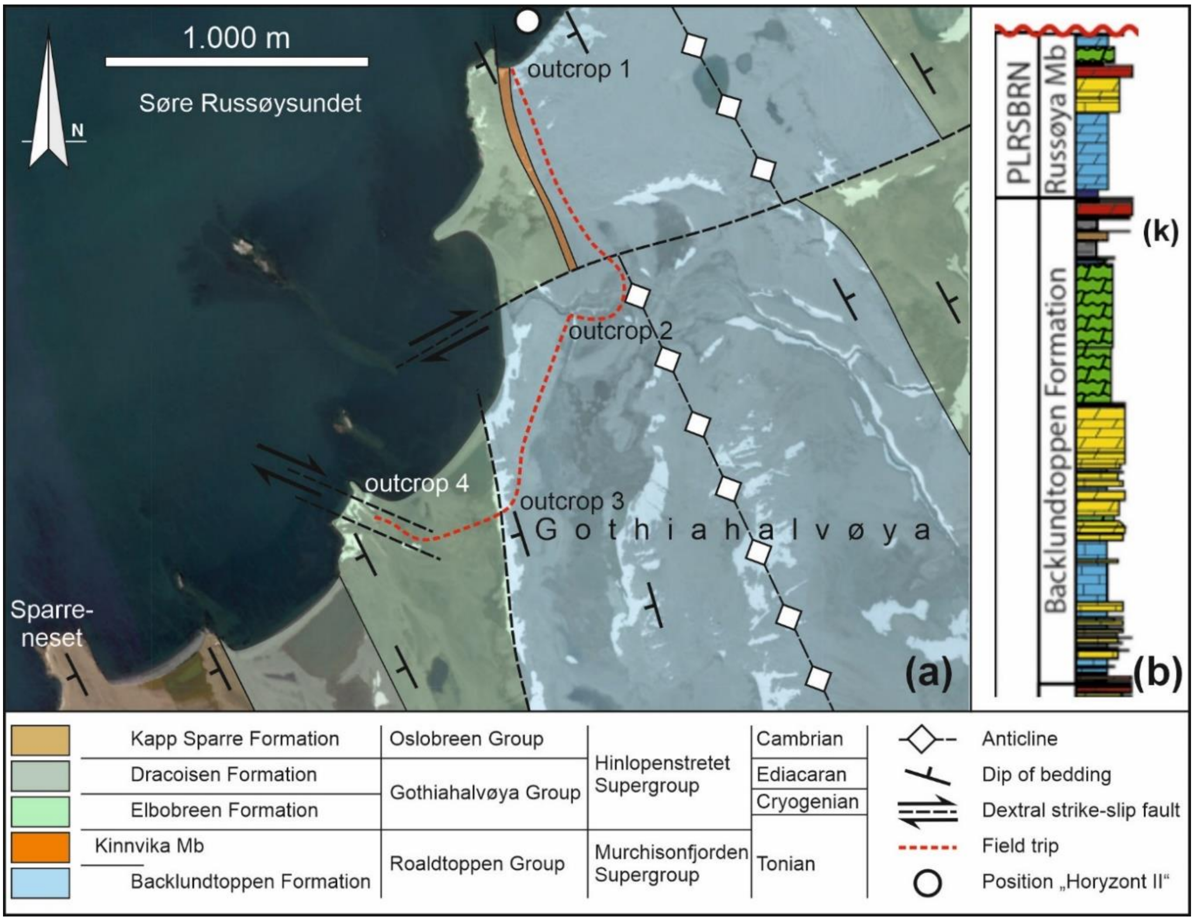

Fig. 4: (a) Geological map of the area NE of Sparreneset; (b) Stratigraphy of the Tonian to Cambrian succession east of Sparreneset (Halverson et al. 2022); (k) Kinnvika Member of the uppermost Backlundtoppen Formation (the figure containing the structural interpretation and stratigraphic scheme was modified by Dr. Karsten Piepjohn).

Outcrop 2 was located south of a WSW-ENE striking dextral strike-slip fault in black limestones of the Backlundtoppen Formation. In Outcrop 3 further southwest, stromatholites of the Backlundtoppen Formation contacts with diamictites of the Elbobreen Formation (Petrovbreen Member).The final outcrop (Outcrop 4) consists of thick, unbedded diamictites from the Wilsonbreen Formation (Figs. 4 and 5; on the map in Fig. 4, they represent the upper part of the Elbobreen Formation).

Structurally, the Murchisonfjorden area exhibits many characteristics of thin-skinned fold and thrust belts. The prominent NNW-SSE-oriented anticlinal folds display steep to overturned western forelimbs, often with evidence of thrust fault displacements. Subsidiary folds vary from upright to inclined structures, some associated with small-scale east-directed back thrusts. Conjugate shear faults related to brittle failure are noted on all scales.

The structure of the visited area is characterized by a large-scale, NNW-SSE striking anticline (Fig. 4). The area west of the anticline represents the gently to steeply WSW-dipping limb of the anticline consisting of sedimentary units of the Backlundtoppen, Elbobreen, Dracoisen, and Sparreneset formations (Fig. 4a). In outcrop scale, the deformation of the west limb of the anticline is characterized by the formation of metres- to tens-of-metres-scale subordinary, mostly ENE-vergent, folds and, in some cases, the formation of a steeply ENE-dipping fracture cleavage, which is mainly exposed in clastic rock units but mostly absent in limestones and dolomites.

Fig. 5. Outcrop 4 – matrix-dominated Wilsonbreen Formation diamictite at Sparreneset, SW Murchisonfjorden, with a large K-feldspar granite clast (photo: Krzysztof Michalski).

The large anticline and related folding, thrusting and cleavage-formation are part of a large, at least 60 km wide fold belt between the Veteranen Fault in Ny-Friesland (Spitsbergen) in the west and the Lady Franklinfjorden Fault (Nordaustlandet) in the east (e.g. Piepjohn et al. 2022). The large-scale folding has affected the entire Tonian, Cryogenian, Ediacaran, and Lower Paleozoic sedimentary succession across the Hinlopenstretet and therefore can be related to the Caledonian Orogeny.

The Murchisonfjorden area lie out of the main Caledonian tectonic-metamorphic zone. The original sedimentary structures are well preserved since the rocks here did not reach the anchi-metamorphic grade. The relatively low temperatures to which these rocks were subjected during the Caledonian orogeny potentially may have preserved the unique primary pre-Caledonian paleomagnetic record (Maloof et al. 2006; Michalski et al. 2023; Bal et al. 2025).

Pressing scientific issues

- Radiometric age determinations in the NE Svalbard Neoproterozoic sections, including detrital zircons analyses, are needed for provenance studies and maximum likelihood depositional ages (MLDA) determinations;
- Detailed paleomagnetic analyses in locations not subjected to Caledonian metamorphism to aid in distinguishing between primary Proterozoic and Lower Palaeozoic signals and secondary overprints related to Caledonian thermal alterations and Cretaceous magmatism;
- Testing Neoproterozoic True Polar Wander models – detailed paleomagnetic studies of Tonian Akademikerbreen Group, NE Svalbard.

SVALBARD NORDKAPP–METAMORPHIC BASEMENT (5/6 September 2024)

Objectives and geological background

Just before midnight on the 5 September, R/V Horyzont II arrived in Beverlysundet and was anchored in the innermost part of the sound east of Laponiafjellet (Figs. 6 and 7). The geology in this area is dominated by igneous rocks of the lower crustal level of Nordaustlandet (e.g. Flood et al. 1969; Gee et al. 1999; Johansson et al. 1999, 2001, 2004; Dallmann et al. 2002; Tebenkov et al. 2002; Elvevold and Dallmann 2014). Large areas of northern Laponiahalvøya and the islands in the north (Chermsideøya, Sjuøyane) consist of massive, coarse-grained granite bodies of the Kontaktberget Granite west and the Laponiahalvøya Granite east of Birdvågen (Fig. 6). The relation between both granite bodies is still a matter of debate: the question is if the Kontaktberget and Laponiahalvøya granites represent two different granites with an intrusional boundary and different ages or if they are just two varieties of the same granite with a transition zone between both varieties.

South of Beverlysundet and on Chermsideøya and Castrénøyane, dark-coloured metasedimentary rock units are included in the Laponiahalvøya Granite (Fig. 6) which are migmatized but partly show remnants of the structural inventory of the original metasediments which predate the intrusion of the Laponiahalvøya Granite. Concerning the geological maps, these rocks can be related to the Duvefjorden Migmatite Complex, widespread in the eastern parts of Nordaustlandet. A narrow occurrence of these migmatitic rocks was also exposed in the area visited by the SvalGeoBase II participants at Laponiafjellet.

A third granite is exposed in central Chermsideøya. There, granites of the Rijpfjorden Granitoid Suite have intruded the Laponiahalvøya Granite and the Duvefjorden Migmatite Complex (Fig. 6). The Rijpfjorden Granitoid Suite represents the youngest magmatic event on Nordaustlandet and was formed during the final stage of the Caledonian Orogeny (Gee et al. 1999; Johansson et al. 1999, 2004).

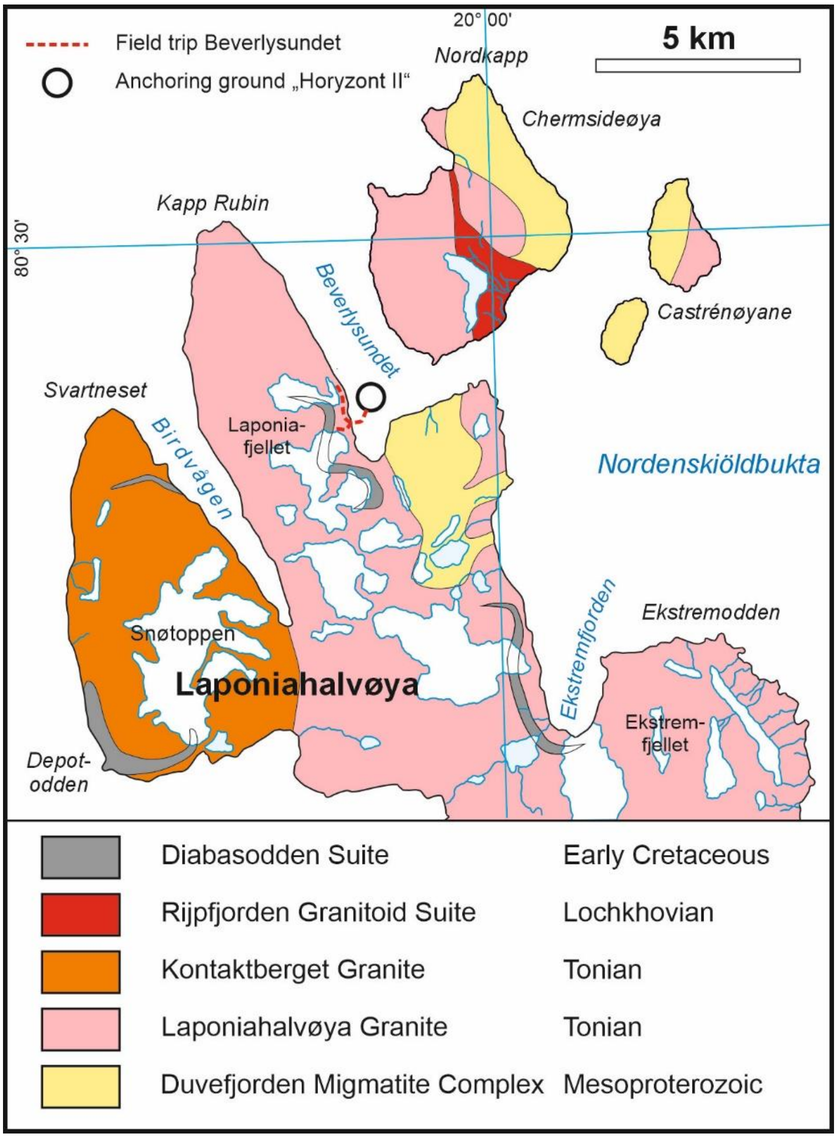

Fig. 6. Geological map of northern Laponiahalvøya, Beverlysundet, and Chermsideøya, modified from Elvevold and Dallmann (2014) (the map was modified by Dr. Karsten Piepjohn).

Fig. 7. Midnight, 5/6 September 2024. Nordkapp, Svalbard – vicinity of Beverlysundet. Aboard the R/V Horyzont II, Prof. Piotr Głowacki dreams of future polar expeditions (photo: Krzysztof Michalski).

The youngest rocks in the area are represented by up to 100 m thick Lower Cretaceous dolerite sills of the Diabasodden Suite at Depotodden, Birdvågen, Laponiafjellet, and Ekstremfjorden (Fig. 6). Except for the dolerite body west of Birdvågen, which dips gently to the S, the other dolerites represent horizontally intruded sills.

Due to the difficult accessibility of the north coast of Nordaustlandet, there are still several important questions regarding pre-Devonian geology, structural history, and the plate-tectonic evolution of the Caledonian and possibly older orogenies. A major question is related to the ages of the different igneous and metamorphic rocks on Nordaustlandet and whether the Grenvillian Orogeny has affected the Nordaustlandet Terrane or only the Caledonian Orogeny.

The widespread migmatites of the Duvefjorden Migmatite Group on Nordaustlandet were interpreted as being the result of the late Mesoproterozoic and early Neoproterozoic Grenvillian Orogeny (Harland 1997; Elvevold and Dallmann 2014) or the Palaeozoic Caledonian Orogeny (e.g. Tebenkov et al. 2002; McClelland et al. 2018). The same applies to the Kontaktberget and Laponiahalvøya granites: a late Grenvillian age (960–940 Ma) was suggested by, e.g. Gee et al. (1995, 1999), Johansson et al. (1999, 2004, 2005), and Tebenkov et al. (2002) whereas McClelland et al. (2018) interpreted a Caledonian (Silurian) age of the granites.

Further fieldwork and sampling are needed in the future concerning the age of the granites, migmatites, and deformation(s) in Nordaustlandet. As long there are no reliable and more detailed data, an interpretation and reconstruction of the Neoproterozoic and Palaeozoic plate tectonic evolution in this part of the Arctic and the relations of the basement terranes of Svalbard to the east coast of Greenland and the north coast of Greenland and Ellesmere Island (Laurentia) are not possible.

Pressing scientific issues

- High precision U-Pb dating of various generations of granitoids;
- Metamorphic evolution of migmatites;
- Better understanding of the paleogeographic position of the Nordaustlandet Terrane.

BOCKFJORDEN – CENOZOIC VOLCANISM/DEVONIAN BASIN (6 September 2024)

Objectives and geological background

On 6 September, the SvalGeoBase II participants visited the Sverrefjellet volcano in southern Bockfjorden. The eruptions that formed the present-day 500 m high volcano are 100,000–250,000 years old and sit on the Hekla Hoek bedrock west of the main Graben fault (Fig. 8). Interbedding of pahoehoe lavas, pillow lavas and coarse cinders at all levels within the edifice suggests that Sverrefjellet grew concurrently with the rise of the glaciers that surround it (Gjelsvik 1963; Skjelkvåle et al. 1989). The present volcanic edifice has been eroded; large erratic boulders on its summit show that it was completely buried during the last ice age, and

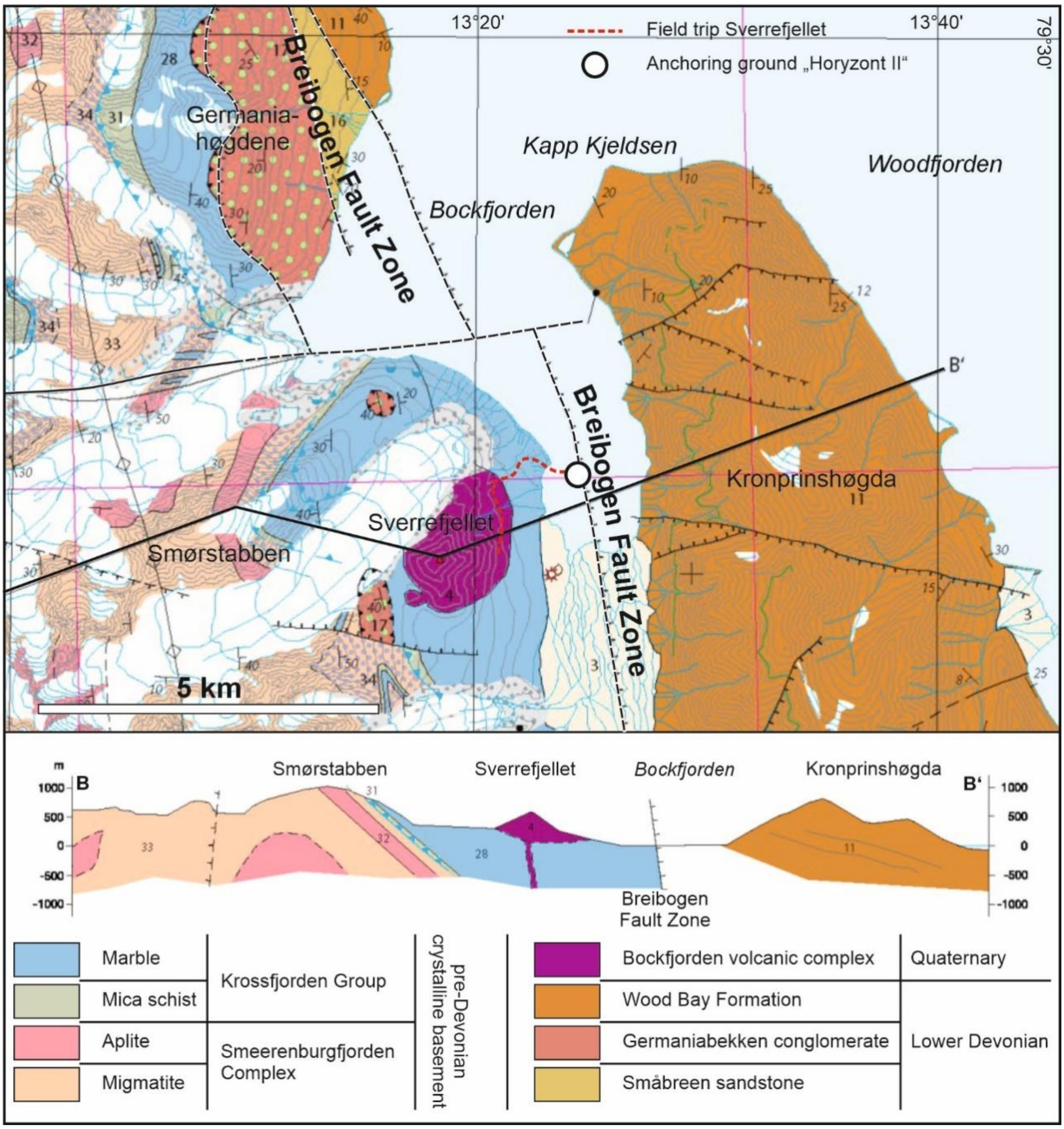

Fig. 8. Geological map of the area around Bockfjorden, after Piepjohn and Thiedig (1994) and Dallmann et al. (2005) (the map was modified by Dr. Karsten Piepjohn).

Fig. 9. Bockfjorden – Andrée Land Devonian Basin east of the Breibogen Fault Zone (archive drone photo: Rafael Kenji Horota; VR Svalbard, Svalbox).

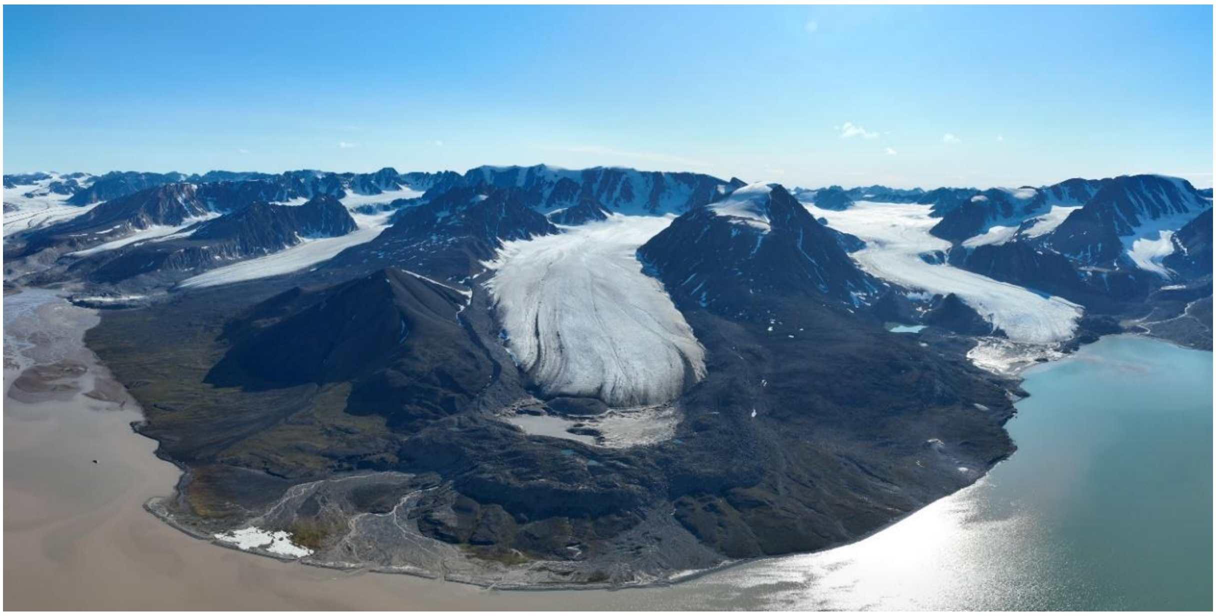

Fig. 10. Bockfjorden – Sverrefjellet volcano (left side of the photo) partially covered from the west by the Adolfbreen glacier. In the background, metamorphosed massifs of the Caledonian basement of Haakon VII Land (archive drone photo: Rafael Kenji Horota; VR Svalbard, Svalbox).

Adolfbreen partly buries its northern flank (Fig. 10). The remaining hill probably represents less than half of the original stratovolcano. Several studies (e.g. Jackson et al. 1984; references therein) have linked Tertiary to Quaternary basaltic volcanism on NW Spitsbergen to the development of the Yermak Plateau. Major deep faults, including the graben-bounding structures along Bockfjorden, probably localize the volcanism (Amundsen et al. 1987; Griffin et al. 2012).

The basement rocks west of the Breibogen Fault Zone are exposed in the main NNW-SSE trending Bockfjorden Anticline (Gee and Moody-Stuart 1966; Gjelsvik 1979). The core of the anticline hosts granitic rocks and migmatites of the Silurian Smeerenburgfjorden Complex (e.g.

Petterson et al. 2009) overlain by mica schists and marbles of the Mesoproterozoic Krossfjorden Group (Fig. 8). Migmatization, metamorphism, and deformation of the basement rocks are related to the Caledonian Orogeny. Tertiary basalt flows in sequences up to 150 m thick.

East of the Breibogen Fault Zone, kilometres-thick clastic deposits of the Old Red Sandstone are exposed. These are part of the 60 km wide and 170 km long, NNW-SSE trending Andrée Land Basin (e.g. Dallmann and Piepjohn 2020), which consists of at least 3 km thick red siltstones and sandstones of the Pragian/Emsian Wood Bay Formation (Friend and Moody-Stuart 1972; Figs. 8 and 9). The stratigraphic position of the isolated blocks of the Germaniabekken conglomerate and Småbreen sandstone at Germaniahøgdene within the Breibogen Fault Zone remains unclear. They may be related to the Lochkovian Red Bay Group of the Raudfjorden Trough west of the basement of the Bockfjorden Anticline. After the deposition of the Old Red Sandstone in Spitsbergen, both the Devonian sedimentary rocks and the pre-Devonian basement rocks were affected by the west-directed Svalbardian tectonic event (e.g. Piepjohn 2000; Dallmann and Piepjohn 2020) which can be correlated with the Ellesmerian Orogeny in northern Greenland and in the Canadian Arctic (McCann 2000; Piepjohn et al. 2015; Dallmann and Piepjohn 2020).

The 80 km, almost linear, Breibogen Fault shows a km-scale down-to-the-east offset at Bockfjorden. The base of the Andrée Land Basin between the Breibogen Fault in the west and the Billefjorden Fault Zone in the east is unknown. However, the activation of the Breibogen Fault is possibly a reason for the volcanic activity in the Pleistocene and the ongoing geothermal activity indicated by thermal springs north and south of Sverrefjellet.

Pressing scientific issues

- Regional geodynamic significance of Miocene and Quaternary volcanism in NW Spitsbergen;
- Deciphering relationship of magmatism and thermal hot springs with structural framework;

Fig. 11. Prof. Martin Whitehouse (Museum of Natural History, Sweden; blue jacket) and Prof. Simon Wilde (Curtin University, Australia; yellow jacket) at a xenoliths site in the Sverrefjellet massif (a frame from the film SvalGeoBase II, directed by Sławek Matczak).

- Analysis of the mantle xenoliths (Fig. 11) and other volcanics across northern Svalbard using modern geochemical methods;
- The stratigraphy and thickness of the Devonian Old Red Sandstone (Andrée Land Basin);
- Recognition of the Caledonian Basement underneath the Andrée Land Basin;
- Analysis of the offshore seismic profiles for extension of faults and Devonian Basin;
- Zircon U/Pb analyses of Devonian Basin Fill for provenance.

RAUDFJORDEN – THE CONVERGENT BOUNDARY (7 September 2024)

Objectives and geological background

The primary objective of the landing in Raudfjorden on the morning of 7 September 2024 was to reach the eclogite exposure in the western part of the fjord, north of the Rabotdalen valley (Fig. 12).

The group landed south of Alicehamna on the Svalisstranda coast, which is composed of rocks from the Princesses Alicefjellet Formation, a widespread quartz conglomerate within the Early Devonian Red Bay Group.

East of this formation lies a thin unit of garnet-mica schist with mylonitic textures (Montblanc unit), followed by garnet biotite-amphibolite gneiss of the Richardalen Complex (Fig. 13).

On the southern slope of Princesses Alicefjellet, north of Rabotdalen, an eclogite lens occurs within the biotite-amphibolite gneisses (Fig. 13). The protolith of this body was likely a mafic dyke that intruded into the gneisses before the Caledonian Orogeny, undergoing metamorphism under high-pressure/low-temperature conditions, similar to those found in subduction zone complexes.

The group reached the eclogite exposure after an hour’s walk from the coast.

The interpretation of the tectonic position, age, and geochemical analysis of the metamorphic complexes and post-Caledonian sedimental cover visited in Radfjorden can be found in the

Fig. 12. On the morning of 7 September Raudfjorden greeted us with a wintery landscape. The photo presents an eastward view of the snow-covered exposures of the Montblanc Unit and the Richardalen Complex, with Raudfjorden stretching in the background (drone image taken with a Mavic 3 Pro by Anna Sartell and Rafael Kenji Horota; VR Svalbard, SvalBox).

Fig. 13. Lenses of eclogite, surrounded by garnet-rich orthogneiss, represent mafic dykes that were metamorphosed under high-pressure conditions. South-eastern slope of Prinsesse Alicefjellet (archive photo 2023: Krzysztof Michalski).

following scientific articles: Gee (1966), Dallmeyer et al. (1990), Gromet and Gee (1998), Dallmann et al. (2002), Labrousse et al. (2008), Elvevold et al. (2014), Beranek et al. (2020), Dallmann and Piepjohn (2020), Koglin et al. (2022), Mazur et al. (2022), Dallmann (2015).

Pressing scientific issues

- Direct isotopic dating of eclogite facies assemblage using e.g. Lu-Hf and U-Pb garnet techniques;
- Modern P-T models for eclogites and their host rocks;
- Metamorphic evolution of the Montblanc unit;
- The paleogeographic position of the Richarddalen Complex during high-pressure (HP) metamorphism.

BLOMESLETTA – THE HIGH ARCTIC LARGE IGNEOUS PROVINCE (8 September 2024)

Objectives and geological background

The landmasses around Ekmanfjorden (Figs. 14–16), northern Isfjorden, are characterized by Devonian to Triassic sedimentary successions intruded by the Early Cretaceous Diabasodden Suite. An introduction to this magmatism on Svalbard was given in the abstract “Diabasodden and its Suite – the High Arctic Large Igneous Province on Svalbard (HALIP) and its type locality” (this volume). Ekmanfjorden is located ca. 45 km north-west from the type locality Diabasodden. Blomesletta, one of the most accessible places to observe these dolerites in Ekmanfjorden, is a low-lying coastal plain at the southeastern end of the fjord. Here, the magma intrudes the Permian carbonates and cherts, as can be seen at the exposed contact along the coast (marked with a red star in Fig. 14, see also the photograph of the contact in Fig. 15).

Nejbert et al. (2011) sampled the central part of this thick undulating sill and obtained a K-Ar date of 93.9 ± 3.3 Ma. Further HALIPs in this locality and others were visited during two extensive field campaigns in 2020 (led by A. Sartell) and 2021 (led by O. Galland). The geometry of the intrusions found in the Ekmanfjorden area is discussed in detail in Galland et

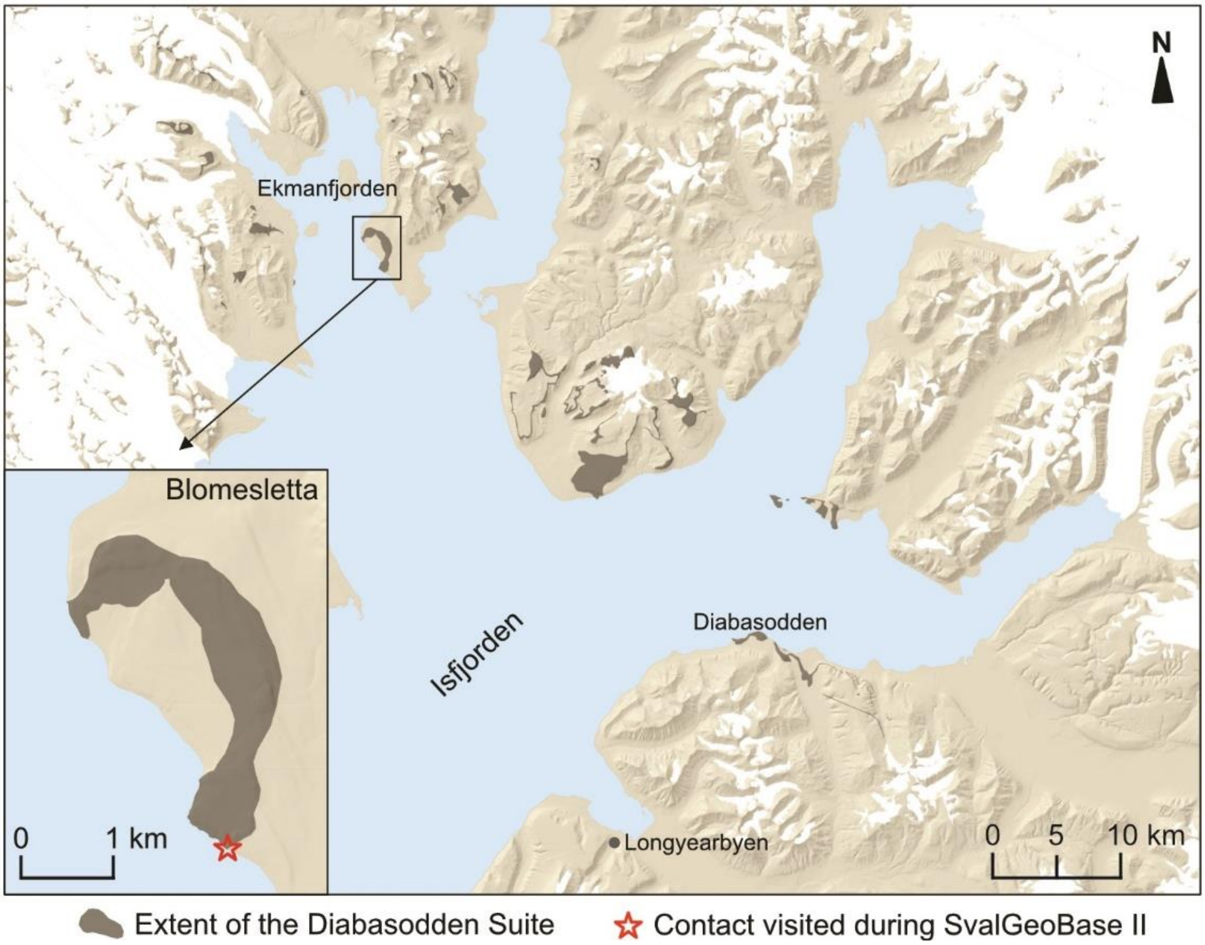

Fig. 14. Topographical map over central and northern Isfjorden, Svalbard, illustrating the extent of the High Arctic Large Igneous Province, regionally called the Diabasodden Suite, in dark grey. The inset map shows the intrusion visited at Blomesletta, Ekmanfjorden. Red star indicates the location of the contact between the dolerite and the Permian strata, visited during SvalGeoBase II. The glacier extents, land area and digital elevation are from the Norwegian Polar Institute (2014a,b), and the extent of the Diabasodden Suite is a modified version of the Geological map of Svalbard (Norwegian Polar Institute 2016), based on field observations made in 2020 and 2021.

al. (in revision). U-Pb geochronology of samples collected during these expeditions suggests that the magma was emplaced earlier than indicated by the K-Ar age (Sartell et al., in revision) and that the emplacement was coeval with the intrusion at Diabasodden, U-Pb dated by Corfu et al. (2013). The intrusions at Diabasodden and in Ekmanfjorden, including Blomesletta, were emplaced at ca. 125–123 Ma (Sartell et al., in revision; Corfu et al. 2013). Petrographically, Blomesletta dolerite has a similar composition to that described at Diabasodden, with plagioclase and clinopyroxene phenocrysts in a matrix of plagioclase, clinopyroxene and Fe-Ti oxides (Sartell 2021; see abstract “Diabasodden and its Suite – the High Arctic Large Igneous Province on Svalbard and its type locality” for more details on the petrography of the Diabasodden Suite).

Pressing scientific issues

- Further high-precision U-Pb dating of magma emplacement, along with comprehensive geochemical analyses (whole-rock, isotope, and mineral geochemistry), to investigate magma sources and the evolution of the HALIP on Svalbard in comparison to the circum-Arctic region;

- Research on magma-sediment interactions: examining contact metamorphism processes, the influence of magmatic intrusions on material migration within the sediments (including hydrocarbon migration), the release of volatile compounds into the atmosphere, and the subsequent climatic changes during the Cretaceous.

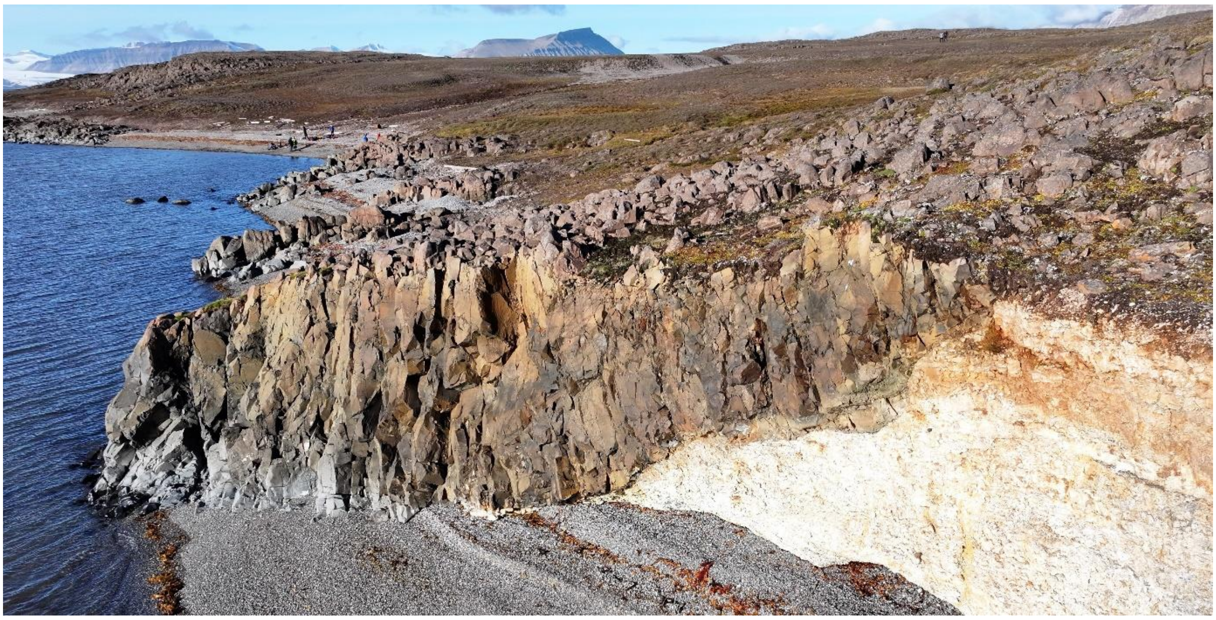

Fig. 15. Ekmanfjorden – Blomesletta. The contact between Permian sedimentary rocks of the Kapp Starostin Formation and a Cretaceous magmatic intrusion (drone image taken with a Mavic 3 Pro by Anna Sartell and Rafael Kenji Horota; VR Svalbard, Svalbox).

Fig. 16. R/V Horyzont II in Ekmanfjorden (drone image taken with a Mavic 3 Pro by Anna Sartell and Rafael Kenji Horota; VR Svalbard, Svalbox).

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ABSTRACTS
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The Eurekan West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya

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The northernmost segment of the West Spitsbergen Fold-and-Thrust Belt on Spitsbergen (Fig. 1a) is exposed on Brøggerhalvøya (Fig. 1b). There, the trend of the fold belt turns from a NNW-SSE direction between Sørkapp Land and Oscar II Land into an almost E-W direction and is truncated to the west by the eastern boundary fault of the Forlandsundet Graben (Fig. 1b). The tectonic transport directions and vergences of the folds are toward the northeast and north which is different to the general east-northeast transport directions in the southern continuation of the fold-and-thrust belt in Oscar II Land and south of Isfjorden. The Eurekan deformation on Brøggerhalvøya is dominated by mostly SW-dipping thrusts forming a stack of nine nappes with tectonic transports to the NE and locally to the N (Fig. 1b; Piepjohn et al. 2001b; Saalmann and Thiedig 2001, 2002). Near the coast of Kongsfjorden and in the western part of Brøggerhalvøya, the lower five nappes (Garwoodtoppen, Kongsfjorden, Kvadehuken, Kjærfjellet, Ny-Ålesund nappes) repeated the post-Caledonian succession and are characterized by flat-and-ramp geometries. In the southwest, the upper part of the nappe-stack consists of four nappes with steeply SW-dipping listric basal thrusts which almost entirely consist of basement rocks (Nielsenfjellet, Bogegga, Trondheimfjella, Moefjellet nappes). The Caledonian basement rocks and the post-Caledonian sedimentary rocks are folded and thrust-faulted together indicating thick-skinned tectonics. The second large-scale structure, characteristic of the Eurekan deformation on Brøggerhalvøya is represented by a kilometre-scale, NE- to N-vergent fold structure which is similar in size to the ENE-vergent folds in the central and southern segments of the West Spitsbergen Fold and-Thrust Belt (e.g., Braathen and Bergh 1995; Braathen et al. 1995; Manby and Lyberis 2001; Piepjohn and von Gosen 2001; von Gosen and Piepjohn 2001). This fold structure has been overthrust by the Nielsenfjellet nappe in the central part of the nappe stack.

Based on a simple line-length balancing of the nappe-stack along a cross section through Kjærfjellet and Scheteligfjellet, an average 60% shortening was estimated, corresponding to

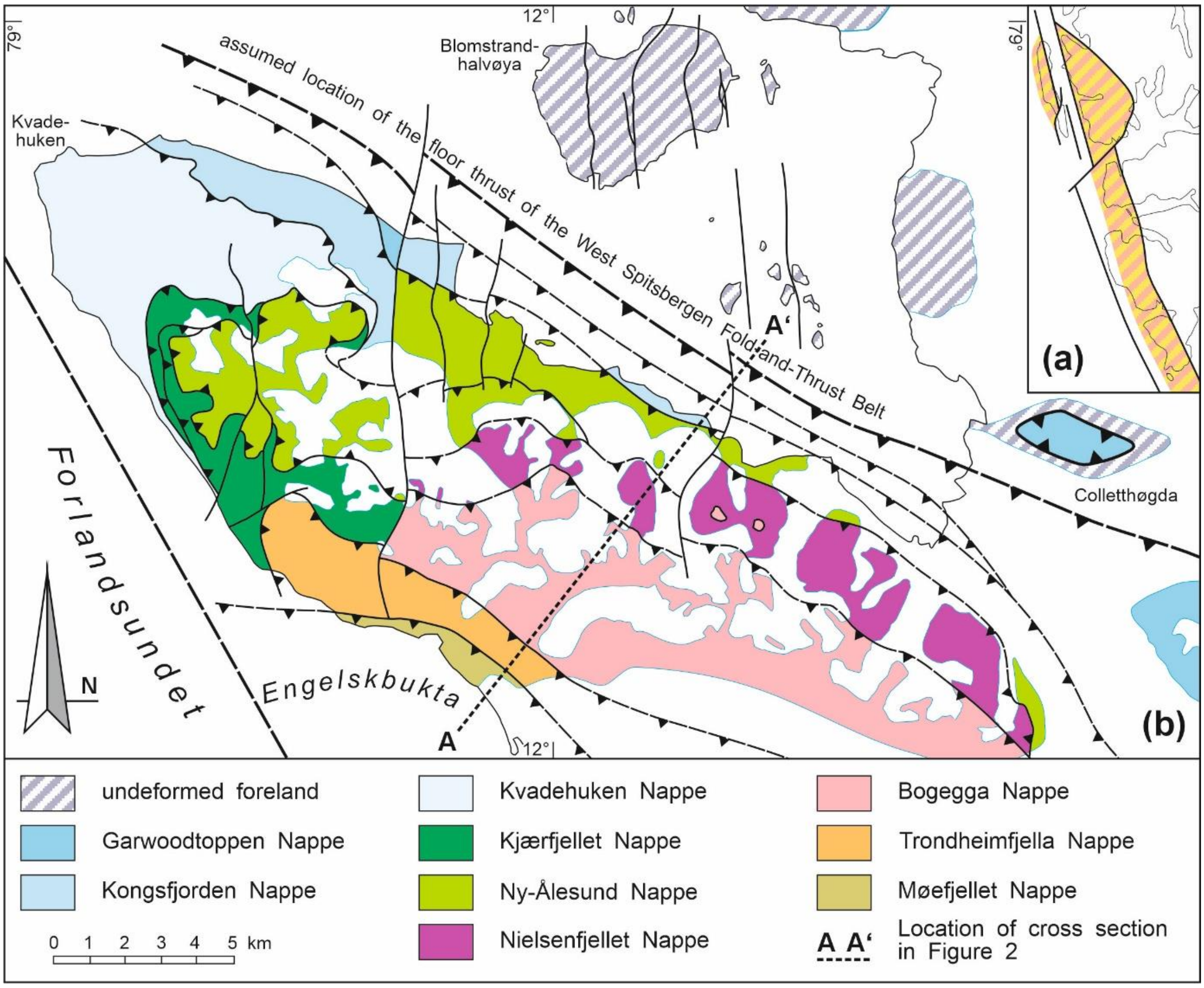

Fig. 1: (a) Location of the West Spitsbergen Fold-and-Thrust Belt between Sørkapp in the south and Brøggerhalvøya in the north; (b) Tectonic map of the NE-directed nine nappes or thrust sheets of the Eurekan West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya (Piepjohn et al. 2001a, b; Saalmann and Thiedig 2001, 2002).

11–27 km (Piepjohn et al. 2001b) that, with an appropriate amount of shortening for the basement-dominated nappes represents one of the highest amounts of shortening within the entire West Spitsbergen Fold-and-Thrust Belt.

The formation of the West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya can be separated into three stages (Saalmann and Thiedig 2001, 2002): The first stage (D1) was characterized by the structuring of thrust sheets along flats and ramps, predominantly involving post-Caledonian sedimentary rocks. This was followed by the second stage (D2) dominated by kilometres-scale folds (F2) involving the post-Caledonian sequence, the post-Caledonian cover succession and the D1-thrust sheets. During the third stage (D3), basement-dominated nappes were carried along listric thrust planes over the lower D1-part of the nappe stack truncating the F2 structure. The deviating vergences, despite the originally ENE-directed shortening during D2 also in this area, can be explained by the pre-existing basement topography causing oblique ramping on the sole thrust in Kongsfjorden and buttressing against the Nordfjorden High that was uplifted already in Paleocene times (Saalmann and Thiedig 2001).

The age of the Eurekan deformation and formation of the West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya is still a matter of debate, although the geological situation in the Ny-Ålesund coal mine (Orvin 1934) and at Orvin Gorge west of Zeppelinfjellet (Piepjohn et al.

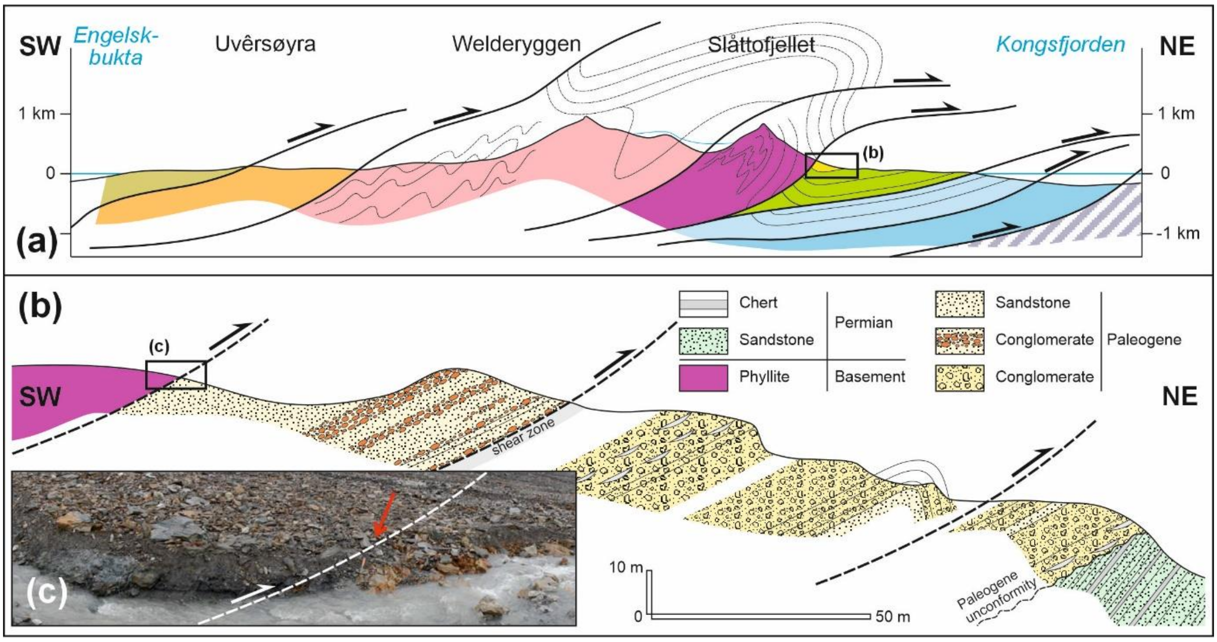

Fig. 2: (a) SW-NE-cross section through the Eurekan West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya. For legend see Fig. 1; (b) Outcrop situation of folded Paleocene conglomerates and sandstones overthrust by basement phyllites of the Nielsenfjellet nappe, redrawn from Piepjohn et al. (2001a); (c) Picture of the contact between basement phyllites (left) and Paleocene sandstones (red arrow) exposed after the retreat of the ice of Austre Lovénbreen in the last few years.

2001a) indicates that the Paleocene deposits were involved. Due to the retreating ice of Austre Lovénbreen a new outcrop was recentely exposed east of Slåttofjellet (Fig. 2). There, a gently SW-dipping succession of Paleocene sandstones and conglomerates unconformably overlies Permian cherts and sandstones (Fig. 2b). Lyberis and Manby (1993) have argued that undeformed Paleocene deposits unconformably overlie imbricated (deformed) Permian rocks east of Ny-Ålesund indicating that the Eurekan deformation pre-dated the deposition of the Paleocene rocks. The tectonic situation in the outcrop at Austre Lovénbreen, however, shows that the Permian rocks are not more intensely deformed than the overlying Paleocene sandstones and conglomerates (Fig. 2b). In contrast, the presence of local, NE-directed thrusts and NE-vergent folds in several metres-scale in the Paleocene strata (Fig. 2b) supports that they were involved in the deformation after their deposition. This is supported by the geological situation in this area, which indicates that the phyllites of the Nielsenfjellet Nappe were carried northeastwards over the Paleocene Ny-Ålesund Basin of the Ny-Ålesund nappe (Fig. 2a–c). This indicates that the formation of the West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya also took place during the first stage of the Eurekan deformation in the lower Eocene (Piepjohn et al. 2016).

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An Alternative Hypothesis for Forming the Eurekan Fold and Thrust Belts of Spitsbergen and North Greenland

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Abstract

The 300 km long, 80 km wide, NNE-NE-directed West Spitsbergen fold and thrust belt and the N-directed Eurekan fold and thrust Belt of North Greenland have much in common with foreland fold and thrust belts. Kinematic reconstructions suggest that before the opening of the Eurasian Basin and the Norwegian–Greenland Sea, Svalbard was linked to North America. The Greenland–Svalbard separation is widely believed to have occurred due to a right-lateral strike-slip along the De Geer Fracture Zone. Many models attribute the formation of both fold belts to dextral transpression along this fracture zone as Svalbard separated from Greenland. In this work, an alternative model explains the origin as the result of Greenland-Svalbard convergence driven by the anticlockwise rotation of Greenland during the opening of the Labrador Sea – Baffin Bay. The characteristics of Svalbard's fold and thrust belt are outlined, and the supporting evidence is critically assessed, ensuring the validity and reliability of our findings.

1. INTRODUCTION

Svalbard, situated on the northwestern margin of the Barents Sea shelf, separated from North Greenland during the opening of the North Atlantic and Arctic Ocean Basins in the Late Palaeocene-Eocene (CHRON 25/24, 59/56 Ma, Talwani and Eldholm 1977; Vogt et al. 1982; Srivastava 1985). From the Oligocene to the Recent Times, the northward propagation of the Knipovich Ridge (Dumais et al. 2021) led to a marked thinning of the broad continental crust along the western margin of Svalbard. This thinning was accompanied by significant subsidence and the deposition of thick Tertiary sediments (Myhre et al. 1992; Eiken and Austegard

1987). The stretching of the continental lithosphere subsequently gave rise to a 3 km uplift of the rift shoulder of Svalbard and explains the present elevation of the WSFTB and the 10-120 eastward tilt of the Central Tertiary Basin (Manby and Lyberis 1996 and references therein).

Svalbard and North Greenland were subjected to significant folding and thrust faulting. In the present-day locations, the NNE-NE-directed West Spitsbergen Fold and Thrust Belt (WSFTB) formed while the north-directed Eurekan Fold and Thrust Belt (EFTB) developed in North Greenland.

The WSFTB is widely accepted as characterised by foreland propagating fold and thrust belt deformation. The structurally higher thrust nappes, which involve the basement, are characterised by listric thrust faults, suggesting a thick-skinned origin. Further east, where the nappes involve the Lower Palaeozoic–Mesozoic sequences and have stair-case geometries, have a thin-skinned origin.

Our research presents two contrasting models for forming and timing the two Cenozoic fold and thrust belts in the North Atlantic-Arctic Ocean Realm. Over several years, we meticulously gathered and analysed field data, including stress tensor determinations, from the entire length of WSFTB and the Kap Washington area of the EFTB of North Greenland, ensuring a comprehensive investigation.

2. THE STRIKE-SLIP MODEL

Most of the authors propose that the Northeast-directed West Spitsbergen Fold and Thrust Belt (WSFTB) and the North-directed Thrust Belt of North Greenland were the products of dextral transpression motion along the De Geer Fault Zone (e.g., Harland 1969; Lowell 1972) in the Late Palaeocene. The separation of the Svalbard–Greenland Blocks was facilitated by an intervening zone of weakness first identified by De Geer (1926) as the De Geer Fracture Zone.

These models require that the fold belt formed between the Latest Palaeocene and Oligocene (56–36 Ma) times. The transpressional model's mechanism for forming the WSFTB is intricately linked to the age and strain recorded within the Tertiary rocks. The weak deformation recorded by the Tertiary rocks in the Central Tertiary Basin and the Kongsfjorden area is invoked to support an Eocene timing for the primary fold belt deformation (see discussion by Harland 1995 and Maher et al. 1995). Implicit in this hypothesis is that the entire Tertiary succession must pre-date the onset of the deformation. The uncertainty of the precise age of the terrigenous Tertiary sediments has led to controversy regarding the age and mechanism of formation of the West Spitsbergen Fold Belt. However, it has been noted (e.g., Steel and Worsley 1984) that there is no sedimentary record (intraformational breccias or conglomerates) of any marked tectonic activity during the accumulation of the Tertiary succession, underscoring the pressing need for more evidence. Furthermore, there is some uncertainty in the exact location of the De Geer fault zone. Indeed, reported geophysical evidence suggests that all the major faults are listric extensional structures and show little evidence of lateral displacement (e.g. Austegard et al. 1988).

The NNE-directed WSFTB and North directed Eurekan Fold Belt of North Greenland exhibit the near-normal angular relationship between the fault zones, and the fold and thrust transport directions contrast markedly with those developed in association with well-established incontrovertible strike-slip fault zones such as the San Andreas and the Dead Sea fault zones. To overcome this contradiction in their hypothesis, Harland (1995) and other authors (e.g. Maher et al. 1995) allude to a decoupled transpression model, which requires the presence of an unidentifiable offshore dextral strike-slip fault while the onshore compression direction is orthogonal to the continental margin. The decoupling hypothesis would, however, require that the upper crust of Svalbard behave as a ridged block during the WSFTB formation. The pre-Devonian rocks within the WSFTB are extensively affected by brittle and ductile structures, suggesting that the upper crust did not behave rigidly. Furthermore, the transpressional models invoke a series of complex motions between Greenland and Svalbard in a short period (e.g. Braathen et al. 1995). These models, based on structural evidence only, fail to consider that a 125 km thick lithospheric plate is characterised by a significant moment of inertia and rates of change of direction take place over many (10's) millions of years, not 2 or 3 as implied by the transpressional models (e.g. Braathen and Berg 1995).

It is worth noting that the slow-spreading Nansen Ridge in Eurasia Basin became active ca 56 Ma while on the North Atlantic seafloor-spreading along the Knipovich Ridge, from 20 Ma, propagated northwards to connect the two oceans via the Molloy Transform Zone (Dumais et al. 2021). Thus, the separation of Svalbard from North Greenland was achieved essentially by rotation of the former driven by seafloor spreading rather than by strike-slip along the difficult-to-locate De Geer Fracture Zone.

3. ALTERNATIVE MODEL

The model presented here was arrived at by combining quantitative analyses of plate kinematics, structures including folds, slip vectors on fault planes, and a stress tensor analysis of the entire fold belt. Our study aimed to determine the stress pattern related to the relative motion of Greenland and Svalbard. We measured the orientations of fault planes and slickenside lineations in meso- and mega-structures along the entire WSFTB and Central and Eastern Spitsbergen. Several measurements were taken from each location to minimise the effects of rotations. The chronology of fault motions was established from stratigraphic and field evidence. Folds, cleavages, tension gashes and stylolites were also considered. The data were collected over a seven-year field mapping programme. Additional data was collected while participating in the BGR-funded CASE I & II projects along the WSFTB (1992) and the Eurekan Fold Belt, North Greenland (1994). These observations confirm that the WSFTB and the early stages of the Eurekan Fold Belt deformation of North Greenland resulted from the significant Svalbard–Greenland convergence in the Late Cretaceous-Palaeocene. This convergence, accompanying the initial opening of the Labrador Sea and before the spreading in the North Atlantic and Arctic Ocean basins, is a critical element of the alternative hypothesis (Fig. 1).

It is important to note that numerical modelling (England and Jackson 1989) demonstrates that the width of the deformed zone across the boundary of two continental blocks is directly influenced by their relative motion. Convergence results in a wide deformation zone relative to length, while strike-slip leads to a narrow zone relative to the length. For instance, the 1000 km long dextral E Anatolian Fault only produced a 100 km fold and thrust belt with E-W folds and thrusts cut by NE-SW sinistral strike-slip. Most strike-slip fold belts are characterised by shear zones, rotated folds, and intersecting cleavages that develop as the folds rotate during the progressive strike-slip movement. While no such features are present in the WSFTB, it exhibits, instead, many characteristics found in well-known foreland-propagating fold and thrust belts, such as those in the Canadian Rockies, the Southern Appalachians, and the Moine Thrust Belt of Scotland.

Details of the main structural features of the WSFTB and the Eurekan Fold belt of the North Greenland fold and thrust belt are presented by Manby and Lyberis (1996), Lyberis and Manby (1999); Manby and Lyberis (2000) along with the stress tensor analyses from the entire length of both domains.

Srivastava and Tapscott (1986) present a model showing the successive positions of Svalbard and Northeastern North America for fixed Greenland before the opening of the Labrador Sea through CHRON 25, CHRON 13 times and the Present Day. This reconstruction shows the joint seafloor spreading along the Nansen and Knipovich Ridges. The De Geer Fracture Zone represents a zone of weakness, allowing the Greenland Svalbard separation. As the two ridges

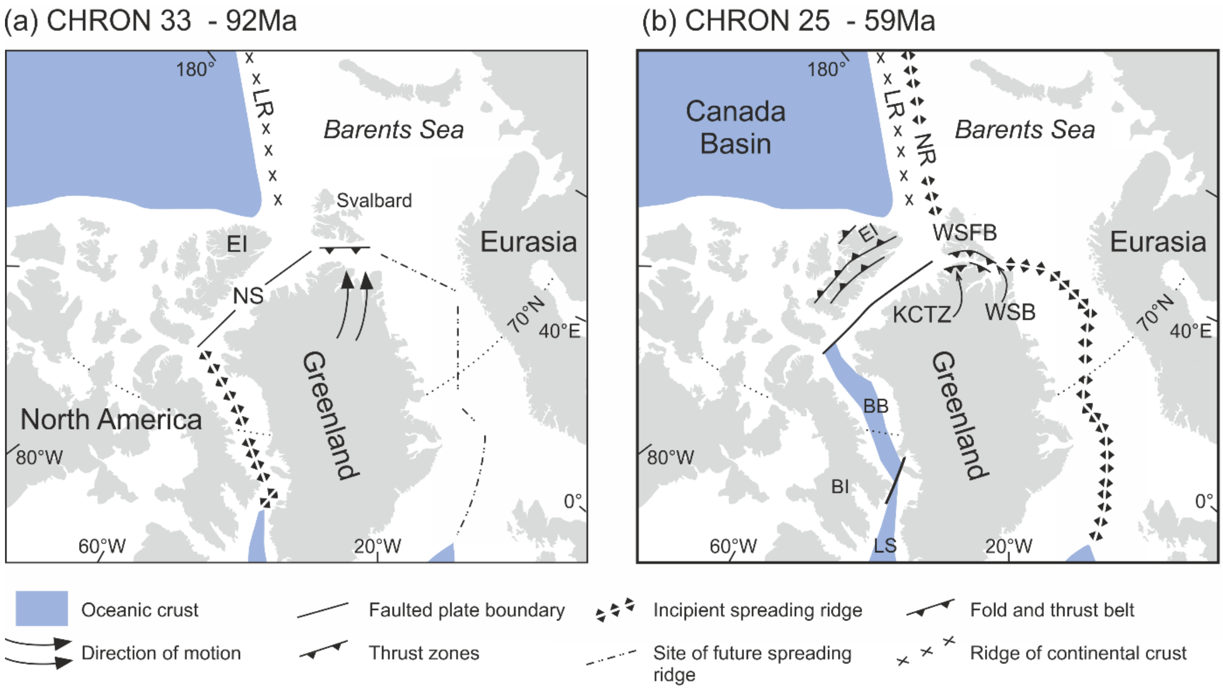

Fig. 1: (a) Greenland and Svalbard Relative positions at CHRON 33 (92 Ma). After Roest and Srivastava (1989), the kinematic model assumes that Svalbard was linked via Lomonosov Ridge to North America; (b) Greenland and Svalbard Relative positions at CHRON 25 (25 Ma). Abbreviations: BB – Baffin Bay, BI – Baffin Island, EI – Ellesmere Island, LS – Labrador Sea, LR – Lomonosov Ridge, NR – Nansen Ridge, NS – Nares Strait, KCTZ – Kap Cannon Thrust Zone, WSFB – West Spitsbergen Fold Belt, WSB – Wandel Sea Basin.

spread, Svalbard rotated globally from the initial De Geer weakness, implying that the De Geer Zone did not become a transform influencing the WSFTB deformation.

These Finite-Difference slip vectors for the CHRON 24–21 and CHRON 21–13 intervals, which give the relative motion of Svalbard concerning Greenland, are oriented N134 and N104, respectively. Such directions would provide a significant extensional component along the N160-oriented Greenland–Svalbard boundary, i.e., no offshore strike-slip fault. The transpressional models, which imply considerable compression across the Greenland–Svalbard boundary, are not supported by the above kinematics for CHRON 25/24–13 (59–36 Ma).

The present-day structure of Svalbard and the offshore region incorporates several N-S to NNW-SSE faults, some of which may be inherited from the Caledonian orogeny. As noted above, seismic reflection profiling of the western offshore region has identified several listric extension faults that cut through relatively undeformed post-WSFTB sediments. These include the Hornsund Fault and the Forlandsundet Graben. The geophysical profiling does not support the view that the two are strike-slip in origin or are linked to form a left-stepping pull-apart basin, as suggested in some transpression models.

4. SUMMARY

Most investigators agree that the West Spitsbergen, North Greenland Fold, and Thrust belts exhibit the same characteristics as other well-known Foreland propagating fold and thrust belts. In both regions, the fold axial traces and thrust front parallel the continental margin, and the principal stress axial trend is orthogonal to the continental margin and thrust fronts.

All well-established on-shore strike-slip regimes are characterised by fold axial traces arrayed at an acute angle to the main strike-slip faults. Such arrangements have yet to be recognised in Svalbard-Greenland.

Fold and thrust belts formed in well-established strike-slip regimes are characterised by rotated folds and intersecting transverse cleavages. Such features have yet to be recognised in Greenland and Svalbard.

The strike-slip model explains the deformation as the result of a decoupling or partitioning of the dextral strike-slip motion, which cannot be located along an ill-defined offshore fault zone(s). At the same time, orthogonal compression was applied across both continental margins as Svalbard separated from North Greenland.

The lack of certainty on the age of the Tertiary sediments on Svalbard, the weak nature of their deformational structures, and the proposal that these features can be attributed to the main Fold and Thrust Belt weaken the strike-slip model.

The model favoured here uses field and geophysical data, including kinematic reconstructions of the timing and causes of the Fold and Thrust belts' deformation.

Before the North Atlantic – Arctic Ocean Basins opened, the Svalbard–Barents Shelf was located North of Greenland. Kinematic reconstructions for the Cretaceous-Palaeocene time show that the opening of the Labrador Sea generated an anticlockwise rotation of Greenland towards the Svalbard–Barents Shelf block, initiating the deformation of the two.

The beginning of Svalbard's separation from North Greenland along the De Geer Fracture Zone coincided with the opening of the Eurasian Basin (ca. 59 Ma). There are conflicting opinions on the location of the De Geer Fracture off the west coast of Svalbard. Geophysical seismic reflection profiling indicates that most offshore faults are predominantly extensional, not strike-slip.

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Tectonic Evolution of the Wandel Sea Basin, Eastern North Greenland: Insights from Structural Data, Detrital Zircons Geochronology, Mineralogy, Fluid Inclusions, Vitrinite Reflectance and Conodont Color Alteration Index

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Abstract

The Wandel Sea Basin (WSB) in eastern North Greenland is represented by a Late Paleozoic-Mesozoic rock succession unconformably overlying Caledonian tectonic units. In Peary Land major NE-dipping normal faults cut through the basin and separate it in two sectors. In the Whyckoff Land sector towards the North-East, the WSB succession unconformably covers Paleoproterozoic quarzites and is folded and metamorphosed up to lower amphibolite facies. In the Herluf Trolle Land sector of the south-western part, the WSB succession is undeformed, non-mature and unconformably onto Silurian flysch and carbonatic rocks. Campanian detrital zircons in the Herlufsholm Strand Formation indicate a possible correlation of this area with the Late Cretaceous volcanism of Kap Washington and constrain the peak metamorphism to the Maastrichtian-Early Paleocene. The Late Paleocene-Early Eocene Thyra Ø Formation post-dates the folding and the paleostress obtained from fault-slip inversion along major normal faults indicates tectonic inversion with compression followed by strike-slip faulting.

Keywords: Eurekan deformation, North Greenland, transpression.

1. INTRODUCTION

The Wandel Sea Basin (WSB) was defined by Dawes and Soper (1973) as a post-Devonian basin unconformably overlying the Silurian flysch-type sequences and the Caledonian tectonic units. The sequence starts with Upper Carboniferous-Lower Permian siliciclastic and calcareous rocks of the Mallemuk Mountain Group followed by Mesozoic sandstones and black shales. The evolution of the basin follows a NE-SW extensional phase separating Greenland from Svalbard since Late Paleozoic time. The pioneering work made after the “Kilen Expedition” in the 1980 (Håkansson et al. 1993) defined the basic geology, stratigraphy, and structural geology of eastern North Greenland and culminated with peer-reviewed papers, reports, and geological maps in the 1990s and later.

The general view of the authors was to relate the tectonic evolution of the area to strike-slip tectonics (Pedersen and Håkansson 1999; Håkansson and Pedersen 2001; 2015). The NW-SE trending faults referred to the Trolle Land Fault System, associated with the rift phases during the development of the WSB were interpreted as strike-slip faults active during the Late Cretaceous-Early Paleocene associated to the Wandel Hav strike-slip Mobile Belt (Håkansson and Pedersen 2001). The authors correlate this fault system with similar fault trends in the Kronprins Christian Land area. In particular, major evidence for strike-slip movements associated with this fault trend was interpreted from the offset of basement rocks that crop out in the Amdrup Land area. Here Carboniferous limestones unconformably rest on basement rocks and metasediments referred to the Independence Fjord Group (Fig. 1). Since similar rocks that crop out along the Caledonian front to the NW are interpreted to be part of the same tectonic unit, the consequence is almost 50 km of right-lateral movement accommodated along the fault.

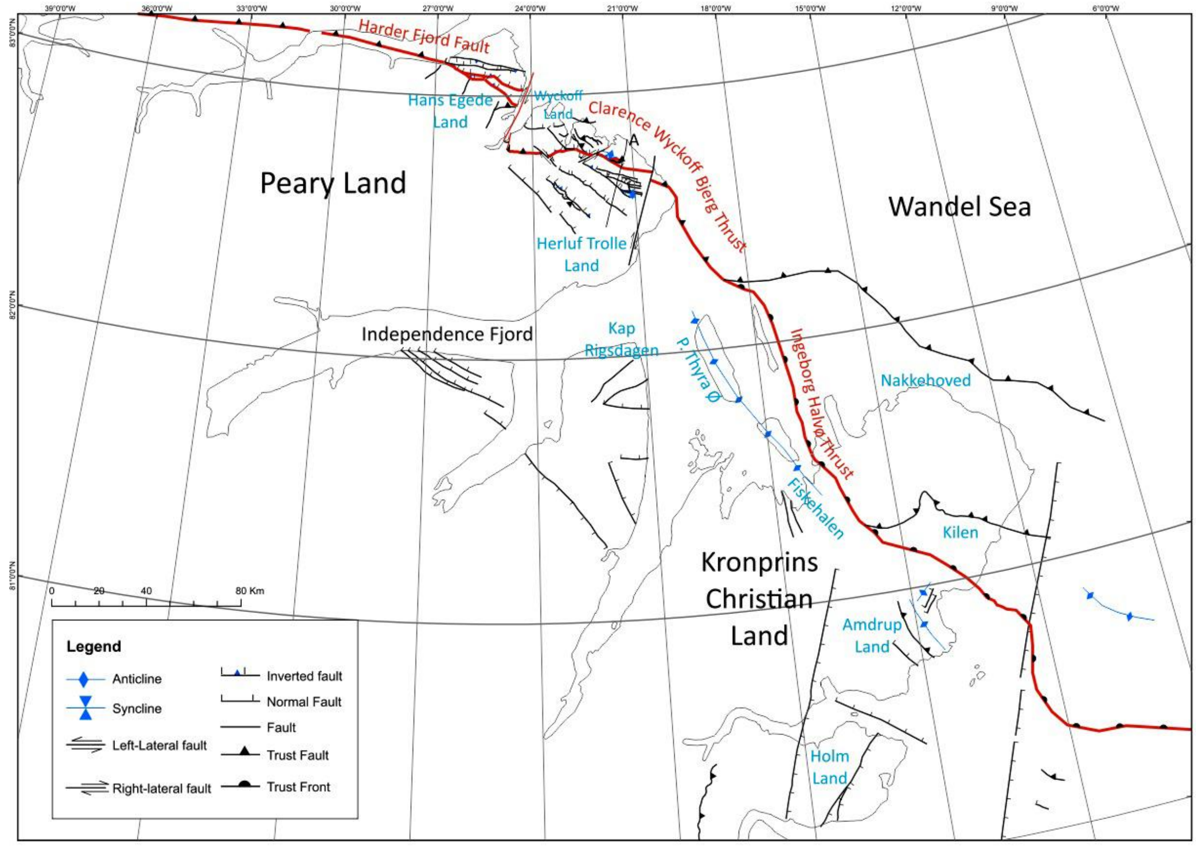

Fig. 1. Structural map of eastern North Greenland from Peary Land to Kronprins Christian Land. The Harder Fjord Fault together with the Clarence Wyckoff Bjerga Thrust and the Ingeborg Halvø Thrust represent the tectonic contact between metamorphic rocks of the Wandel Sea basin and immature rocks of the basin. A-location of the geologic cross-section shown in Fig. 2.

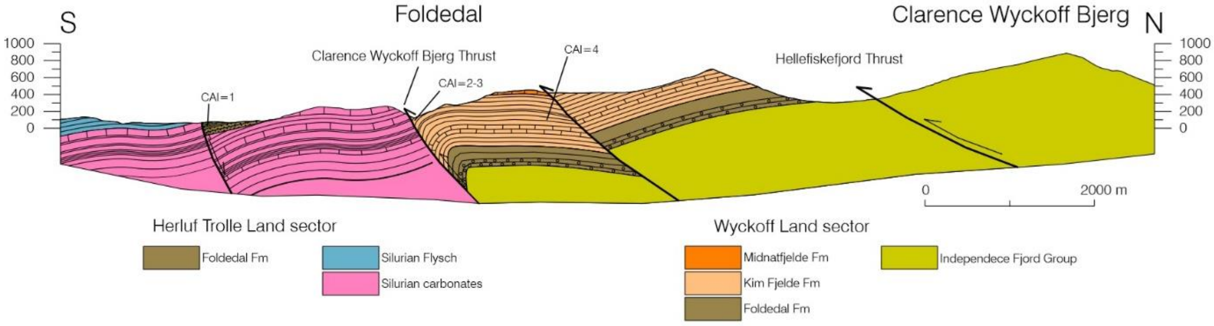

Fig. 2. Geologic cross-section of the northern part of Peary Land (see Fig. 1 for location). Upper Paleozoic rocks of the Wyckoff Land sector show higher thermal maturity compared to the Upper Paleozoic rocks of the Herluf Trolle Land sector as indicated by the Conodont Color Alteration Index (CAI).

A thermal event was recognized in the Wandel Sea Basin sediments (Pedersen and Håkansson 1999). It was well described by organic metamorphism from Vitrinite Reflectance (VR) and Conodont Color Alteration Index (CAI) (Rasmussen and Håkansson 1996) and from Fluid Inclusion (FI) analyses. Due to the absence of dykes and sill intrusions and to the size of the area overprinted by the metamorphism, the interpretation relates this thermal event to tectonic activity along faults belonging to the Wandel Hav Strike-Slip Mobile Belt (Pedersen and Håkansson 1999). Manby and Lyberis (2000), described the deformation in Trolle Land and Kronprins Christian Land as related to a NE-SW oriented compressional event pre-dating the opening of the Atlantic Ocean. The authors suggested a compression orthogonal to the continental boundary between Greenland and Svalbard. Later, von Gosen and Piepjohn (2003) interpreted the structures in Peary Land and Kronpins Christian Land as related to the Eocene Eurekan deformation suggesting transpressive tectonics along NW-SE trending faults like what was suggested by Håkansson and Pedersen (1982).

The structural interpretation and the tectonic model describing the evolution of the Wandel Sea Basin seem, however, inadequate. The current interpretation is unable to explain the most important thermal overprint observed. Both, Manby and Lyberis (2000) and von Gosen and Piepjohn (2003) did not consider the high thermal maturity of the Wandel Sea Basin sequence. In fact, strike-slip movement along faults described by previous authors pre-dates the Paleocene Thyra Ø Formation that in turn was interpreted as post-orogenic sequence.

2. DATA

The data presented in this study are based on fieldwork in North Greenland in 2012 and 2013 along with collection of oblique photos taken from a helicopter. The interpretation of structural data and the kinematics along major faults together with structural mapping are supported by a dataset of new analyses for Fluid Inclusions, Vitrinite Reflectance, Conodont Colour Alteration Index, mineralogy, and U-Pb age from detrital zircons. Structural analysis along major faults provides a new kinematic model that differs from published models and, together with the analytical data, could explain the strong thermal overprint affecting the Upper Paleozoic-Upper Cretaceous sediments of the Wandel Sea Basin.

3. RESULTS

During two field seasons in North Greenland (2012 and 2013) it was possible to observe folds and thrust faults clearly related to a compressive event involving Late Cretaceous sediments (e.g. Herlufsholm Strand Fm in Peary Land and the Kilen Group) (Guarnieri 2015; Svennevig et al. 2016). Tectonic activity along strike-slip faults and their offset are observed to be a minor event in the general deformation of the area and, in some places, not recognised or even absent.

Moreover, the absence of intrusions in the area, the size of the thermal overprint and the general increasing of maturity from SW to NE together with the style of the deformation, suggest an alternative tectonic setting. The thermal overprint should be considered as regional metamorphic event, and the understanding of this metamorphism seems to be crucial for the tectonic evolution of this area and its conjugate margin, Svalbard and the western Barents Sea.

Deformation in the Wandel Sea is considered Eurekan as in the West Spitsbergen and in North Greenland and it is related to the opening of the North Atlantic and Arctic oceans. Plate tectonics reconstruction established a major convergence stage in the Paleocene followed by strike-slip stage in the Eocene (Guarnieri 2015; Svennevig et al. 2016). The thermal overprint highlighted by Håkansson et al. (1993) is now more constrained by new data. In particular the paleotemperature shows that maximum temperatures and the distribution of metamorphic rocks are not related to local sources, but they follow structural trends as major normal faults that were re-activated as thrust faults during basin inversion before the Eurekan (Fig. 1). The peak of temperature was reached in the latest Cretaceous-Paleocene as a combination of sedimentary and tectonic burial. Folds and thrusts represent the main structural style of deformation affecting the Wandel Sea Basin with minor strike-slip faults and the estimated shortening due to compression varies across the area with a maximum of 50–70 km in the southern sector.

4. CONCLUSIONS

The main deformation style in eastern North Greenland is associated to compressive structures. Strike-slip faults post-date compressive structures in the Wandel Sea Basin and this evidence could be interpreted as strain partitioning during transpression with compressive structures landwards with thrusting and basin inversion locally overprinted by strike-slip faults.

The main conclusions can be summarized as follows:

- Middle Paleocene–earliest Eocene (pre-Eurekan) compression with SSW to SW-ward directed thrusts and basin inversion bringing metamorphic rocks of the Wandel Sea Basin against immature sediments;
- Eocene strike-slip tectonics (Eurekan) with NW-SE trending faults locally offset compressive structures.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

The North Atlantic Caledonides: from Iapetus Opening to the Scandian Collision and Beyond

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The North Atlantic Caledonides record a full Wilson cycle including all its phases starting with opening of the Iapetus Ocean, accretion of island arcs and potentially microcontinents, and major collision between Baltica and Laurentia (Gasser et al. 2024). The latter was followed by an orogenic collapse phase giving foundation to future opening of the Atlantic Ocean. Traditionally, it is assumed that the Caledonian Orogeny commenced in the latest Cambrian and terminated in the Early Devonian. However, the Arctic sector of the North Atlantic Caledonides yields evidence for major tectonothermal event peaking in the Late Devonian and lasting until the Mississippian. This event is manifested for example by formation of regionally metamorphosed rocks in greenschist-to-eclogite facies, locally reaching ultrahigh pressure conditions (Gilotti et al. 2024; Kośmińska et al. 2020). All these rocks are thought to have Laurentian ancestry. Hence, the current understanding of the North Atlantic Caledonides is not comprehensive without taking into account the events responsible for formation of the aforementioned rock units within the Laurentian portion of the orogen. Interestingly, this latest phase of the Caledonian Orogeny in the North Atlantic region is contemporaneous with the major phase of the Variscan Orogeny farther south. The question arises whether these two orogenic cycles are indeed separate entities or perhaps they are tightly connected and represent different evolutionary phases of the same superorogenic cycle, eventually leading to the formation of Pangea.

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Tectonic Evolution of the Circum-Arctic

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The Eocene to recent opening along the modern Gakkel spreading ridge is fairly well understood, but there is little consensus on Arctic reconstructions for Cretaceous and older events. Most workers agree that the Canada Basin opened (at least in part) as the result of rifting initiated c. 135 Ma; this age is inferred from pre- to syn-rift sedimentation on the conjugate margins, now the margins of Arctic Alaska and Arctic Canada (Houseknecht and Connors 2016; Hutchinson et al. 2023), and is supported by a shared syn-rift depositional history (Hutchinson et al. 2023). However, 1) the actual age of Canada Basin seafloor remains unknown, i.e. the age of sea-floor spreading after the on-set of rifting, and 2) as ages for the High Arctic large igneous province (HALIP) become more refined, the relationship between Canada Basin opening and the HALIP becomes central to basin opening scenarios (Dockman et al. 2018). Both of these issues are further complicated by the disparate geological timescales in common use today (Malinverno et al. 2012; Ogg 2020).

Gravity and magnetic (aeromagnetic and ship-bourn) data record what is interpreted as a fossil spreading ridge in the Canada Basin with inferred ages of 142 Ma (maximum) to 120 Ma (minimum) (Grantz et al. 2011; Chian et al. 2016; Døssing et al. 2020). This time frame overlaps with the Cretaceous Normal Superchron, thus restricting magnetic reversals in the Canada Basin to pre- or post-date the long Createaceous quiet period. Differences between magnetic anomaly timescales allow Canada Basin magnetic anomalies to be pre-120 Ma or post-83 Ma (Malinverno et al. 2012) or pre-130 Ma or post-124 Ma (Ogg 2020). Recent age data from the High-Arctic Large Igneous Province (HALIP) apparently record three main pulses of magmatism at c. 125 Ma, 95 Ma, and 80 Ma which lies within this critical window of time, and is used to invoke extension-drives-plume magmatism (Hadlari 2024), rather than the conventional view that plumes facilitate extension. Clearly, more work remains to be done in order to resolve some of these argue that the HALIP post-dates extension. Without agreement on the magnetic polarity timescale, the timing of tectonic events remain problematic.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

A Global Full-plate Model for the Past 2 Billion Years

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Global plate reconstructions with continuously closed topological boundaries, also known as full-plate models, provide a key framework for understanding Earth's history. These models serve as essential boundary conditions for exploring mantle thermochemical evolution, surface dynamic process, and global climatic changes. Here we present the first global full-plate model for the past 2 billion years (Li et al. 2023; Wu et al. 2024). Our model is constructed using a set of newly developed apparent polar wander paths (APWPs) based on novel weighted-mean statistics and a critically assessed list of paleomagnetic poles. The model is then optimized with geodynamic considerations and tested against geological constrains. Key differences between our model and the existing ones include: (i) Our model is built on a paleomagnetic reference frame ensuring that all plates with paleomagnetic constraints are positioned at their "correct" paleolatitudes; (ii) Our model constrains the paleolongitude using the orthoversion hypothesis, which posits that supercontinents form about 90 degrees longitudinally away from their predecessors; (iii) We provide two alternative models with different paleolongitudinal options (Fig. 1). While our model inevitably contains significant uncertainties due to the limitations of available data and should be used with caution, it lays the groundwork for further testing and refinement by the scientific community as new critical data and enhanced databases become available.

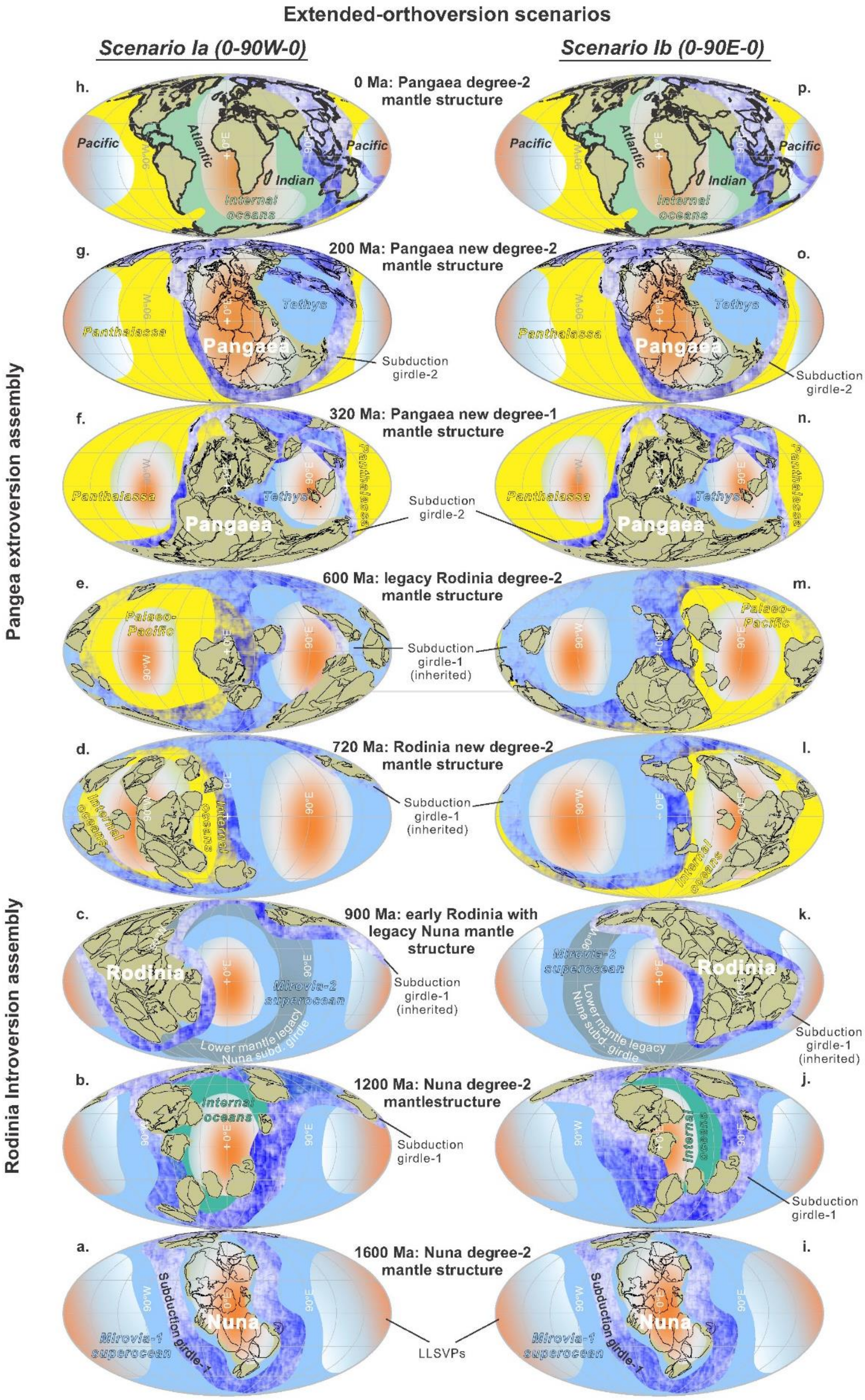

Fig. 1. Cartoons illustrating the implications of two alternative scenarios based on the extended-orthoversion geodynamic assumption where a 90° longitudinal change occurs between supercontinents and associated mantle structures (e.g., LLSVPs, and the I_{mins} as defined by the two antipodal LLSVPs). (a–h) Scenario Ia where Nuna is centered at 0°E, Rodinia at 90°W, and Pangaea at 0°E (0–90 W-0). (i–p) Scenario Ib where Nuna is centered at 180°E, Rodinia at 90°E, and Pangaea at 0°E (0–90 E-0).

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Current Paleomagnetic Database of Svalbard

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1. INTRODUCTION

The paleomagnetic investigation of the Svalbard Archipelago can be divided into two distinct groups. Research on the Caledonian basement primarily focuses on testing hypotheses that before final Caledonian amalgamation Svalbard existed as separate crustal blocks – terranes, provinces. Paleomagnetic studies of Late Palaeozoic and younger rocks aim to quantify the paleogeographic position of Svalbard in relation to Baltica (Laurussia). In the latter case, Svalbard is considered as a single lithospheric block, consolidated during the Caledonian orogeny (sensu lato).

2. TESTING THE SCALE OF SEPARATION OF SVALBARD CALEDONIAN TERRANES

Harland and Wright (1979) proposed that before Caledonian consolidation, Svalbard existed as smaller lithospheric blocks dispersed along the eastern and northern margins of Greenland.

Here we adopt the nomenclature proposed by Harland (1997) for dividing Svalbard into the Caledonian Western, Central, and Eastern Terranes. The amalgamation of the Terranes was considered to have occurred in Late Devonian time (Harland and Wright 1979). Svalbard hosts large-scale, north-south trending mylonite zones that exhibit several horizontal kinematic indicators, such as Billefjorden Fault Zone, along which such crustal displacements could have occurred. However, the scale of postulated displacements is yet to be quantified.

The Proterozoic to early Palaeozoic successions present an ideal opportunity for palaeomagnetic experiments. There are, however, significant challenges. Unfortunately for two of the three Terranes (Western and Central) the primary palaeomagnetic record was entirely obliterated during Caledonian tectonogenesis, when metamorphic processes remagnetised the rocks (Burzyński et al. 2017; Michalski 2018; Michalski et al. 2012, 2014, 2017). Theoretically, if we assume that the amalgamation of terranes occurred only in the Late Devonian time and was linked to the activity of large-scale strike-slip faults, the scale of their separation should be measurable based on previously imposed secondary Caledonian remagnetisation, which is potentially associated with the main phase of the Caledonian collision in the Late Silurian. However, although both isotopic and palaeomagnetic records are based on the same fundamental process—the cooling of carrier minerals below their critical temperature—precisely determining the absolute age of secondary palaeomagnetic directions linked to metamorphism remains a significant challenge.

Ongoing palaeomagnetic studies suggest that the primary pre-Caledonian palaeomagnetic record may have been preserved only in selected areas of the Eastern Terrane that escaped Caledonian metamorphism. Maloof et al. (2006) identified three palaeopoles from Eastern Svalbard, which they interpreted as representing primary palaeomagnetic signals from 805–790 Ma (Fig. 1). They observed significant shifts of over 50° in the palaeomagnetic directions, which they attributed to a pair of true polar wander (TPW) events. However, the primary nature of at least one of these palaeopoles was questioned by Michalski et al. (2012, 2023), who pointed out that some of the sites sampled by Maloof et al. (2006) may have been affected by low-grade Caledonian metamorphism.

During palaeomagnetic expeditions to Eastern Svalbard in 2022 and 2023, the NEOMAGRATE project team collected an additional 400 independently oriented Neoproterozoic palaeomagnetic samples from 58 sites around Hinlopenstretet. These samples represent the Tonian Kapp Hansteen volcanics, the Veteranen Group carbonates and siliciclastics, the Akademikerbreen Group carbonates, as well as the Cryogenian carbonates and tillites of the Polarisbreen Group. The presence of a pre-Caledonian palaeomagnetic signal would suggest that this segment of the Caledonian belt was not subjected to east-directed over-thrusting. However, both Caledonian and Mesozoic remagnetization events have been identified in the region. The former may be linked to mineralization processes at the Caledonian orogenic front, while the latter could be associated with Cretaceous dolerite magmatism in eastern Svalbard.

Although the palaeomagnetic studies of eastern Svalbard alone will not verify the hypothesis of the Svalbard Caledonian Terrane separation, they are of significant for the paleogeographic reconstruction of the Rodinia supercontinent and the verification of the proposed Neoproterozoic True Polar Wander events.

3. QUANTIFICATION OF SVALBARD POST-CALEDONIAN PALEOGEOGRAPHIC POSITION

Most published palaeomagnetic results confirm that Svalbard has been part of Baltica at least since the Late Palaeozoic (Fig. 1). Palaeomagnetic data indicate the stabilisation of the Barents Sea platform and no significant displacement between Svalbard and continental Europe (within the resolution of the palaeomagnetic method) at least since the Devonian (Halvorsen 1989; Jeleńska and Lewandowski 1986; Nawrocki 1999; Watts 1985) or possibly even from the Silurian (Michalski et al. 2012). However, when analysing post-Caledonian Svalbard reconstructions based on palaeomagnetic results, it is important to be aware of the following limitations.

Due to post-orogenic uplift and erosion, no Silurian sedimentary cover is preserved on Svalbard. Consequently, the Silurian palaeomagnetic record is represented solely by secondary remanent magnetisation directions in pre-Silurian rocks. These likely formed during the exhumation of metamorphosed complexes, when ferromagnetic minerals cooled below their

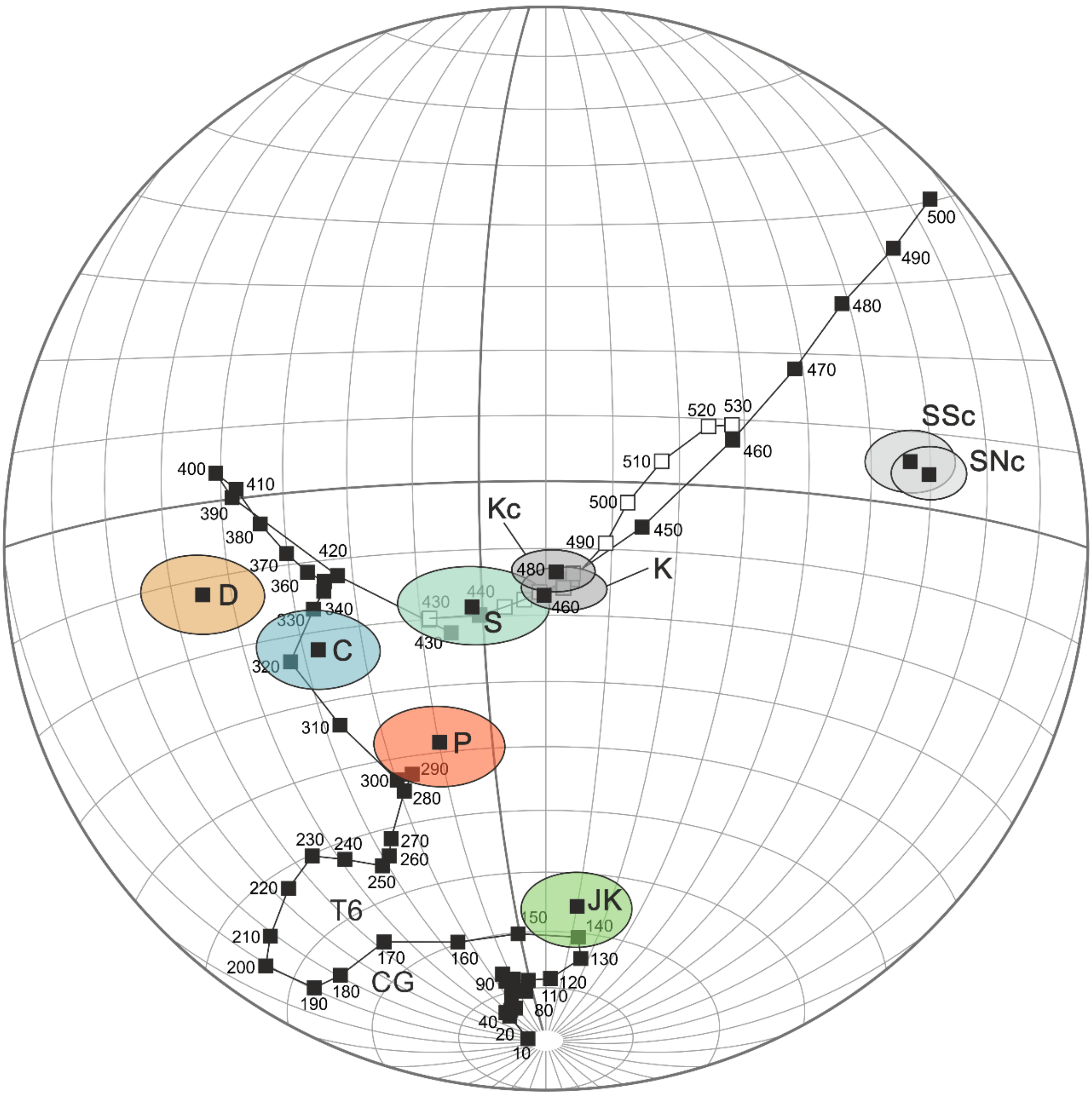

Fig. 1. Palaeopoles from Svalbard with their confidence limit ellipses (α95) plotted against Phanerozoic Apparent Polar Wander Paths (APWPs) of Laurussia (palaeopoles 0–430 Ma, filled squares), Baltica (palaeopoles 440–530 Ma, filled squares), and Laurentia (palaeopoles 440–530 Ma, open squares). The reference APWPs were derived from the GMAP 2012 database (Torsvik et al. 2012), with ages of specific points on the reference curve indicated. Symbols of palaeopoles identified in Palaeozoic and Mesozoic Svalbard formations: JK – Halvorsen (1989); P – Nawrocki (1999); C – Watts (1985); D – Jeleńska and Lewandowski (1986); S – Michalski et al. (2012) (note the coincidence of post-Caledonian Svalbard palaeopoles with their corresponding age segments on the reference curve). Palaeopoles identified by Maloof et al. (2006) in the Neoproterozoic succession of the Eastern Svalbard Terrane: K, Kc, SSc, SNc (note the coincidence of palaeopoles K and Kc with the Caledonian sector of the reference curve).

blocking temperatures. As mentioned earlier, precisely dating these secondary components using radiometric methods remains highly challenging (Michalski et al. 2012).

Palaeomagnetic studies of the red clastic deposits from the Devonian and Carboniferous of Spitsbergen have identified stable, potentially primary palaeomagnetic directions carried by hematite (Jeleńska and Lewandowski 1986; Watts 1985). So far, however, these studies do not include an inclination error correction, a well-known effect that leads to an underestimation of inclination due to the sedimentary deposition of ferromagnetic grains.

The paleomagnetic record in younger Permian and Triassic formations is based on less stable, medium- and low-coercivity grains of magnetite, titanomagnetite, and maghemite (Dudzisz et al. 2019; Nawrocki 1999). These minerals are prone to remagnetization, including that associated with the widespread Cretaceous magnetism on Svalbard. Finally, in the case of studies on Cretaceous dolerites (Halvorsen 1989), key challenges remain: the precise dating of individual magma intrusions, the elimination of secular variations, and the complex magnetization structure of igneous complexes formed through multiple stages of magma injection.

4. CONCLUSIONS

Palaeomagnetic studies of Svalbard play a crucial role in reconstructing the palaeogeography of the Arctic. Research on the Proterozoic successions of the Eastern Svalbard Terrane offers valuable insights into global full-plate models, particularly regarding the palaeogeography of the supercontinent Rodinia. In contrast, palaeomagnetic investigations of Svalbard's post-Caledonian rock sequences offer crucial information on the stability of the Barents Sea platform during the late Palaeozoic and Mesozoic.

One of the main challenges in palaeomagnetic studies of Svalbard is distinguishing between primary and secondary palaeomagnetic signals. A critical part of the palaeomagnetic workflow involves applying appropriate tectonic corrections for rotations linked to Caledonian, Svalbardian (?) and Eurekan contraction, as well as those associated with extensional processes related to opening of the North Atlantic and Eurasian Basin. In studies of sedimentary sequences, it is also essential to account for inclination shallowing corrections.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Palaeomagnetic Data Obtained from Recent Deglacial Sediments in the Baltic Sea: Modern Analogues May be the Key to Understanding (Much) Older Records

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1. INTRODUCTION

Palaeomagnetic data obtained from diamictite have provided evidence of low-latitude Neoproterozoic glaciations at sea-level (Evans 2000, Hoffman and Schrag 2002). Yet, knowledge about the mechanisms that cause these deposits to obtain a natural remanent magnetization (NRM) is incomplete due to the lack of work on relatively recent analogues. We utilise an extensive palaeomagnetic data set from the Baltic Sea Basin (BSB) to illustrate how glacially influenced deposits are prone to significant inclination error, which can lead to false virtual geomagnetic poles and hence palaeolatitudes if a geo-axial dipole (GAD) model is assumed.

2. METHODS

A total of approximately 1.6 km of core was recovered from 6 sub-basins of the BSB during International Ocean Discovery Program (IODP) Expedition 347 – Baltic Sea Paleoenvironment (Andrén et al. 2015). The recovered material consisted primarily of sediments that were deposited after the last retreat of the Scandinavian Ice Sheet. During the expedition onshore science party (OSP) a total of 1779 discrete paleomagnetic subsamples were taken from working halves of split cores and their NRM measured before and after alternating field demagnetization at 5 mT (in addition pilot samples taken from each lithologic unit were also demagnetized up to a maximum of 100 mT).

During the OSP it was noted that inclinations trended with increasing depth below the seafloor towards shallower than GAD predictions at most sites (GADs range between 70° and 75°). Some subsamples had reversed directions that were ascribed to high energy sedimentary environments (Andrén et al. 2015). A compiled palaeomagnetic dataset with 1423 palaeomagnetic directions was subsequently constructed by removing data from: (i) the core-catchers, (ii) lithologic units identified as folded and/or disturbed, and (iii) sections of cores known to be compromised by sediment expansion (Obrochta et al. 2017). We then subdivided the compiled palaeomagnetic data into two distinct groups that were based on the classification of the expedition sedimentologists into "glacially influenced" (e.g. diamicton and varved clays) and "non-glacially influenced" (e.g. greenish black organic clays deposited in estuarine or marine environments). Note that due to the aims of the expedition different lithologic units were sampled at different resolution, which resulted in significantly more paleomagnetic data from the non-glacially influenced deposits.

3. RESULTS

Figure 1 shows the whole palaeomagnetic data set and its projection onto Upper and Lower hemispheres. While the majority of the data points plot on the Upper hemisphere there is a large distribution and numerous subsamples have inclinations around 0°, including many that are negative.

We present the inclinations of the two sedimentologically-classified groups as histograms in Fig. 2. The group of influenced sediments is characterised by a roughly bimodal distribution with inclination peaks of about 5° and 45°, which are significantly lower than the range of GAD predictions for the sampled sites (70–75°). In contrast the non-glacially influenced sediments show a distinct main peak at 70–75°, in agreement with the GAD predictions and regional palaeomagnetic secular variations, although there is a tail of data with low inclinations. There is a distinct possibility that the subdivision of the data set into two groups led to some misplacement of data, but the size of the data set is big enough to draw some conclusions.

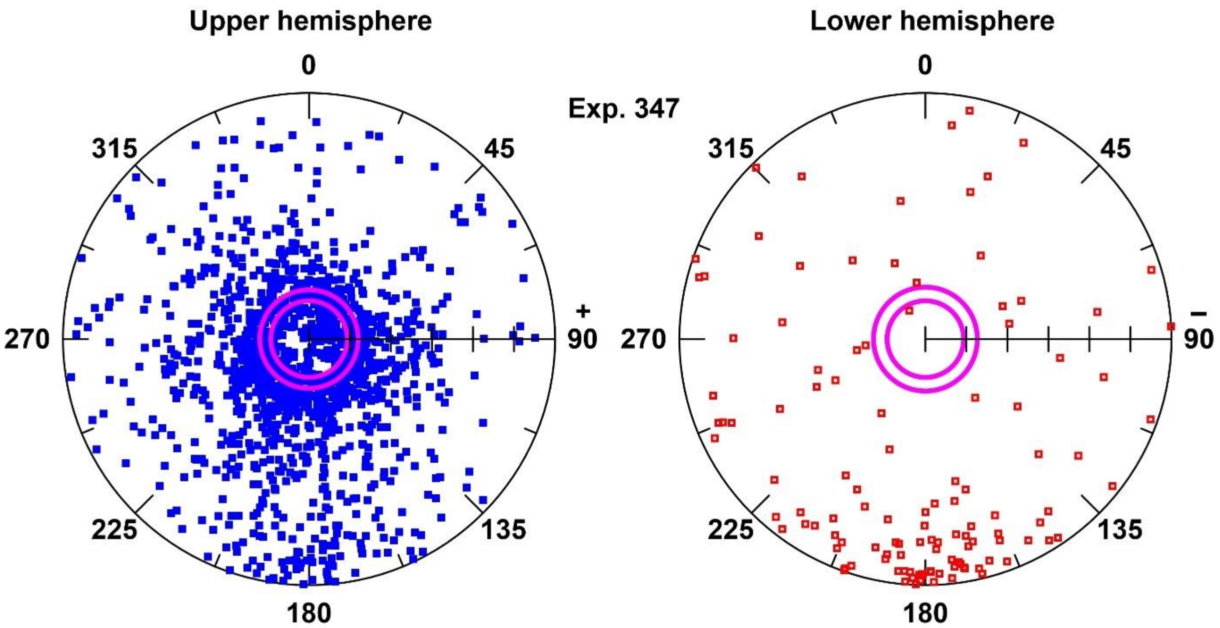

Fig. 1. Stereo plots of the complied paleomagnetic dataset divided into a group that plots on the Upper hemisphere (blue, positive inclination) and another that plots on the Lower hemisphere (red, negative inclination). Magenta circles show the minimum (outer) and maximum (inner) range of inclinations predicted by a GAD model for the latitudes of the site locations.

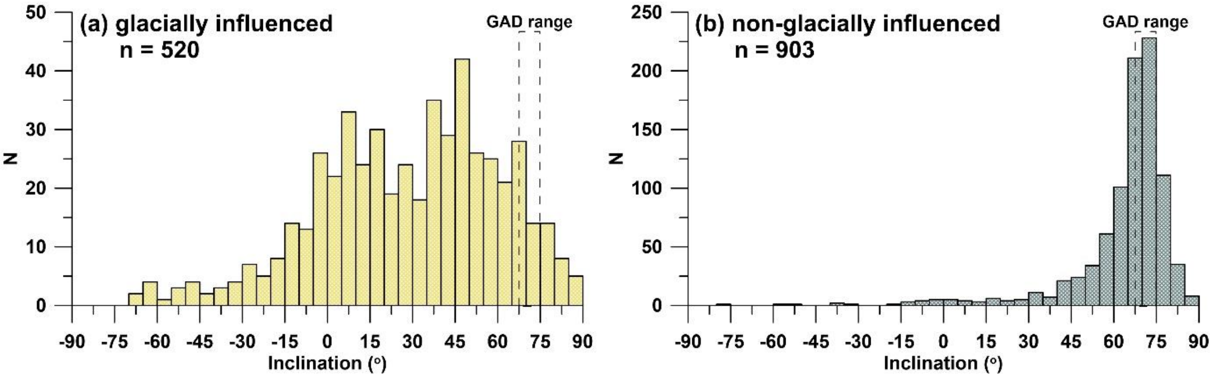

Fig. 2. Histograms that show the range of paleomagnetic inclinations for: (a) glacially influenced sediments and (b) non-glacially influenced sediments recovered during IODP Expedition 347. The group of glacially influenced sediments is characterised by a broad, but roughly bimodal distribution of inclinations, with the vast majority shallower than the GAD predictions. The group of non-glacially influenced sediments has a much narrower distribution, with a peak within the range of GAD predictions.

4. CONCLUSIONS

The compiled and filtered paleomagnetic dataset obtained from the BSB illustrates the established problem of inclination shallowing in coarse-grained sediments, which is relevant to palaeomagnetic studies of sedimentary rocks that aim to define palaeolatitudes and contribute to paleogeographic reconstructions (e.g. Vaes et al. 2021). Further measurements and sampling of non-glacially influenced sediments from three of the IODP-347 sites (M0060, M0061, and M0062) were able to reconstruct PSV (Snowball et al. 2019, Herrero-Bervera and Snowball 2020). Of course, without independent prior knowledge of the regional Quaternary geology and accepted palaeogeography, conversion of the paleomagnetic data obtained from the glacially influenced sediments in the BSB into paleogeography could lead to the misinterpretation of glaciers located at sea level near the equator. Our investigation of the IODP Expedition 347 paleomagnetic data set shows the importance of sampling paleomagnetically suitable sedimentary rocks for paleogeographic studies and an understanding of the NRM acquisition processes, which also include deposits formed during the Proterozoic and Neoproterozoic (e.g. Evans 2006, Schmidt et al. 2009).

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Neoproterozoic Diamictites of Polarisbreen Group (Nordauslandet, Svalbard) – Paleomagnetic and Petrographic Investigations

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Our research unveils new palaeomagnetic and petrographic results from 50 independently oriented samples representing Cryogenian Polarisbreen Group diamictites. These findings, collected in 2022 from the Neoproterozoic sequence of Murchisonfjord, represent a significant advancement in our understanding of the palaeomagnetic record preserved in rocks formed during the Cryogenian glaciations (e.g. Halverson et al. 2004, 2018a,b, 2022; Hoffman et al. 2012; Millikin et al. 2022). The sampling includes two sites from the Petrovbreen Member of the Elbobreen Formation and six sites from the Wilsonbreen Formation.

Our principal component analyses (PCA) have revealed a substantial contribution from a post-folding, high-inclination palaeomagnetic component, which demagnetised up to 320 °C. The calculated palaeopole falls within the Late Cretaceous–Palaeogene–Neogene sector of the Baltica Apparent Polar Wander Path (APWP), suggesting a possible link between remagneti-

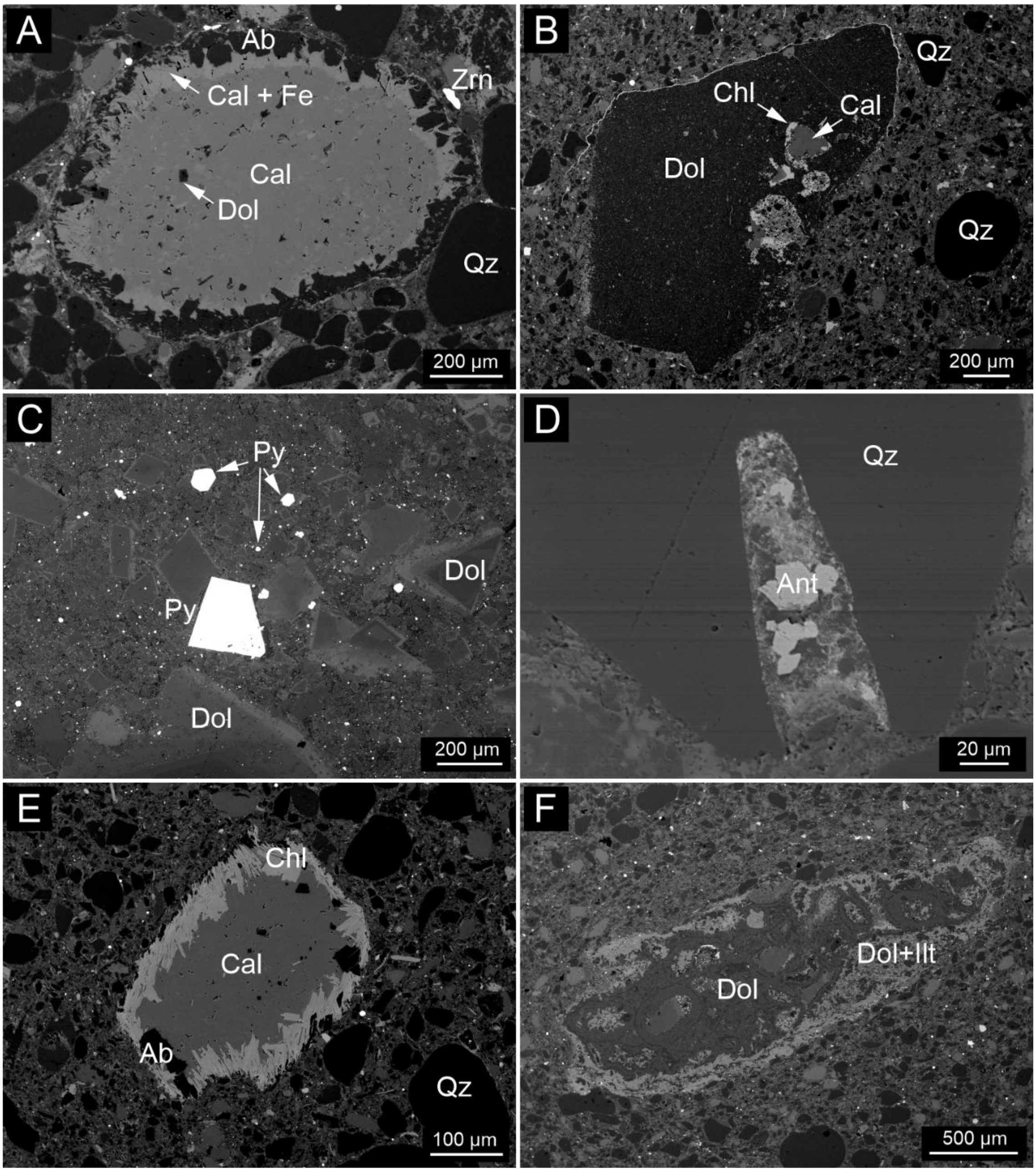

Fig. 1. Backscattered electron (BSE) images of Cryogenian diamictites of Murchisonfiord (Nordaustlandet): A – Calcite clast with a recrystallised rim of diagenetic albite (outer rim), Fe-rich calcite (inner rim), dolomite replacing calcite inside, and a visible zircon (Wilsonbreen Fm); B – Dolomicrite clast with chlorite and secondary calcite enclosures (Wilsonbreen Fm); C – Large euhedral pyrite between dolomite crystals in the matrix, with Fe-rich dolomite overgrowing dolomite (Petrovbreen Mb); D – Secondary Ti-oxides (anatase) in quartz (Wilsonbreen Fm); E – Micritic calcite clast with outer chlorite and albite overgrowths (Wilsonbreen Fm); F – Dolomitic clast with a rim composed of dolomite and clay minerals (illite) (Wilsonbreen Fm). Abbreviations: Ab – albite, Ant – anatase, Cal – calcite, Chl – chlorite, Dol – dolomite, Fe – iron, Ilt – clay minerals, Py – pyrite, Qz – quartz, Zrn – zircon.

sation and Late Cretaceous Svalbard magmatism (e.g. Senger et al. 2014). Great circle analyses indicate an additional contribution from a low-inclination component, potentially associated with Caledonian remagnetisation (cf. Michalski et al. 2023).

Our detailed petrographic and mineralogical investigations have unveiled unique diagenetic overprints in both diamictite units. The mineral association observed in the analysed rocks, suggests that they did not undergo low-grade metamorphism. The observed mineral overgrowths (Fig. 1A) and evidence of mineral alterations (Fig. 1B) indicate significant fluid flow through sediment pore spaces, potentially during the processes of compaction and lithification. Fe phases are predominantly represented by pyrite (Fig. 1C) and Fe-dolomite. Fe-Ti oxides are exclusively present as secondary diagenetic anatase (Fig. 1D), which formed simultaneously with the diagenetic mineral association, including chlorite group minerals (chamosite), albite, calcite (Fig. 1E), Fe-dolomite, clay minerals (illite) (Fig. 1F), and quartz. No ferromagnetic (sensu lato) minerals were identified during integrated optical and SEM-EDS investigations, but the presence of magnetite in the analysed rocks was confirmed by saturation isothermal remanent magnetisation (SIRM) experiments.

This study is part of the NEOMAGRATE project, a substantial research endeavor funded by the Polish National Science Centre (NSC) and spanning from 2022 to 2026. The project, titled “Rate of Tectonic Plate Movement in the Neoproterozoic – Verification of the Neoproterozoic True Polar Wander Hypothesis”, is a testament to our commitment and the resources invested in advancing our understanding of Earth’s history.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Architecture of the Caledonian Fold Belt South of Murchisonfjorden, Western Nordaustlandet

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At the south coast of Murchisonfjorden in western Nordaustlandet, a complete sequence of the Neoproterozoic to Lower Paleozoic Murchisonfjorden and Hinlopenstretet supergroups is exposed (Fig. 1; Fairchild and Hambrey 1984; Knoll and Swett 1990, Harland et al. 1993, Halverson et al. 2004, Dallmann 2015). The lower part of the succession is composed of km-thick dark grey siltstones and white and red quartzites of the Tonian Frankliniansundet and Celsiusberget groups. The clastic formations are overlain by limestones of the Tonian Roaldtoppen Group and again clastic deposits and diamictites of the Cryogenian/Ediacaran Polarisbreen Group. The youngest part of the sedimentary succession consists of dolostones and limestones of the Cambrian–Ordovician Oslobreen Group. In Nordaustlandet, the Oslobreen Group is represented by the Kapp Sparre Formation at Sparreneset and Krossøya (Fig. 1). The entire succession is characterized by very low-grade metamorphic conditions. Sedimentary structures like cross-bedding and ripple marks as well as Neoproterozoic fossils are still well preserved (Anderson et al. 2022).

The deformation of the Neoproterozoic and Lower Paleozoic sedimentary succession is dominated by intense folding between Hinlopenstretet in the WSW and Skarberget in the ENE (Fig. 1). In the western part (Fig. 2), the structural architecture is characterized by a km-scale anticline-syncline pair with subvertical axial planes, deformed the clastic deposits and limestones of the Oslobreen, Polarisbreen, and Roaldtoppen groups (Fig. 2). Similar upright synclines and anticlines in eastern Ny-Friesland west of Hinlopenstretet were observed (Piepjohn et al. 2019). Towards the east, the structural architecture is characterize by two major WSW-vergent fold-structures at Roaldtoppen and Fargefjellet mainly in clastic deposits and thick quartzites of the Celsiusberget and Franklinsundet groups with subvertical fore limbs and a wide, almost horizontal back limb between Skarberget and Søre Franklinbreen in the east (Fig. 2). These observations suggest that the shift in fold geometry from west to east may be

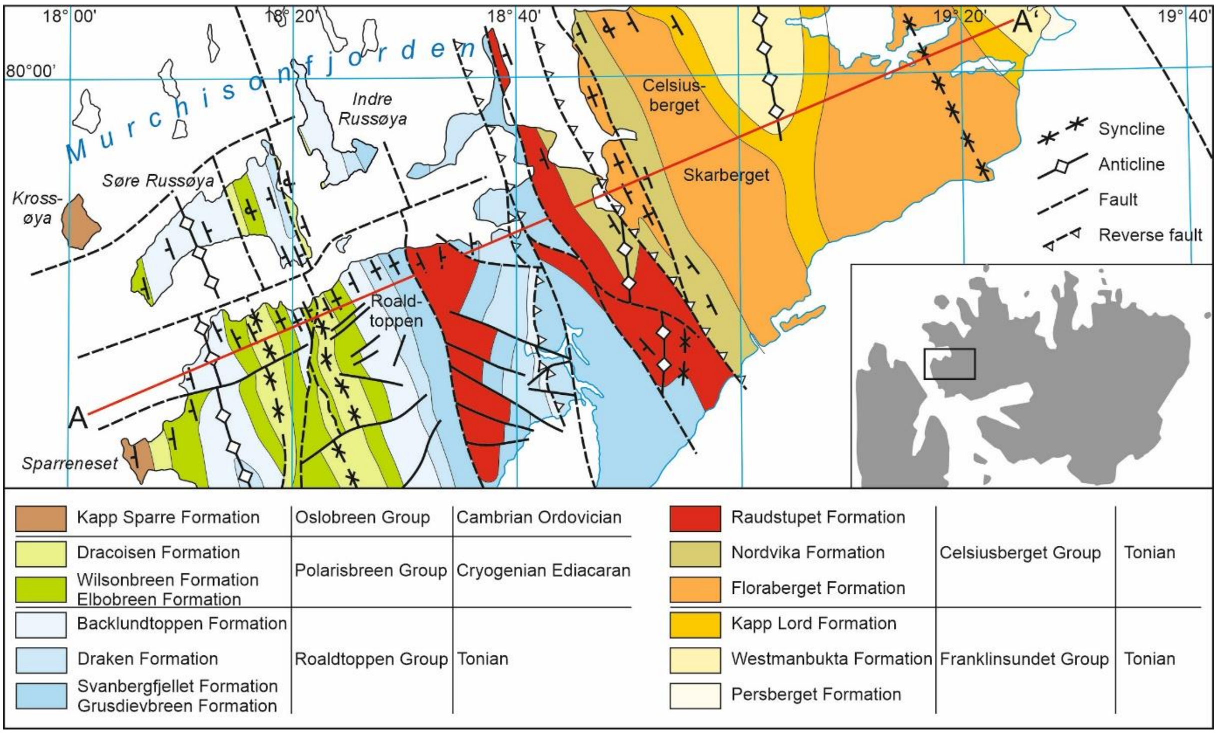

Fig. 1. Geological Map of northern Gothiahalvøya in western Nordaustlandet south of Murchisonfjorden, modified from Kulling (1934), Flood et al. (1969), Hoffman et al. (2012), and own field work.

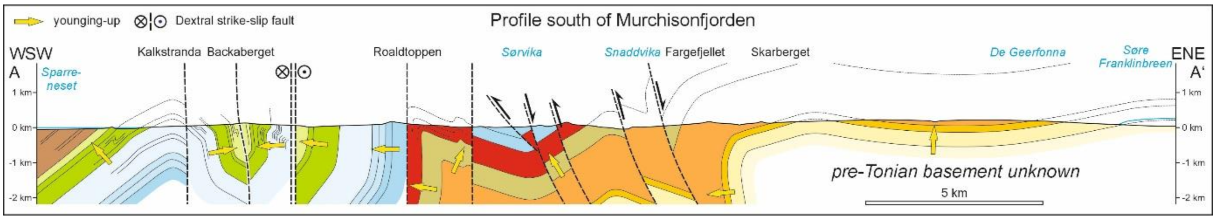

Fig. 2. Geological cross section through the folded Neoproterozoic to Lower Paleozoic Murchisonfjorden and Hinlopenstretet supergroups of western Nordaustlandet between Sparreneset in the WSW and Søre Franklinbreen in the ENE. For location of cross section and legend see Fig. 1.

related to differences in lithological competence, particularly related to the presence of thick quartzites in the eastern part of the succession. The ENE-dipping short limb between the two short limbs is truncated by several steeply ENE-dipping, brittle reverse fault, which have been partly reactivated by extensional movements (Fig. 2).

The NNW-SSE orientation of large-scale F1-fold-structures indicates a general WSW-ENE shortening. The sandstones and siltstones of the Franklinsundet Group, Nordvika Formation and Raudstuped Formation are affected by an intense fracture-cleavage S1, which mostly dips towards ENE. S1 cleavage planes are less developed in the quartzites of the Floraberget Formation and mostly absent in the limestones of the Roaldtoppen Group.

The deformation in the western part of Nordaustlandet is relatively simple and characterized only by phase D1 with ENE-WSW shortening, represented by km-scale F1-folds, an ENE-dipping fracture-cleavage S1 and the formation of steeply ENE-dipping, west-directed zones of reverse and thrust faults related to the Caledonian compression. The WSW-directed tectonic transport is supported by the cross-cutting relation of bedding/cleavage, the orientation of the reverse faults and the orientation of parasitic folds in the fold limbs.

After the Caledonian shortening, the western part of Nordaustlandet was affected by NNW-SSE striking faults (D2), which cut through the F1-fold structures and short limbs and are characterized by brittle strike-slip tectonics, similar to the structural evolution of eastern Ny-Friesland west of Hinlopenstretet (Piepjohn et al. 2019).

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The Hadean: Was It Really Hell-like?

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1. INTRODUCTION

The term "Hadean" was first introduced by Preston Cloud (1972) for the earliest eon in Earth history. It was derived from the Greek word meaning "God of the Underworld", but was frequently interpreted to mean that the early Earth was hell-like (cf. Wilde 2022a). This was supported by the view that it was a hot and turbulent place at this time. Implicit in the definition was that it defined the time before preservation of the earliest known rocks. With the discovery of the oldest known magmatic zircon at 4.03 Ga in the Acasta gneiss in the Northwest Territories of Canada (Bowring and Williams 1999), consensus was reached that the Hadean commenced at 4000 Ma (4 Ga), as originally proposed by Plumb and James (1986), although it remained "informal" until its recommendation and adoption in 2012 by the International Subcommission on Precambrian Stratigraphy and the International Union of Geological Sciences (IUGS) (Van Kranendonk et al. 2012).

So, was the early Earth really hell-like? It is generally agreed that the Earth underwent complete melting following its accretion, resulting in its differentiation into a core, mantle, and primordial crust. But how do we know what it was like at the Earth's surface if there are no rocks preserved from the Hadean? The answer lies with the discovery of detrital zircon crystals older than 4 Ga in the Narryer Terrane of the Yilgarn Craton in Western Australia (Froude et al. 1983; Compston and Pidgeon 1986). Subsequent work here and elsewhere has led to the discovery of more zircon crystals older than 4 Ga (see Fig. 1 for global distribution), with the oldest being a single site on a Hadean grain recording an age of 4404±8 Ma (2σ) from Jack Hills in the Narryer Terrane (Wilde et al. 2001). Aided by the concurrent development over the past two decades of evermore precise analytical techniques at the micro- and nano-scales, and for a growing range of elements and isotopes, it has been possible to make what appear to be reasonable deductions as to what conditions might have been like at the surface during the Hadean.

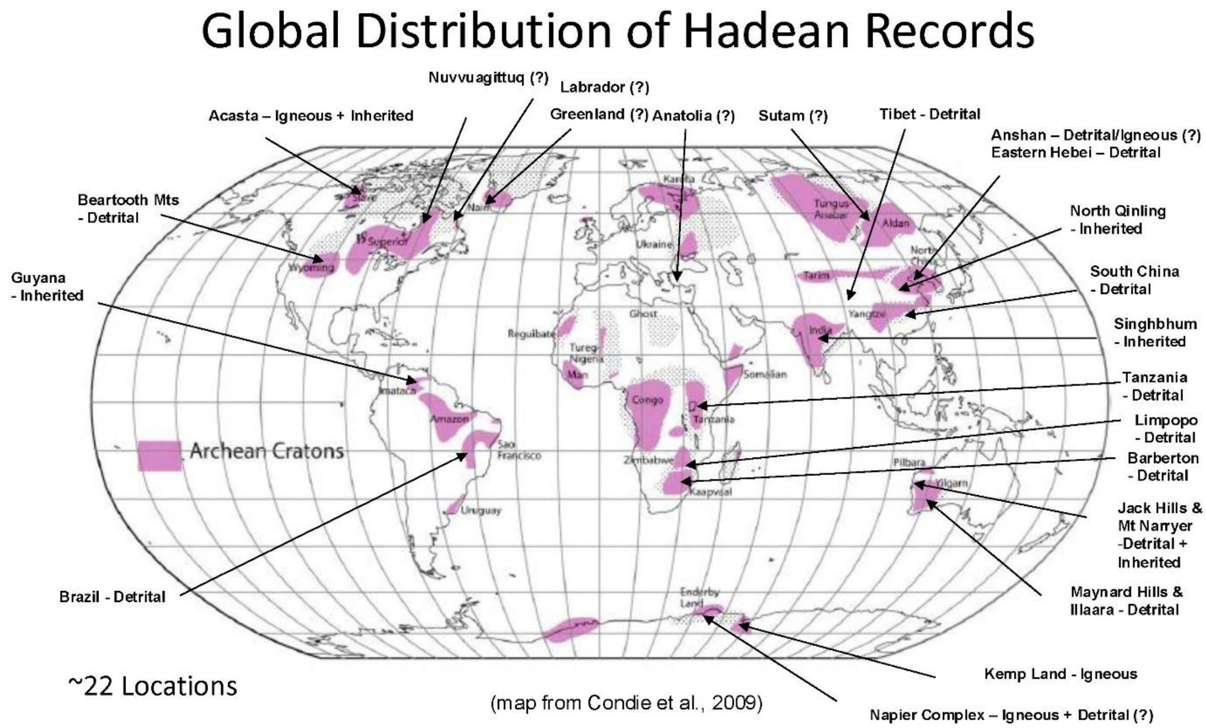

Fig. 1. The currently known global distribution of Hadean zircon. Abundant Hadean grains are only found at Jack Hills and Mt Narryer in the Yilgarn Craton of Western Australia, with many of the localities only recording single detrital grains. Note that when followed by (?), this means that the age is questioned due to reverse discordance or has not been substantiated by additional studies. Nuvvuaqittuq in NE Canada is where Nd isochrons record Hadean ages, but where zircon only records Eoarchean ages.

2. THE EVIDENCE

Early work at Jack Hills identified elevated $\delta^{18}O$ in several Hadean zircon grains, including the oldest (Wilde et al. 2001; Mojzsis et al. 2001), leading to the interpretation that these crystals formed in a magma at least partially derived through the incorporation of material that had interacted with liquid water at the Earth's surface. Such grains with elevated $\delta^{18}O$ were subsequently referred to as "supracrustal" zircon (Cavosie et al. 2005). Collectively, these data pointed to the early development on Earth of both continents and oceans. This required fairly rapid cooling following accretion, melting, and crystallization of an early magma ocean, leading to the "Cool Early Earth" hypothesis (Valley et al. 2002). However, the precise nature of the host rock(s) in which the zircon formed has been subject to considerable debate, ranging from formation in rocks derived from a crystalline magma ocean to S-type granite (see discussion in Wilde 2022b). Indeed, it was shown by Wang and Wilde (2018), based on extensive Lu-Hf data, that the Hadean grains at Jack Hills were not derived from a single protolith and that mafic, intermediate and felsic sources existed on the early Earth. One of the key features was that the Hf data in this and other studies (Harrison et al. 2005; Kemp et al. 2010), pointed to the parent rocks being derived from precursors formed at ca. 4.5 Ga, close to the age of the Earth itself. In addition, this early crust was not destroyed, but continuously reworked in the Narryer Terrane until at least 2.6 Ga, as recorded by the strongly negative εHf values of the zircon in Neoarchean granites (Kemp et al. 2010).

In more recent studies, a backup to the early oxygen data came from zircon trace element studies (Turner et al. 2020), both indicating no change across the Hadean/Archean boundary. In addition, the trace element data suggested a likely andesitic source, leading to the possibility that plate tectonics may have been operative in the Hadean. This was not a new idea and had previously been suggested by Ichikawa et al. (2017) and Maruyama and Ebisuzaki (2017), with the latter based on theoretically modelling of how and when the Earth had received its volatiles (the ABEL model). This lack of change cross the Hadean/Archean boundary is also a feature of the hafnium data, where time-series analysis of the extensive Lu-Hf database shows that there is periodicity in the extraction from the mantle that has not changed from the Hadean to the Phanerozoic, with the implication this is either an inherent feature of the Earth's mantle since its formation, or that plate tectonics was operative in some form since the Hadean (Mitchell et al. 2022). Finally, a recent paper has reported additional oxygen data that reveals not only elevated "supracrustal" values but also unusually low $\delta^{18}O$ values in ca. 4.0 Ga and 3.4 Ga zircon, interpreted to indicate emergent land by 4 Ga and the onset of the first hydrological cycle on Earth (Gamaleldien et al. 2024).

3. CONCLUSIONS

The evidence presented above indicates a number of interesting aspects with respect to conditions during the Hadean. The favoured interpretation of the zircon oxygen data is that the Earth cooled down relatively quickly and, together with the zircon trace element data, that there was no change across the Hadean/Archean boundary. This was likewise the case with the periodicity revealed by the zircon Hf data. Whether this is a reflection of some form of Hadean plate tectonics remains to be substantiated, but it does indicate a degree of uniformitarianism throughout Earth history. That such information can be gleaned from minute crystals of zircon is testimony to the growing ability to analyse an ever-increasing number of elements and isotopes at the micro- to nano-scales. Collectively, these data provide an insight into conditions on the early Earth that cannot be obtained by other means as no rocks are known to have survived from the Hadean. On balance, conditions during the majority of the Hadean, at least from ca. 4.4 Ga onwards, seem not to have been vastly different to those in the Archean from 3.9 to 2.5 Ga, although the real reason for a lack of rocks prior to 4 Ga remains a mystery. As such, conditions for most of the Hadean – excluding the early accretion and magma ocean events – were evidently not hell-like.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Geological Constraints on Claims for Earth's Earliest Life in the Eoarchean of Greenland and Labrador

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The time at which life on Earth began is one of humankind's most enduring scientific questions, complicated by the increasing difficulty both in identifying and accurately dating evidence of life the further back in time one looks. During the Hadean eon (>4.0 Ga), from which by definition no rock record is preserved, and into the early Archean eon, the inner solar system was subjected to intense meteorite bombardment, with impacts commonly thought to have "frustrated" (Maher and Stevenson 1988) the development of a persistent biosphere on the Earth. Prior to ca. 3.5 Ga (with the appearance of stromatolites in Pilbara, Australia), there are no preserved body or trace fossils. Instead, evidence for biological activity relies on chemofossil evidence, typically in the form of tiny graphite remnants that record a light carbon isotope signature ($\delta^{13}C < -20‰$) commonly attributed to organic activity. In itself, this evidence is far from unambiguous as there are potential abiotic pathways to isotopically light carbon, but accepting this at face value, two other key factors are required in order to support the veracity and true antiquity of these putative chemofossils (Whitehouse and Fedo 2007). First, it is generally accepted that the host rocks in which the chemofossils are found must represent a near surface environment with access to surface water necessary for metabolism to function. Second, and only if the first criterion is met, in order to claim great antiquity the host rock must be dated unambiguously.

Debates about Earth's earliest life in the form of chemofossils have played out in the Eoarchean of the North Atlantic Craton, specifically at two localities in Greenland, the Isua Greenstone Belt and the island of Akilia, and another in the Saglek area of northern Labrador. The status of each of these claims, both viable and discredited, has been reviewed in detail by Whitehouse et al. (2019) and is summarised here.

At Isua, Rosing (1999) documented low $\delta^{13}C$ in graphite from metamorphosed rocks derived from turbiditic sediment on the western side of the supracrustal belt. This is a suitable host rock for life and intercalated volcanics provide a reliable ca. 3.7 Ga age. However, speculation based on Pb isotopes that the organisms might have been photosynthesising cyanobacteria (Rosing and Frei 2004) has been challenged as a non-unique interpretation (Fedo et al. 2006) and their true nature remains a matter for debate.

Claims for >3.83 Ga chemofossils from the island of Akilia, which has experienced strong polyphase deformation and multiple episodes of high-grade metamorphism, were first made by Mojzsis et al. (1996). These have proven highly controversial and are now largely discredited. The very existence of isotopically light graphite as inclusions in apatite in a presumed "banded iron formation" was initially called into question. Subsequent studies have reported its presence, albeit in apatite that is only 1.7 Ga old (Whitehouse et al. 2009). The "BIF" interpretation of the host rock also has been questioned, with a suggestion that it is potentially a metasomatic quartz vein intruding deep-seated ultramafic rocks (Fedo and Whitehouse 2002). Supportive evidence in the form of mass-independent fractionation of (pre-2.4 Ga atmospheric) sulfur isotopes (Mojzsis et al. 2003) could not be reproduced (Whitehouse et al. 2005). Additionally, the claimed >3.83 Ga age relies on ambiguous field relationships with TTG gneisses that have been claimed to, but do not directly, cross-cut the supposed metasediments. Direct Sm-Nd isochron dating yields only 3.65 Ga, so even if the biogenicity is real, it would be younger than Isua and so of lesser interest. All aspects of the long-running Akilia saga have been exhaustively reviewed by Whitehouse et al. (2009).

Another chemofossil claim appeared in the Saglek region of northern Labrador, from where Tashiro et al. (2017) reported isotopically light carbon in gneisses derived from pelitic sediments supposedly deposited before 3.95 Ga. Although the host rock in this case is a suitable potential host for bioactivity, the age estimate relied on a combination of dubious field relationships extrapolated over many 100's of metres, together with a highly subjective interpretation of zircon geochronology in which a statistically rigorous treatment was not utilised; instead, a few of the oldest zircon analyses were selected arbitrarily to yield the oldest possible age. More egregiously, this study also ignored long-published geochronology (Schiøtte et al. 1989) and Hf isotopes (Stevenson and Patchett 1990) from the host rocks that are consistent only with a substantially younger (ca. 3.2 Ga) age. Ongoing work on the same gneiss outcrop used by Tashiro et al. (2017) to propose their 3.95 Ga age reveals a complex sequence of magmatic and structural events that contradicts previously published interpretations. Critically, a granite that cross-cuts gneissosity and was previously used to provide a minimum age of ca. 3860 Ma for metamorphism and ductile deformation, contains significant xenocrystic zircon from the host gneiss. Based on zircon rims, granite emplacement instead likely occurred at ca. 2.7 Ga, during and after deformation, which is consistent with a regionally recognised event (Whitehouse et al., in prep.). In addition, the claimed relationship between these gneisses and graphite-bearing metasediments can be refuted by ages from detrital zircon in the latter, indicating deposition after ca. 3Ga. This case is a demonstration that often it is not just the isotopic evidence for life which can be problematic – the context of a claim is equally critical.

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Eoarchean Zircons in the Napier Complex, East Antarctica

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1. INTRODUCTION

There is not much evidence as to the nature of the Earth's earliest crust. The available information has been gleaned mostly from the studies of the oldest crystals of mineral zircon ($ZrSiO_4$), either detrital grains (e.g. Wilde et al. 2001) or from oldest known igneous rocks, such as the Acasta orthogneiss in the Slave Province of Canada with an age of 4.03 Ga (e.g. Bowring and Williams 1999; Iizuka et al. 2006). One of areas, where Eoarchean rocks (4.0–3.6 Ga) occur and protoliths that include some of the oldest crust on Earth occur, is the Napier Complex of Enderby and Kemp Lands in East Antarctica, including Tula Mountains of Enderby Land (e.g. Black et al. 1986; Kusiak et al. 2013a,b; Król et al. 2020) and Aker Peaks in Kemp Land (Belyatsky et al. 2011; Kusiak et al. 2021). The Napier Complex is an Archean craton composed mostly of high-temperature gneisses and granulites. The craton was metamorphosed at least twice, et ca. 2.8 Ga and ca. 2.5 Ga under granulite to ultrahigh-temperature (UHT) granulite condition (e.g. Kelly and Harley 2005; Harley et al. 2019). The UHT metamorphism had temperature as high as >1100 °C (e.g. Hokada et al. 2004), making these some of the highest temperature metamorphic rocks found in the Earth's crust.

2. RESULTS

Here we present zircon results from three cases: 1) presence of Pb nanospheres in grains from Gage Ridge, 2) Lu-Hf data from Aker Peaks, and 3) oxygen results.

Metallic Pb nanospheres

Already the first publication documenting U-Pb geochronology of these rocks discussed the issue of the reversely discordant data recognized during in-situ analysis (Williams et al. 1984). Ion imaging of analysed zircon grains revealed zonation of Y and Ti characteristic for magmatic grains. However, distribution of ^{206}Pb and ^{48}Ti (Fig. 1) does not correspond to either magmatic zonation or crystal imperfections. Some of these patches yield ^{207}Pb/^{206}Pb ages of >4 Ga, mostly reversely discordant. Other areas document data with ages younger than the magmatic crystallization age. Reversely discordant data are result of ancient Pb mobilization being independent of the oxygen isotope, REE content and metamictization of zircon (Kusiak et al. 2023).

It has been documented by Transmission Electron Microscopy (TEM), that in some of the ancient grains >3.4 Ga metallic lead nanospheres of 5 –30 nm in size occur. These nanospheres are randomly distributed, they occur either as droplets or in polyphase inclusions up to 80 nm across and contain amorphous Si-rich phase, together with unidentified Ti and Al-bearing phases (Fig. 2). Where inclusions contain multiple phases, Pb occurs as single or multiple nanospheres without crystal facets. No hydrous Pb phase(s) or voids large enough to penetrate the focused ion beam (FIB) foils were documented.

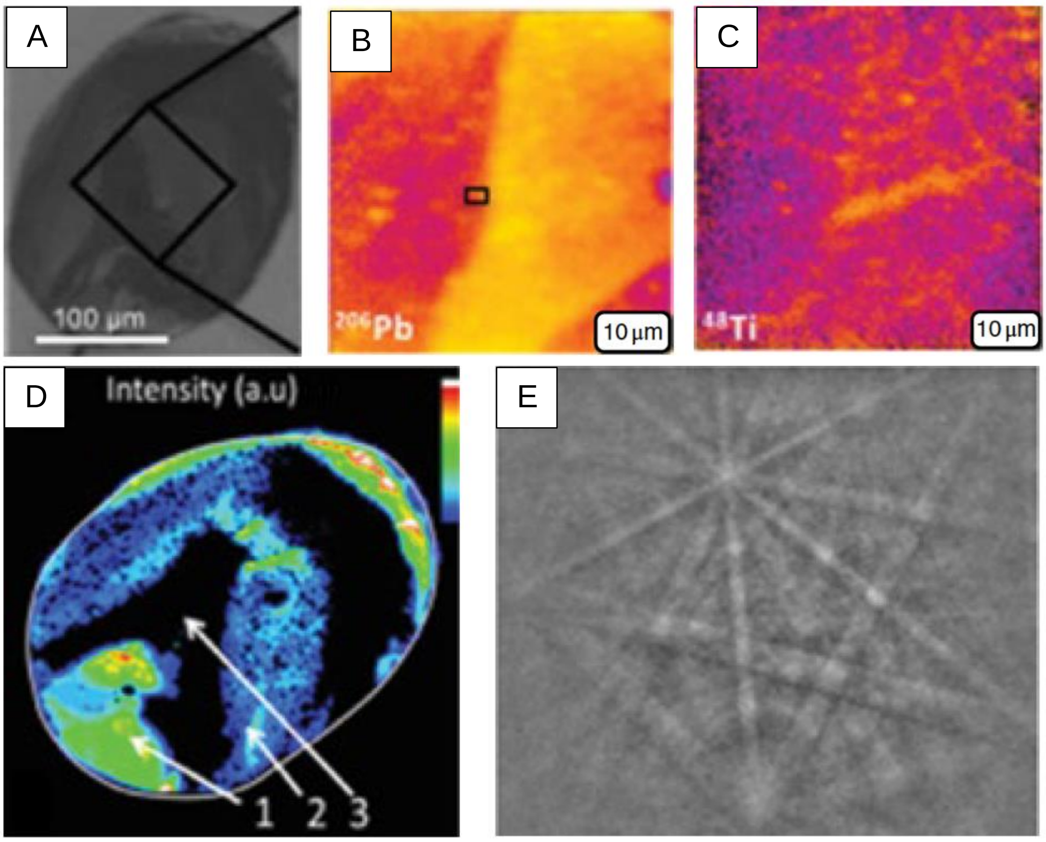

Fig. 1. Zircon grain n3850-47: (A) CL image, black box representing area covered in B) and C); (B) SII image of ^{206}Pb; (C) SII image of ^{48}Ti; (D) Raman spectroscopy image with marked zones of different crystallinity: zone 1 (moderately radiation damaged area), zone 2 (amorphous area), zone 3 (glassy area with retained zircon composition); (E) Electron diffraction pattern (EBSP) obtained from a crystalline component (zone 1) of the same grain. Modified after Kusiak et al. (2017).

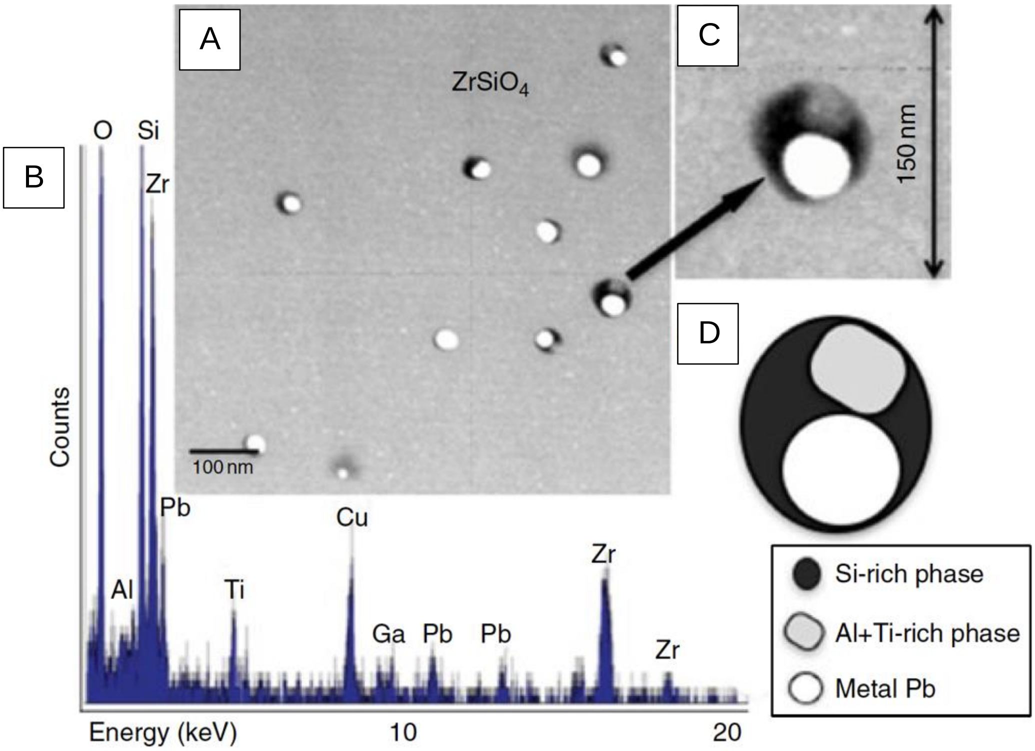

Fig. 2: (A) High-angle annular dark-field (HAADF) TEM image of zircon from Gage Ridge with Pb nanospheres, and (B) the EDX spectrum of zircon rich in Pb and the silicate matrix enriched in Ti-Al (Cu peak comes from Cu grid under the FIB foil); (C) enlarged area with metal Pb (white), Al+Th-rich phase (grey) and Si-rich phase (dark grey); (D) clarification sketch of image (C). Modified after Kusiak et al. (2015).

Lu-Hf isotopes

Aker Peaks in Kemp Land is 200 km east from the Tula Mountains of Enderby Land. Zircon grains from trondhjemitic and mafic gneisses were analysed by secondary ion mass spectrometry (SIMS) and yield concordant U-Pb dates between 3.86 Ga and 3.70 Ga. This age can be attributed to magmatic and possibly to metamorphic activity (Kusiak et al. 2021).

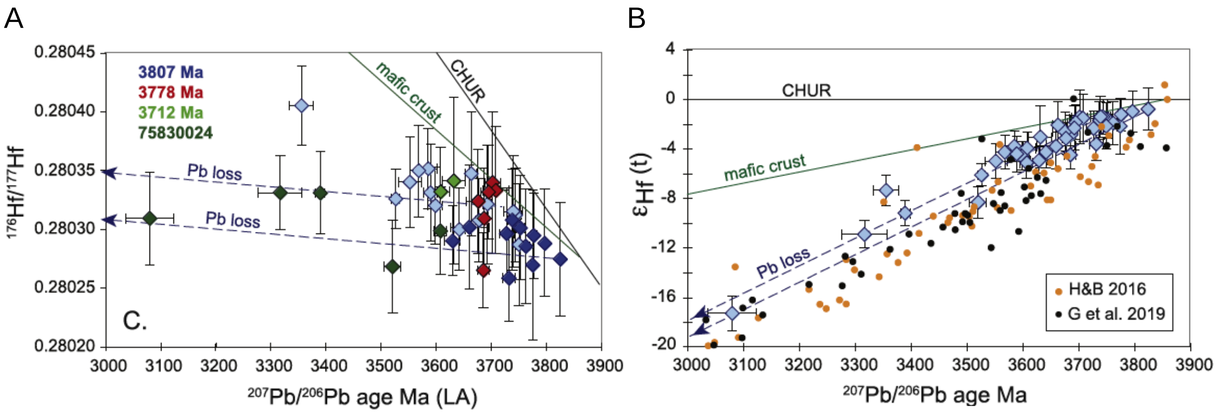

Fig. 3: (A) $^{176}Hf/^{177}Hf$ versus $^{207}Pb/^{206}Pb$ age subdividing data by sample and by SHRIMP upper intercept age group for the trondhjemitic gneiss; (B) Comparison between the Aker Peaks zircon data (Kusiak et al. 2021) with that reported for zircons of Napier Complex gneisses from Mount Sones and Gage Ridge by (H&B) Hiess and Bennett (2016) and (G) Guitreau et al. (2019). Modified after Kusiak et al. (2021).

Concurrent analysis of $^{207}Pb/^{206}Pb$ ratios and Lu-Hf isotopes in the trondjemitic sample by laser ablation ICPMS provided initial εHf(t) estimates for this age range that are slightly sub-chodritic (values 0 to –2; Fig. 3). This can be attributed to the incorporation of older crust into the magmatic protoliths of the gneisses although there is no requirement that these crustal sources would be older than Eoarchean.

Oxygen data

The question as to whether there was emergent land in the Eoarchean (4.0–3.6 Ga) is fundamental not only for understanding Earth's evolution but also for life itself. Magmatic rocks with isotopically light oxygen can indicate interaction of magmas or their sources with surface water (e.g. meteoric water). Consequently, the presence of such rocks in the geological record of the early Earth can provide an indicator for the emergence of land. Zircon from two Eoarchean orthogneisses in the Tula Mountains, Napier Complex, East Antarctica, show such light isotopic signatures. A ca. 3.75 Ga trondhjemitic gneiss and a ca. 3.55 Ga dioritic gneiss, both with high Y-HREE-Nb-Ta that can be ascribed to the melting of shallow sources at < 1.0 GPa, contain zircon with exceptionally low $\delta^{18}O$ values of 1.0–2.7‰ (normalized to Vienna Standard Mean Ocean Water; Król et al. 2024). The lowest $\delta^{18}O$ value in zircon previously reported from Paleoarchean orthogneisses is 3.7‰ at 3.56 Ga (Fig. 4).

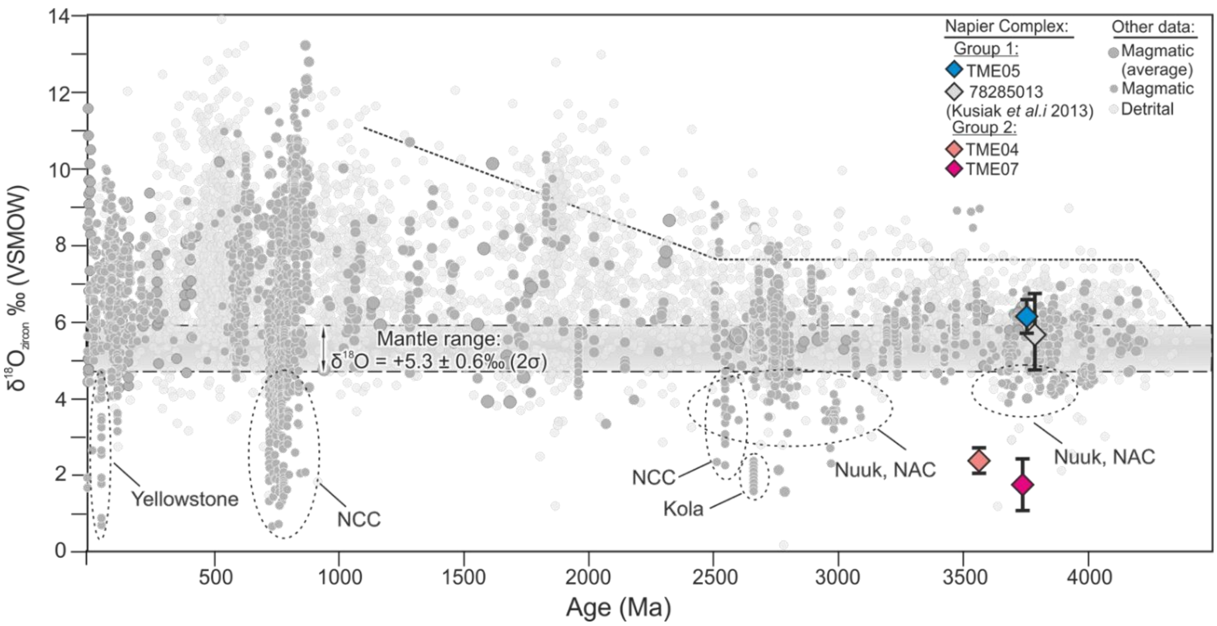

Fig. 4: Compilation of $\delta^{18}O$ versus age for magmatic and detrital zircon throughout Earth history. The data points are plotted at their respective crystallization ages determined by U–Pb geochronology. Zircon $\delta^{18}O$ data from sample 78,285,013 represent granitic gneiss from Gage Ridge, Tula Mountains (Kusiak et al. 2013a). The upper dashed line indicates the evolution of "maximum" _$\delta^{18}O$ in zircon through geological history (Valley et al. 2003). The mantle zircon $\delta^{18}O$ range represented by grey band is from Valley et al. (1998). NAC — North Atlantic Craton; SCC — South China Craton. Modified after Król et al. (2024).

3. SUMMARY

Pb nanospheres in zircon: Documenting the micro-composition and mineralogy of Eoarchean zircon and Pb-enriched domains is essential for understanding the processes of Pb redistribution in zircon and its effect on geochronology.

Lu-Hf in zircon: The scatter in the U-Pb dataset is attributed to isotopic disturbance of Pb during the UHT metamorphism at 2.5 Ga. If data are not corrected, results can lead to overestimation of model crust formation ages, a critical problem in the search for evidence of Hadean crust in Eoarchean rocks and for estimation of timing and rate of ancient continental growth.

Oxygen in zircon: We show that although the generation of such isotopically light signatures can be achieved through mixing with seawater during a hydrothermal event, the proportion of oxygen from seawater would have to be exceptionally high. In contrast, only a small and more realistic proportion of water with much lighter $\delta^{18}O$, such as that characteristic of meteoric water would be required. These new results, therefore, are consistent with the presence of shallow magmatic or hydrothermal systems involving meteoric water at 3.73 Ga, providing the earliest known evidence for the emergence of land on Earth.

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Arctic Nanogranitoids and What We Can Learn from Them

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Primary melt inclusions are small droplets of melt trapped in minerals during their growth in the presence of a melt phase (Sorby 1858; Roedder 1984; Frezzotti 2001). In magmatic rocks melt inclusions have been described since 1858, when Henry Clifton Sorby recognized them in feldspar, pyroxene, and leucite crystals in erupted lavas (Sorby 1858). Already back then, Sorby was able to observe and recognize under the microscope glassy and crystalized inclusions referring to them as “glass-cavities” and “stone-cavities”, respectively.

In metamorphic rocks, melt inclusions generally occur – as for their magmatic counterparts – either as glass or crystallized into a cryptocrystalline assemblage with a variable composition named nanorocks (Bartoli and Cesare 2020). When these polycrystalline inclusions display an assemblage similar to that of a granitoid, they are called nanogranitoids (Cesare et al. 2015). Melt inclusions in regionally metamorphosed felsic rocks were first described by Cesare et al. (2009). They were identified in the inner part of garnets in the granulites of the Kerala Khondalite Belt in India (Cesare et al. 2009). This study was groundbreaking as it was the first preserved anatectic melt analyzed in situ (Cesare et al. 2009). The study of melt inclusions in metamorphic rocks with modern techniques allows the investigation in situ of natural anatectic melts and the determination of the physico-chemical conditions at which anatexis took place (Cesare et al. 2015; Ferrero et al. 2018). Anatexis is one of the main processes responsible for crustal differentiation and thus studying melt inclusions allows its direct investigation (Cesare et al. 2009) also in terms of volatile budget (Bartoli et al. 2014; Carvalho et al. 2018; Ferrero et al. 2021, 2023; Borghini et al. 2023). Moreover, in subduction settings, where melts and fluids are responsible for the transfer of elements from the crust to the mantle, the study of melt inclusions allows the direct investigation of crust-mantle interaction and deep volatile and incompatible elements cycles (Borghini et al. 2020, 2023, 2024). Nanorocks are widespread almost all over the world, including a few localities in the Arctic (Nicoli et al. 2022; Janák et al., in review) and they are reported in different geological settings (Bartoli and Cesare 2020). In this contribution, we present two examples of melt inclusions trapped in garnets of metamorphic rocks from the Arctic in SE Greenland and NW Norway.

In SE Greenland the samples studied are part of the Mesoarchean (2800–3000 Ma) Kangerlussuaq basement surrounding the Skaergaard intrusion (Kays et al. 1989). This basement is mainly composed of felsic intrusions, tonalites-trondhjemite-granodiorite (TTG) and grey gneisses interlayered with metasediment lenses and amphibolites (Kays et al. 1989). Melt inclusions occur in stromatic migmatites which are part of a metasedimentary lens, and have a melanosome dominated by garnet and biotite (partly chloritized) and a leucosome containing feldspar and quartz with minor oxides, chlorite, apatite, and zircon (Nicoli et al. 2022). The melanosome and leucosome form alternating bands that define the main fabric of the rock. Two generations of garnets were recognized: (i) large xenoblatic garnets (up to 5 mm in size) and (ii) smaller idioblastic garnets overprinting the main fabric (Nicoli et al. 2022). Both garnet generations contain melt and fluid inclusions, with melt inclusions more abundant in the first generation and fluid inclusions more abundant in the second. Both types of inclusions are randomly distributed, forming clusters in the inner part of garnets, indicating that the garnet was growing in presence of a melt and a fluid phase (Ferrero et al. 2018). Melt inclusions are up to 15 μm in size and they were investigated by micro-Raman spectroscopy to determine the mineral assemblage that differs in the two garnet generations. In the xenoblastic garnets, melt inclusions contain quartz/cristobalite, kumdykolite ($NaAlSi_3O_8$ orthorhombic polymorph), kokchetavite ($KAlSi_3O_8$ hexagonal polymorph), and phlogopite. In the idioblastic garnets instead, the melt inclusions assemblage is made of quartz, K-feldspar, chlorite and ± H_2O. Fluid inclusions are significantly bigger, they are up to 40 μm and they contain a constant assemblage in both generations of garnet, including siderite, graphite, pyrophyllite, CO_2, and CH_4. The presence of carbonate, C-phases and hydrates in the same inclusions suggests that the fluid is COH-rich (Nicoli et al. 2022). Thermodynamic modelling suggested a supra-solidus evolution between 0.5 and 0.8 GPa. The first generation of garnet is stable at 950–1000 °C and 0.6–0.8 GPa whereas the second is stable at 825–950 °C and 0.5–0.7 GPa. The garnet/melt pairs considering the differences are snapshots of two different melting events taking place at the pressure-temperature conditions of formation of the two different garnet generations (Nicoli et al. 2022). This case study reports the oldest occurrence of preserved melt inclusions and also shows for the first time the supra-solidus history of this area. The coexistence of melt and fluid inclusions indicates fluid-melt immiscibility and, thus, partial melting in presence of a COH fluid.

In NW Norway, the samples are from the Nordmannvik Nappe – part of the Norwegian Artic Caledonides. This Nappe is made of polymetamorphic rocks, including mylonitic micaceous gneisses, garnet amphibolites, marbles, calcsilicates and ultramafic lenses (Andresen 1988). Nanogranitoids, along with diamond-bearing fluid inclusions, occur in garnet-kyanite migmatitic gneisses located in a megalens of the Nordmannvik Nappe at Heia (Janák et al. 2024). These gneisses are finely foliated and contain melanocratic and leucocratic domains.

The melanocratic domains host garnet and kyanite porphyroblasts, biotite and white mica whereas the leucocratic portion is dominated by feldspars, quartz, and garnet (Janák et al. 2024). Melt and fluid inclusions occur in the inner parts of garnets organized in clusters or isolated. Melt inclusions are up to 100 μm and their mineral assemblage was determined with an electron microprobe. They contain muscovite, paragonite, phlogopite, K-feldspar, albite, quartz, and kyanite (Janák et al. 2024). The latter however is a trapped phase as it is present in the matrix and as mineral inclusion in garnet. Fluid inclusions are 5–10 μm in diameter and were investigated with micro-Raman spectroscopy. They contain CO_2, siderite and magnesite, a minor amount of pyrophyllite, biotite, white mica, diamond, and ± graphite. The association of carbonates, C-phases and hydrates suggests that the fluid is COH. Diamond is an index mineral of ultra-high pressure (UHP) conditions and its presence in a fluid coexisting with melt suggests that partial melting in Heia gneiss took place at UHP conditions in the presence of a COH fluid. This is one of the first examples of fluid-melt immiscibility at UHP conditions (Janák et al. 2024).

Melt inclusions represent a snapshot of melt produced during anatexis in terms of major, trace elements, and volatiles. The composition of the melt can be measured in situ on glassy inclusions and experimentally re-homogenized nanogranitoids with the electron microprobe (Cesare et al. 2015; Ferrero et al. 2018). Moreover, also trace elements and volatiles concentrations can be directly obtained from the analyses of melt inclusions (see Bartoli et al. 2014; Carvalho et al. 2018; Nicoli and Ferrero 2021; Ferrero et al. 2021, 2023).

In subduction settings, the possibility of targeting melt inclusions trapped in mantle rocks involved in crust-mantle interaction allows not only to quantify the mass transferred from the crust to the mantle but also the deep volatile cycles (Borghini et al. 2020, 2023, 2024). All these processes have an influence on crustal growth, global volatile recycling, Earth habitability, and climate (Borghini et al. 2023).

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Can Lamprophyres in LIPS Constrain Upper Mantle Plume Dynamics?

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Volatile-rich basanitic melts giving rise to camptonite lamprophyre swarms (Brown 1975) in the Orkney Islands, Northern Scotland, have been precisely dated by mantle xenolithic and autocrystic zircon U-Pb geochronology. The results show that melt generation in the mantle, recorded by xenocrystic zircon in camptonites, and emplacement, recorded by autocrystic zircon in a fractionated sannaitic dike, occurred within c. 5 m.y. from each other. The melt-generation zone of the lamprophyres has been modelled to be >90 km depth, in the garnet stability field (REEBOX PRO; Brown and Lesher 2016) and the zircons show Hf-isotopic evidence for the mixing of two suprachondritic sources, the most positive ε_{Hf}-values interpreted to represent influxing asthenospheric mantle. The xenocrystic nature of the zircons from the camptonite and of most of the zircons from the sannaite (?) is evidenced by the texture (sector zoned, homogeneous but also oscillatory zoned), the trace element chemistry (e.g. Grimes et al. 2015; Hoare et al. 2021), high Ti-in-zircon crystallisation temperatures (>900 °C; Crisp et al. 2023) and for the camptonites, the highly zircon-undersaturated nature of the melts (Crisp and Berry 2022). As the zircons in the camptonites were brought to the near surface in highly zircon-undersaturated melts they are also recorders of magma residence time (Zhang and Zu 2016), and hence ascent rates; in this case recording translithospheric magma ascent of around 15 m/s.

The Orkney dike swarm (Fig. 1) has been associated with the Skagerrak centred large igneous province (SCLIP; Torsvik et al. 2008; Lundmark et al. 2011). The main stage (normally represented by flood basalts in a LIP; e.g. Burgess et al. 2017) of the SCLIP is dated to c. 300 Ma (Torsvik et al. 2008; Corfu and Larsen 2020), and xenocrystic zircons in the Orkney camptonite dikes formed up to 7 m.y. prior to the main stage of the LIP. The formation of the mantle zircons can be interpreted as a process reflecting the first partial melting event associated

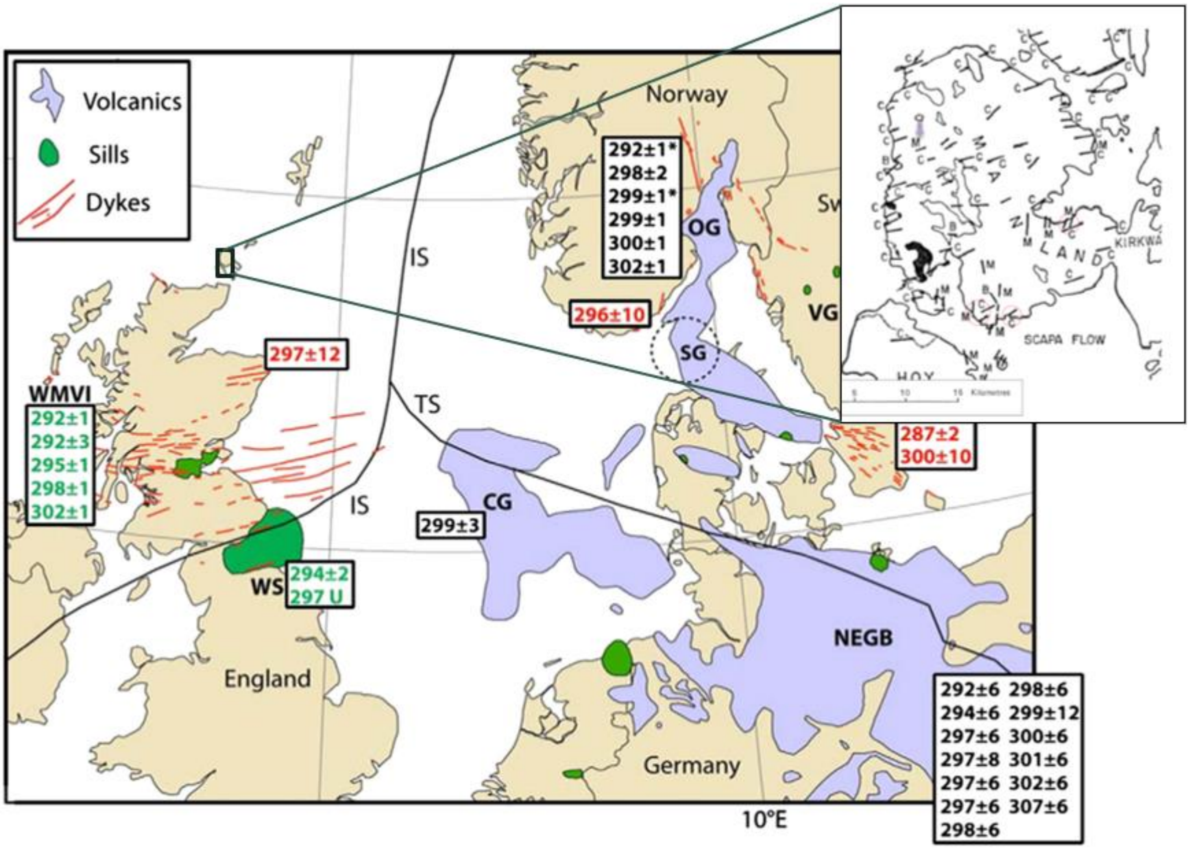

Fig. 1. Overview map of the Skagerak centred large igneous province (SCLIP) and inset showing the Orkney dike swarm(s). Modified from Torsvik et al. (2008) and Brown (1975).

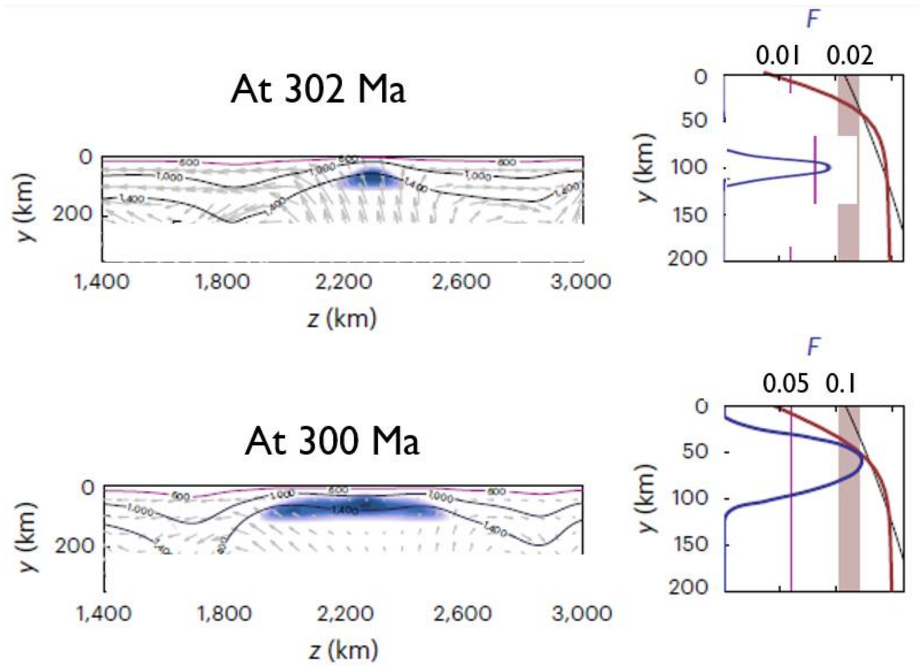

Fig. 2. Conceptual model showing mantle plume impingement at the base of the lithosphere beneath the Orkneys at 302 Ma (upper left panel) and at 300 Ma (lower left panel). At 302 Ma only the tip of the plume has reached the base lithosphere, whereas at 300 Ma the body of the plume has reached the base of the lithosphere. This is reflected in the melt fraction produced and the depth of melting displayed in the upper right panel for 302 Ma and the lower right panel for 300 Ma.

with elevated mantle temperature due to plume-lithosphere interaction (Fig. 2). As such, it places absolute time constraints on upper mantle plume dynamics as a function of mantle potential temperatures (Tp) during different stages of a LIP, determined by the plume ascent velocity in the upper mantle. The modelled conditions at the lamprophyre melt generating stage c. 2 m.y. before the onset of the flood basalt stage (Fig. 2, indicate a Tp of c. 1400 °C (REEBOX PRO; Brown and Lesher 2016). This can be compared to the Tp during the main stage of LIP volcanism, that are typical above 1500 °C occurring at shallower depths, of less than 50 km (e.g. Hole and Millett 2016). Recent, reliable estimates of the Tp at the B1 (main stage) phase of the SCLIP do not exist. However, a highly conservative estimate would be that the mantle potential T increased by 100 °C in 2 m.y., giving direct input into models estimating the plume ascent in the upper mantle, when also considering the shallowing of the melt column and lateral gradients within the plume head (Hole and Millett 2016). Hence, identifying and precisely dating lamprophyre magmas preceding basalt volcanism in LIPs globally provide new constraints to test models of upper mantle plume dynamics when combined with thermal models for plume-ambient mantle interaction.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

A Within-Sill Record of Chlorine Mobilization from Evaporites in Volcanic Basins

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Exceptionally voluminous magmatic episodes in the deep geological past, known as Large Igneous Provinces (LIPs), emplaced millions of km^3 of magma in the crust and on Earth's surface in a geologically limited time (<1 Ma), and released vast quantities (Gigatons) of volcanic and thermogenic gases. The outgassing of volatiles was a significant environmental disruptor, leading in some case to global environmental change and biotic crises (Deegan et al. 2023). LIPs are in fact the only geologic source to rival anthropogenic emissions (Deegan et al. 2023, Capriolo et al. 2022) for volumes and rates of released climate-modifying gases. Reconstructing their degassing histories is thus important as analogue case-studies of present-day and future climate challenges. Studies of LIP volatiles discharge often focus on the two primary climate-modifying volatiles, carbon and sulphur. However, in LIPs whose plumbing systems intruded halogen-rich evaporites, the release of halogens might have been an important environmental and biotic stressor (Svensen et al. 2023). The reactive halogen species generated during eruptions and upon interaction with halogen-rich sedimentary rocks in volcanic basins could cause acid rains and catalyse ozone layer depletion.

A paramount example is the Siberian Traps Large Igneous Province (STLIP), rapidly emplaced at the end of the Permian, synchronous with the most severe terrestrial ecological crisis in Earth's history (251.9 Ma), and the only known mass extinction among insects (Dal Corso et al. 2022, 2024). Palaeontological data suggest that halogens outgassing from the Siberian Traps could have facilitated mutations and DNA damage in life forms via enhanced UVB radiation (Liu et al. 2023). It is still debated whether the ultimate provenance of halogens was the STLIP mantle source or the evaporite series of the Tunguska basin (Broadley et al. 2018; Sibik et al. 2021). We studied 14 sills intercepted by 5 boreholes down to 4 km deep, obtained from locations straddling all across the Lower Tunguska basin (Fig. 1). Whole-rock data suggest that

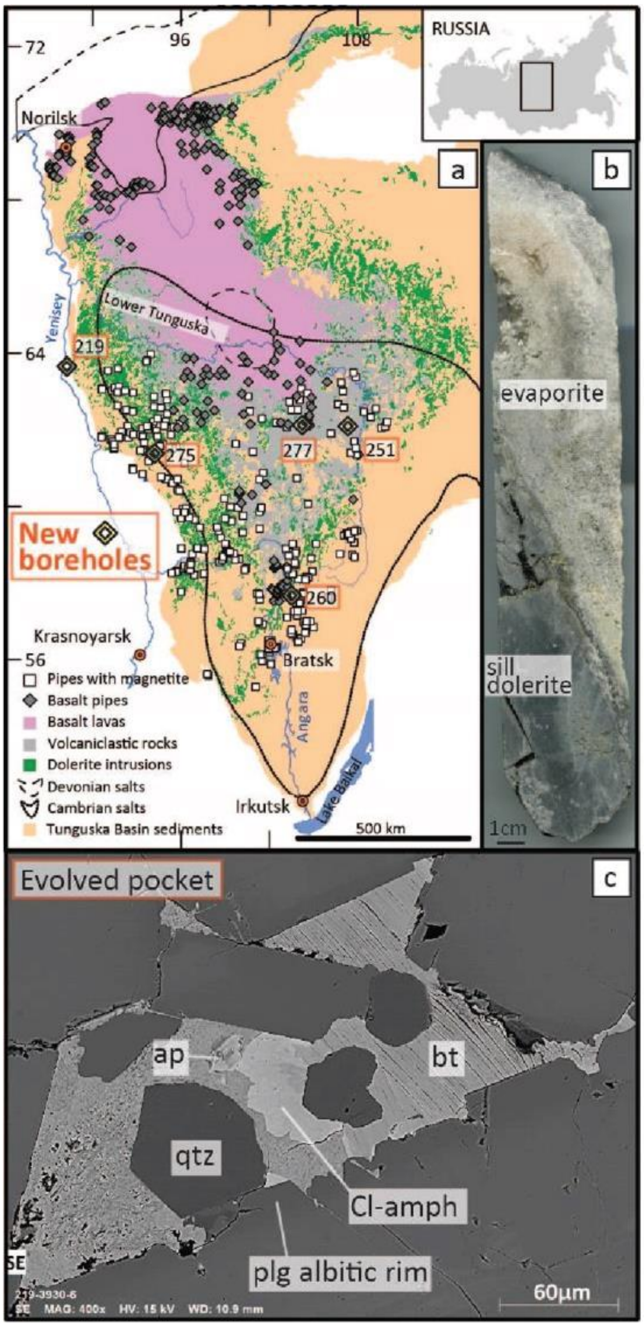

Fig. 1: a) Outline of the Siberian Traps (modified after Svensen et al. 2009) and locations of the available boreholes; b) Core intercepting a sill in direct contact with a halite- and anhydrite-rich evaporitic host-rock; c) SEM image of dikytaxitic pocket containing quartz, apatite, Cl-rich biotite, and Cl-amphibole.

Fig. 2. Sill of the High Arctic Large Igneous Province intruding Permian evaporites of the Gipshuken Formation, in James I Land of Spitzbergen, Svalbard Islands. The sill in this outcrop is 10+ m thick. The black circle indicates the location of the samples with high-Cl biotite. Photo: Hans Jørgen Kjøll, summer 2021.

significant interaction occurred between sills and evaporitic host-rocks (Sibik et al. 2021; Callegaro et al. 2021). The sills are geochemically correlated to the main tholeiitic phase of the Siberian Traps, and with the Noril'sk intrusion, dated coeval to the extinction event (Dal Corso et al. 2024; Callegaro et al. 2021). In addition, we found evidence for late-stage enrichment in chlorine within the sills at the mineral scale. The doleritic sills that developed a relative coarse-grained texture show late-stage evolved pockets. These are pore-filling mineral that form at the late-magmatic to hydrothermal stage among the main framework of doleritic minerals (plagioclase, clinopyroxene, olivine, and oxides, in order of abundance), and comprise a granitic assemblage of quartz, biotite, K-feldspar, apatite, amphibole, and Zr-bearing minerals (Fig. 1). Biotite shows a tendency to incorporate growing amounts of chlorine towards the rims, up to 4.5 wt.%. Mineral boundaries are sometimes filled with pyrosmalite, a Mn- and Cl-rich phyllosilicate. These mineral compositions likely reflect the late-stage circulation of a Cl-rich brine and/or vapor phase in the system, produced by thermal interaction between the sills and the evaporitic host-rocks. Temperatures of crystallization of ca. 600 °C as suggested by Ti-in-quartz geothermometry agree with this interpretation. The presence of hydrothermal vent complexes over the basin suggests abrupt discharge of Cl-rich vapours following pressure buildup at the sills margins (Polozov et al. 2016). The fact that we find high-Cl biotite in sills from all the studied boreholes indicates that Cl mobilization was relevant at the basin scale, and not only a local peculiarity. Overall, these observations support a shallow crustal origin, i.e. from the sedimentary basin, for the halogens released by the STLIP, but further data are needed to confirm the hypothesis (e.g. Cl or S isotope composition). The presence of Zr-rich minerals in the late-stage pockets will potentially allow to obtain an absolute age for the extensive Cl mobilization and release.

Interestingly, similar evidence is found in sills of the Central Atlantic Magmatic Province (ca. 201 Ma) intruded in the Amazonas basin (Heimdal et al. 2019), and in sills of the High Arctic Large Igneous Province in Svalbard (James I Land) intruded in Permian evaporites (Fig. 2). We propose that the Cl concentrations of late-formed minerals serves as a powerful within-sill proxy to detect halogen mobilization from evaporites in volcanic basins.

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Diabasodden and Its Suite – the High Arctic Large Igneous Province on Svalbard and Its Type Locality

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1. INTRODUCTION

During the Cretaceous, the circum-Arctic region was affected by widespread magmatism, known as the High Arctic Large Igneous Province (HALIP). These mainly mafic intrusives and extrusives are found throughout the Queen Elizabeth Islands, northern Greenland, the Alpha-Mendeleev Ridges, the New Siberian Islands, Franz Josef Land, and Svalbard (Senger et al. 2014; Maher 2001). There have been three proposed pulses, from 124 to 120 Ma, from 99 to 91 Ma, and from 85 to 77 Ma (Dockman et al. 2018). Generally, the oldest magmatism is tholeiitic, the middle pulse bimodal, and the youngest pulse alkaline (Tegner et al. 2011). The alkaline pulse is only found in northern Greenland and on the Queen Elizabeth Islands, while the tholeiitic magmatism is found throughout the circum-Arctic, with the exception of Greenland (Dockman et al. 2018; Thórarinsson et al. 2015). This large igneous province has been proposed to be related to a Cretaceous Arctic mantle plume, with a center located ca. 200 km west of Ellesmere Island (Buchan and Ernst 2018).

The HALIP rocks found throughout the Svalbard archipelago are regionally called the Diabasodden Suite, based on its type locality in central Spitsbergen, the main island of Svalbard. In this contribution, the focus will be on characterizing the Diabasodden Suite based on previously published data.

2. THE DIABASODDEN SUITE

The outcrops of the HALIP on Svalbard (Fig. 1) represent magmas that erupted on the surface in the far east, on Kong Karls Land, and that was intruded at various depths in the rest of the Svalbard archipelago. One of the shallowest sills, at Botneheia in central Spitsbergen, has an emplacement depth of ca. 0.5 km, based on the the thickness of the sedimentary units deposited above the intrusion until the early Cretaceous (Dallmann et al. 1999; Norwegian Polar Institute 2016). The emplacement depths cannot be estimated in all places, e.g. in Nordaustlandet, where

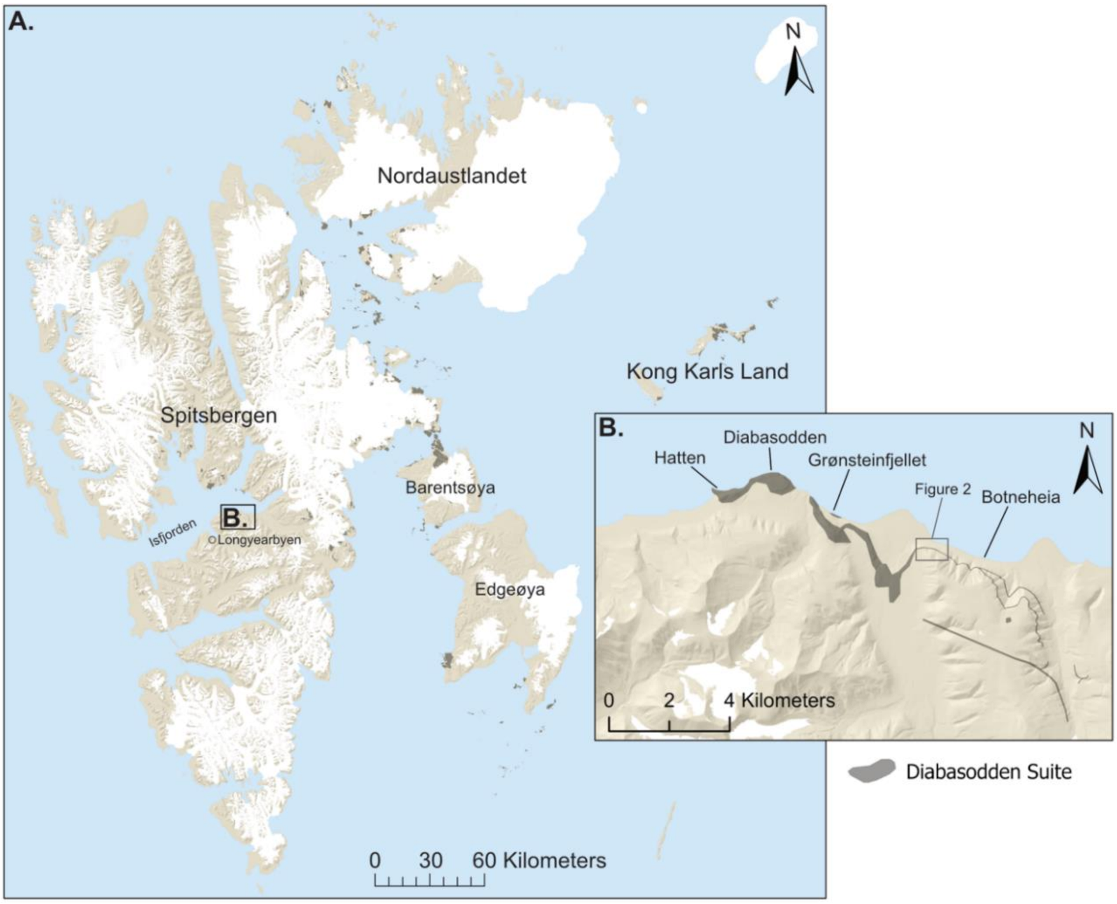

Fig. 1: A. Topographical map over Svalbard, illustrating the extent of the High Arctic Large Igneous Province, regionally called the Diabasodden Suite; B. Map over the type locality of the Diabasodden Suite, and surrounding intrusions. The area shown on the digital outcrop model in Fig. 2 is indicated on the map. The glacier extents, land area and digital elevation are from the Norwegian Polar Institute (2014a,b), and the extent of the Diabasodden Suite is a modified version of the Geological map of Svalbard (Norwegian Polar Institute 2016), based on field observations.

the magma was intruded into the crystalline basement. The thickness of the flood basalts and intrusions themselves vary from a few meters to more than 100 m, based on measurements from digital outcrop models (DOMs, Fig. 2). These are built on high-resolution UAV images acquired all around Svalbard, during various expeditions, e.g. SvalGeoBase II. These images and the resulting DOMs are openly available (Betlem et al. 2023). The Diabasodden Suite magmas were likely emplaced during a short time interval between 125 and 123 Ma, according to available U-Pb geochronology (Corfu et al. 2013; Midtkandal et al. 2016). This indicates that perhaps only the oldest pulse of the HALIP is present on Svalbard.

Petrographically, the Diabasodden Suite is commonly composed of plagioclase phenocrysts (up to 1 cm in size), surrounded by a groundmass of finer-grained feldspars, clinopyroxene, Fe-Ti oxides (up to 5 mm in size), and secondary alteration minerals (Nejbert et al. 2011). Occasionally, olivine is also present. Feldspars are mainly plagioclase, but minor amounts of alkali feldspars are also commonly found in the groundmass. Clinopyroxene is often augite. Fe-Ti oxides occur as needles or stubby crystals of Ti-magnetite and ilmenite. The texture of the Diabasodden Suite rocks is mainly doleritic, but ophitic textures also occur (Nejbert et al. 2011). Geochemically, the Diabasodden Suite is characterized as tholeiitic basalts, with SiO_2 contents ranging from ca. 43 to 49 wt%, FeO_{tot} from ca. 11 to 15 wt%, MgO from ca. 2.5–7.5 wt%, and TiO_2 from ca. 2 to 4 wt% (Nejbert et al. 2011).

Fig. 2. An example of a digital outcrop model from Botneheia, central Spitsbergen (Rodes et al. 2024; Betlem et al. 2023). This intrusion, belonging to the Diabasodden Suite, was emplaced into Triassic shales. The thickness of this particular sill is at A: 33 m, B: 38 m, and C: 23 m.

3. DIABASODDEN

Diabasodden, the type locality of the HALIP on Svalbard, is located in eastern Isfjorden, central Spitsbergen (Fig. 1). These dolerite cliffs tower over the water's edge, with an intrusion thickness of ca. 70 m (Norwegian Polar Institute 2014a). Near the Diabasodden intrusion, several other outcrops of the HALIP can be found, including Hatten, Grønsteinfjellet, and Botneheia (Fig. 1). While Diabasodden is an outcropping sill, both dikes and sills are found at these nearby localities. At Diabasodden, the magma intruded into Triassic strata, namely the shales, siltstones, and sandstones of the Late Triassic Kapp Toscana Group. The highest point of the Diabasodden sill is found at 69 m. a.s.l., while the coeval Early Cretaceous sedimentary units are found further inland on Wimanfjellet at ca. 700 m. a.s.l. Diabasodden has been visited and sampled many times in the past, with several publications as a result (e.g. Gayer et al. 1966; Nejbert et al. 2011; Corfu et al. 2013). One of the three (soon four; Sartell et al. in revision) published U-Pb ages on Svalbard is based on a sample collected at Diabasodden, yielding an age of 124.5 ± 0.2 Ma (Corfu et al. 2013). In addition to geochronology, geochemical data, and petrographic descriptions of dolerites from Diabasodden have also been published (Nejbert et al. 2011; Gayer et al. 1966). These suggest that the Diabasodden sill is characteristic for its Suite, with similar composition and petrography.

Acknowledgments. This contribution is dedicated to the scientists that have built up the knowledge we have today of the Diabasodden Suite, spending long days in the field, in the lab, and publishing data.

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SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

Digital Geology at UNIS: Tools for Supporting Arctic Research, Education, and Expedition Planning

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1. INTRODUCTION

The Arctic is one of Earth's most frontier areas, with numerous unanswered geoscientific questions. In addition, the Arctic is one of the most dynamic areas of the planet, with recent climate change occurring at much higher rates than in the lower latitudes. This phenomenon, the polar amplification effect, is most evident in Svalbard.

Svalbard is a Norwegian high Arctic archipelago comprising all islands between 74–81°N and 15–35°E, including the largest island Spitsbergen. Geologically Svalbard represents an important (and relatively well-accessible) window to understand the tectono-thermal evolution of the circum-Arctic (Senger et al. 2024). There are no indigenous people in Svalbard, but several remote permanent settlements including the "capital" of Longyearbyen. For its high Arctic location, it is easily accessible by regular and affordable flight connections to the Norwegian mainland. It also hosts the University Centre in Svalbard (UNIS), the world's northernmost educational institution.

UNIS is Norway's field university and offers field-based courses at bachelor, master, and PhD level in Arctic geology, geophysics, biology, and technology, with research and teaching conducted throughout the year. The large seasonal variation (Fig. 1) defines the institution's activity throughout the year. Largely as a consequence of this, UNIS is a leading user of digital geological tools that complement traditional fieldwork and extend the short field season to the entire year.

In this contribution we present two interlinked UNIS-led initiatives that openly provide geoscientific data to a broader audience. Specifically we focus on the photosphere-Atlas, VR Svalbard, and an integrated digital outcrop model database, Svalbox. Specifically we outline how data are acquired, shared, and how they are used in the context of Arctic research, education, and expedition planning. Finally, we showcase a virtual field trip developed specifically for the SvalGeoBase II expedition.

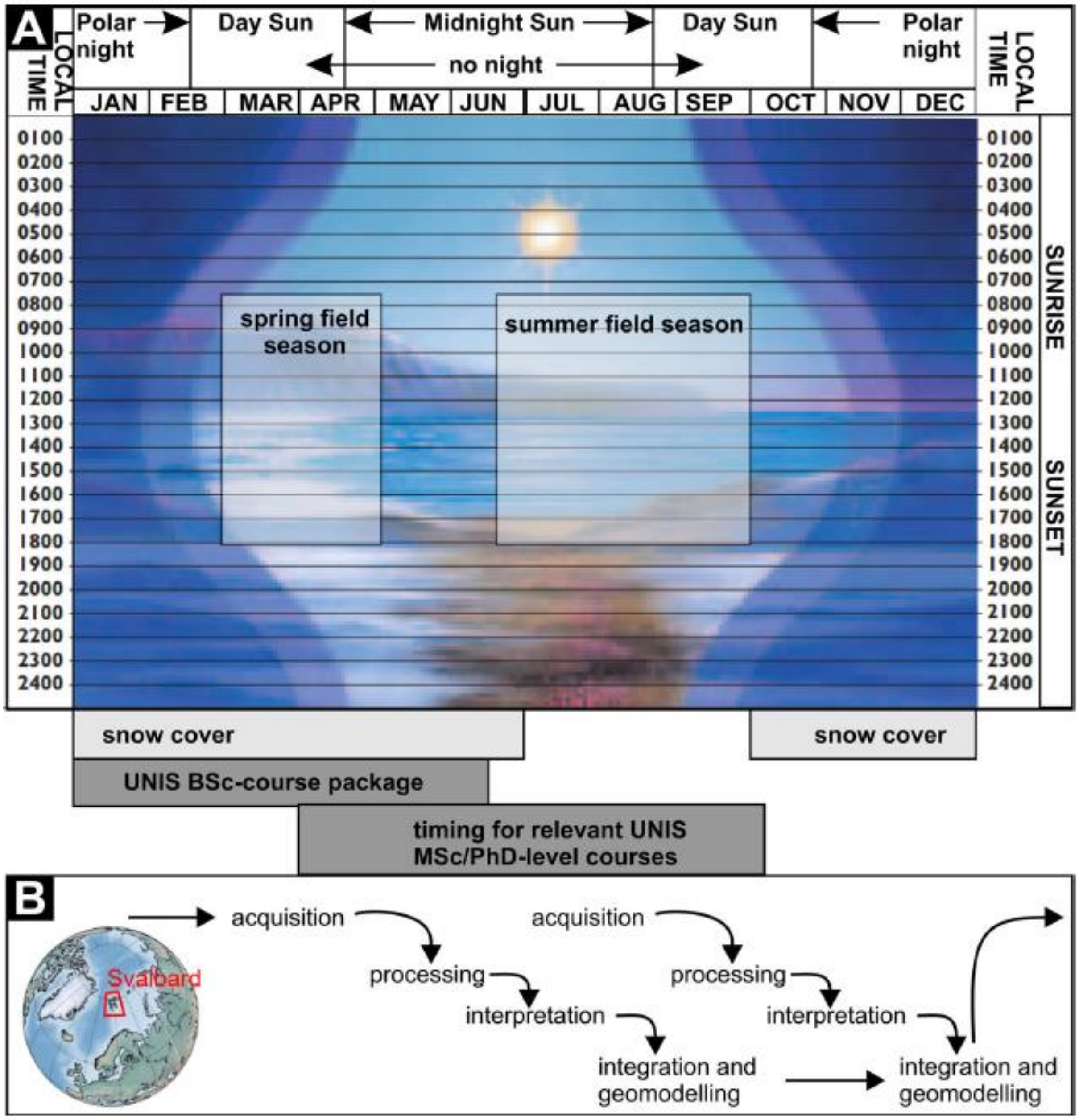

Fig. 1. Seasonal control on course activities in Svalbard: A) Sun diagram for Longyearbyen, overlain with the main field seasons and timing of courses at the University Centre in Svalbard. Sun diagram provided by Longyearbyen Community Council; B) Annual cycle of acquiring photographs for virtual outcrop model processing, interpretation and integration. The inset map shows the position of Svalbard between continental Norway and the North Pole. Figure and caption from Senger et al. (2021).

2. DIGITAL TOOLS

Geoscientists at UNIS have in recent years developed two complementary platforms to share geological data from Svalbard with the global community, VR Svalbard and Svalbox (Fig. 2). Both rely heavily on the use of unmannde aerial vehicles (i.e. UAVs, also known as drones) to acquire standard photographs. Photographs are subsequently processed into digital outcrop models or single photospheres (also known as 360° images). Over the years we have tried many different UAVs, but currently rely on the DJI Mavic 2 Pro and DJI Mavic 3 for the vast majority of data acquisition.

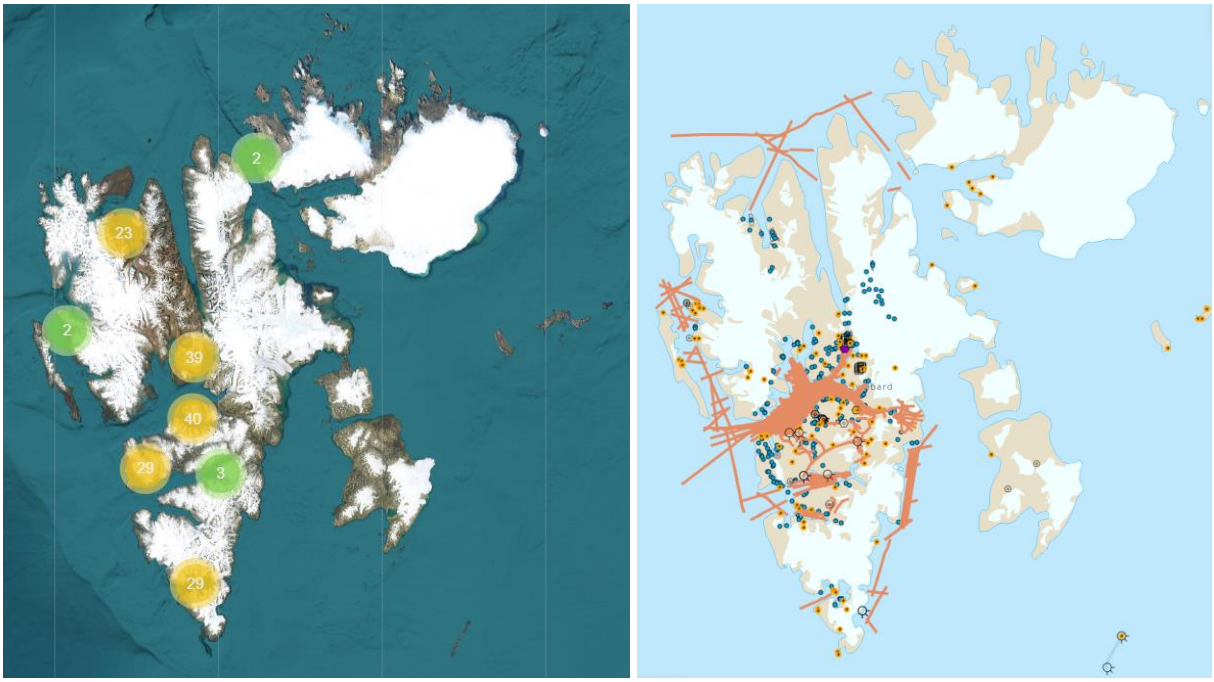

Fig. 2. Openly available digital geological portals led by UNIS: VRSvalbard (left; Horota et al. 2024; www.vrsvalbard.com/map) and Svalbox (right; Betlem et al. 2023; www.svalbox.no/map).

VR Svalbard

VR Svalbard (www.vrsvalbard.com; Horota et al. 2024) is a photosphere-based Atlas of landscapes in Svalbard. Similar to Google Street View, photospheres allow the user to gain an overview of geological elements. As photospheres can be acquired very quickly, they can be taken in parallel with field activities and thus provide a digital representation of the specific conditions (snow cover, weather, etc.) of the field day.

In the platform, virtual field tours are a sequence of panoramic images that are spatially merged to create a virtual experience. Once created, the viewer can virtually experience local and remote field sites. Virtual field tours can be experienced through desktop computers, laptops, tablets, mobile devices, and even in an immersive view mode with head-mounted displays (Horota et al. 2024).

Virtual field guides, on the other hand, are interactive, digital experiences that provide users with a thematic storytelling exploration of a field area. In essence, they capture the real-world environment of a specific location or region through a variety of multimedia content, including images, videos, maps, gifs, and 3D models to teach. Virtual field guide experiences are only visualised via desktop or mobile devices (Horota et al. 2024).

Svalbox

Since 2016 UNIS has been systematically acquiring digital outcrop models (DOMs) and openly sharing them through the Svalbox database (Senger et al. 2022; Betlem et al. 2023). Digital outcrop models (DOMs) have revolutionized the way twenty-first century geoscientists work. DOMs are georeferenced three-dimensional (3-D) digital representations of outcrops that facilitate quantitative work on outcrops at various scales. Outcrop digitalization has been traditionally conducted using laser scanners, but in the past decade, it has seen exponential growth because of efficient and consumer-friendly Structure-from-Motion (SfM) algorithms concurrent with the rapid development of cost-effective aerial drones with high-resolution onboard cameras (Betlem et al. 2023).

The Svalbox DMDb described by Betlem et al. (2023) is a regional DOM database geographically constrained to Svalbard. Svalbard offers exceptional-quality, vegetation-free outcrops with a wide range of lithologies and tectono-magmatic styles, including extension, compression, and magmatism. Data and metadata of the systematically digitalized outcrops across Svalbard are shared according to FAIR (i.e. findable, accessible, inter-operatable, and re-usable) principles through the Svalbox DMDb (Betlem et al. 2023).

These DOMs are georeferenced high-resolution 3D representations of the outcrops and facilitate quantitative sedimentological and structural work. Through Svalbox the DOMs are also put in a regional context through spatial integration of maps (geological, topographical, paleogeographic, geophysical, etc.), surface (digital terrain models, satellite imagery, etc.), and subsurface (boreholes, geophysical profiles, published cross-sections, etc.) data, as illustrated for the Festningen geotope by Senger et al. (2022).

3. APPLICATIONS AND CASE STUDIES

Research

Digital data are of paramount importance for numerous research projects. Svalbox models have been actively used in numerous publications across a range of disciplines, including tectonostratigraphy (Dahlin et al. 2024; Smyrak-Sikora et al. 2021), magmatism (Senger et al. 2013), and structural geology (Ogata et al. 2023).

One of the key benefits for using DOMs is that they are available year-round, not just during the short geological field season in Svalbard. The other major benefit is that DOMs allow more quantitative analyses including measuring thicknesses, orientations, and integrating various data sets (e.g., sedimentary logs, sample locations, shallow geophysical profiles).

Education

DOMs and photospheres viewed with state-of-the-art visualization in the classroom facilitate efficient fieldwork through pre-fieldwork preparation and post-field work quantitative analyses. Both data types are heavily used by UNIS, with documented case studied provided for both bachelor (Senger et al. 2022) and MSc/PhD level courses (Senger et al. 2024).

Horota et al. (2023) integrates photospheres and DOMs together with other geoscientific data (exploration wells, seismic, digital terrain models, publications, etc.) in the context of a thematic data package (Fig. 3). The theme is Svalbard’s most prominent structural feature, the West Spitsbergen Fold and Thrust Belt, and the publication with its rich digital data packages in both Petrel and QGIS serves as a foundation for both research-based teaching and research itself.

Expedition planning, execution, and post-expedition data integration

Digital tools like VR Svalbard and Svalbox greatly facilitate expedition planning, providing a solid overview of the outcrop conditions that is not feasible using regional satellite data. Where available, the data facilitate virtual pre-expedition exploration of the regional study area to identify zones where targeted field work is desired. Access routes and, where relevant, sites for establishing base camp can be planned and discussed with local experts. Detailed field planning will reduce the environmental impact through, ideally, less time needed to be spent in the field.

During an expedition, digital databases can be set up in the base camp to merge the field observations of numerous field parties. Senger et al. (2024), for instance, demonstrates how such data integration worked during a geoscientific expedition to Woodfjorden. DOMs, sample locations and observations including field photos were seamlessly shared across the eleven team members through an application not requiring internet connection.

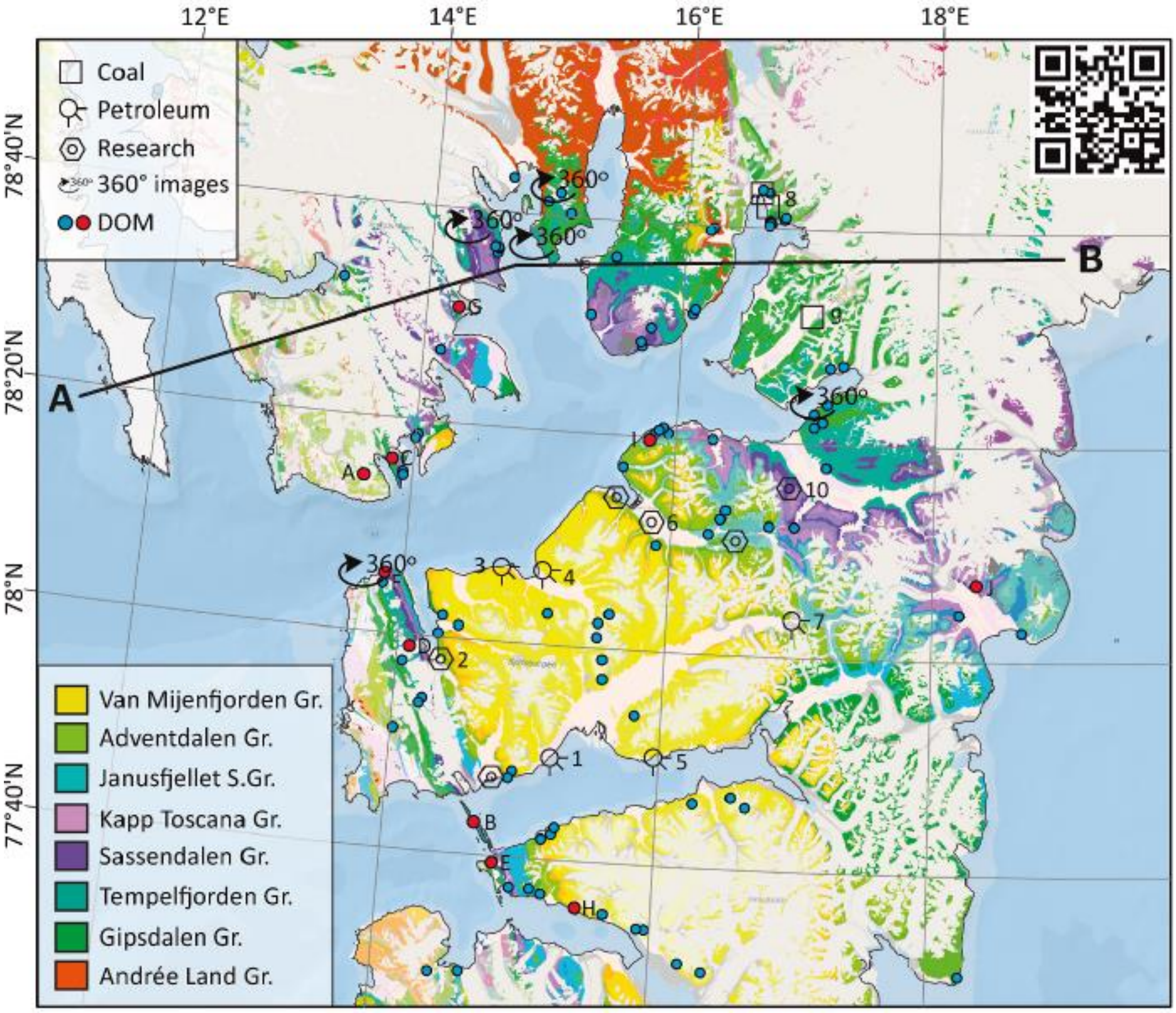

Fig. 3. Geospatial database of all georeferenced data containers provided in the interactive educational data package with this article. The interactive data are also available on the Svalbox online portal, which includes a lot more data sets than extracted for this thematic compilation. Geological map data are courtesy of Norwegian Polar Institute (2014): https://data.npolar.no/dataset/616f7504-d68d-4018-a1ac-34e329d8ad45. Bathymetry data are courtesy of IBCAO (Jakobsson et al. 2012). Figure and caption from Horota et al. (2023).

Following an expedition, digital models serve as a foundation to integrate detailed observations such as sedimentary logs, sample locations and field sketches. Furthermore, the data can be integrated in virtual field trips as a lasting memory for the expedition's participants.

4. SVALGEOBASE II VIRTUAL FIELD GUIDE

The SvalGeoBase II expedition visited many remote sites in Svalbard. Each landing was documented with photospheres. Short descriptions of the landing sites from this report are integrated with photospheres and available DOMs in an online virtual field guide accessible at URL (Fig. 4).

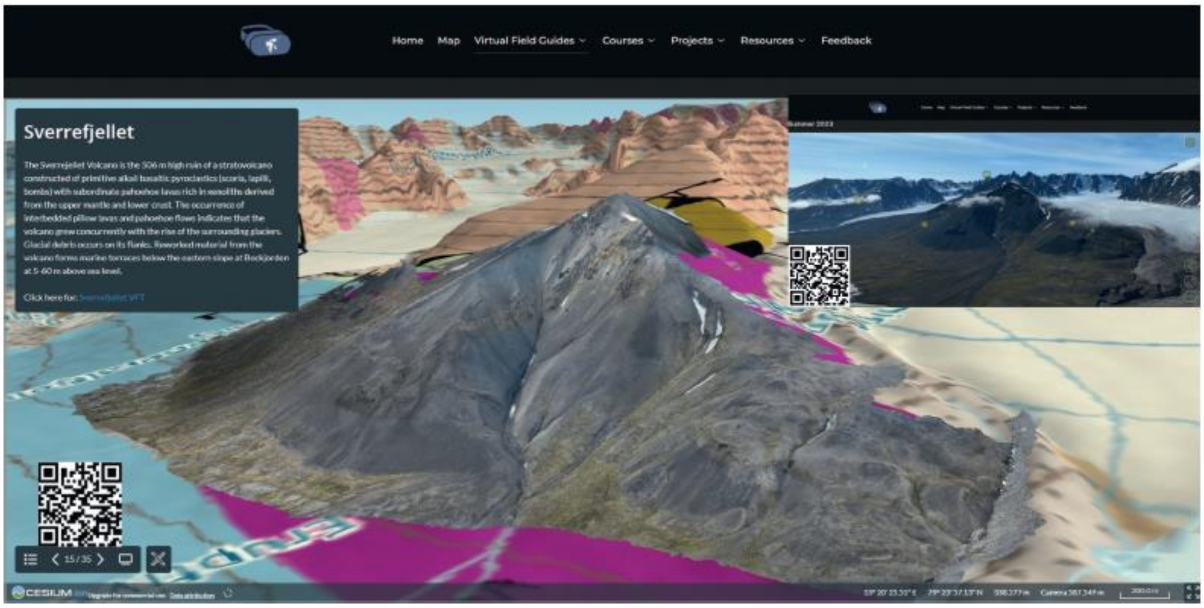

Fig. 4. Data integration and storytelling as a virtual field guide QRcode to URL https://vrsval.bard.com/neogene-quaternary-volcanism-and-thermal-springs/). Integration of ArcticDEM, Bing Satellite, Sverrefjellet DOM, geological map layer of Svalbard, text box and clickable link to the virtual field tour of Sverrefjellet displayed in the upper-right corner, accessible through the QRcode to URL https://vrsvalbard.com/Sverrefjellet/.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

We have presented two central elements of digital geology used at UNIS in Longyearbyen. The VR Svalbard photosphere Atlas provides unprecedented bird's eye views of Svalbard's landscapes, focussing on geological elements. The Svalbox platform provides a growing database of digital outcrop models.

Geoscientists at UNIS will continue to acquire digital geological data for the foreseeable future and openly share it with the community. However, we rely on the Arctic and global geoscientific community to assist with utilizing these models in addressing various research questions. Big data and artificial intelligence may in relatively short time frames allow for semi-quantitative interpretation workflows – but let us not forget that geologists need not to only use digital tools but also spend considerable time out in the field discussing scientific problems with their peers.

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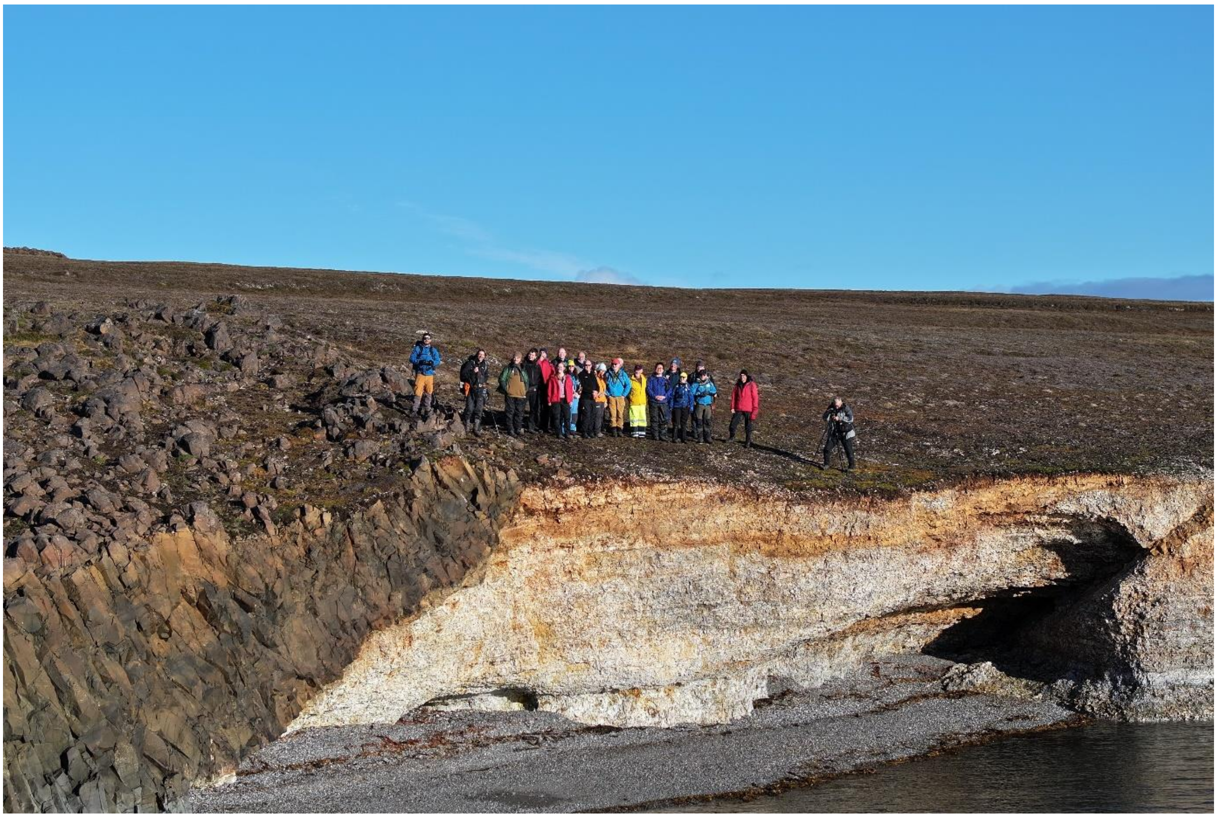
APPENDICES

APPENDIX 1

WORKSHOP PARTICIPANTS



Participants of the SvalGeoBase II geological workshop in Ekmanfjorden (Blomesletta). The photograph captures the contact between Permian sedimentary rocks of the Kapp Starostin Formation and a Cretaceous magmatic intrusion (drone image taken by Anna Sartell and Rafael Kenji Horota; VR Svalbard, Svalbox).

Name	Institution	Scientific expertise
Lars Eivind Augland	University of Oslo	geochemistry
Sara Callegaro	University of Oslo	petrology, geochemistry
Anna Sartell	The University Centre in Svalbard	geochemistry (PhD)
Rafael Kenji Horota	The University Centre in Svalbard	digital geology (PhD)
Simon Wilde	Curtin University	geochemistry
Yebo Liu	Curtin University	paleomagnetism
Geoffrey Manby	Natural History Museum of London	petrology, structural geology
Monika Kusiak	Institute of Geophysics Polish Academy of Sciences	geochemistry
Pierpaolo Guarnieri	Geological Survey of Denmark and Greenland	structural geology
Ian Snowball	Uppsala University	paleomagnetism
Krzysztof Nejbert	University of Warsaw	petrology, economic geology
Krzysztof Galos	Ministry of Climate and Environment (Poland)	economic geology
Karsten Piepjohn	ex-Federal Institute of Geosciences and Natural Resources (Germany)	structural geology
Martin Whitehouse	Museum of Natural History, Stockholm	geochemistry
Victoria Pease	Stockholm University	tectonics, petrology
Thomas Zack	University of Gothenburg	petrology
Alessia Borghini	AGH University of Krakow	petrology
Szczepan Piotr Bal	Institute of Geophysics Polish Academy of Sciences	paleomagnetism (PhD)
Sławomir Matczak	Polish National Television	not aplicable
Krzysztof Michalski	Institute of Geophysics Polish Academy of Sciences	paleomagnetism (coordinator, expedition leader)
Jarosław Majka	Uppsala University/ AGH University of Krakow	petrology, geochemis-try (coordinator)
Piotr Głowacki	Institute of Geophysics Polish Academy of Sciences	glaciology (coordinator)

APPENDIX 2

SVALGEOBASE II ITINERARY (DAY BY DAY)

Day 1 (3 September 2024) – OPENING SESSION

14:10 – Arrival in Longyearbyen – SAS flight from Oslo to Longyearbyen (SK4490)
Bus transfer from Longyearbyen Airport to the town centre
16:00–18:00 – Opening session in Longyearbyen (UNIS)
Safety introduction. Presentations on SSF priorities and the fundamentals of Svalbard's geology
18:00 – Bus transfer to the harbour and embarkation on R/V Horyzont II
19:00 – Dinner
20:00 – Departure from Longyearbyen to Ny-Ålesund

Day 2 (4 September 2024) – EUREKAN FOLD AND THRUST BELT

09:00 – Arrival at Ny-Ålesund
09:00–13:00 – Visit to the Marine Laboratory in Ny-Ålesund, field excursion to the West Spitsbergen Eurekan Thrust and Fold Belt (Brøggerhalvøya) – Landing Site 1 (Fig. 1)
13:00–14:00 – Official lunch on board R/V Horyzont II with representatives of the Ny-Ålesund administration
15:00 – Departure from Ny-Ålesund to Murchisonfjorden (W Nordaustlandet)
16:00–19:00 – Scientific sessions, Part I
19:00 – Dinner

Day 3 (5 September 2024) – BASEMENT GEOLOGY

08:00 – Breakfast
09:00 – Arrival at Murchisonfjorden (Nordaustlandet)
09:00–14:00 – Field excursion to Sparreneset (unmetamorphosed Neoproterozoic/Lower Palaeozoic section of Nordaustlandet – Akademikerbreen Gp, Polarisbreen Gp) – Landing Site 2 (Fig. 1)
14:00 – Departure from Murchisonfjorden (W Nordaustlandet) to Nordkapp (N Nordaustlandet)
14:00 – Lunch
15:00–18:00 – Cruise along the Neoproterozoic outcrops of W Nordaustlandet
18:00 – Dinner
19:00–21:00 – Scientific sessions, Part II
22:00 – Arrival at Nordkapp (N Nordaustlandet)
22:00–24:00 – Field excursion to Beverlysundet (metamorphic basement of the NE Svalbard Province – Brennevinsfjorden Fm, Laponiahalvøya Granite, Ripfjorden Granitoid Suite) – Landing Site 3 (Fig. 1)
24:00 – Departure from Nordkapp (N Nordaustlandet) to Woodfjorden (N Spitsbergen)

Day 4 (6 September 2024) – CENOZOIC VOLCANISM/POST-CALEDONIAN COVER

08:00 – Breakfast
09:00–12:00 – Scientific sessions, Part III
12:00 – Arrival at Woodfjorden (N Spitsbergen)
13:00 – Lunch
14:00–19:00 – Field excursion – Cenozoic volcanism (Bockfjorden Volcanic Complex), Devonian Basin (Wood Bay Formation) – Landing Site 4 (Fig. 1)
19:00 – Dinner
24:00 – Departure from Woodfjorden (N Spitsbergen) to Raudfjorden (NW Spitsbergen)

Day 5 (7 September 2024) – CONVERGENT BOUNDARIES/PLATE TECTONICS

06:00 – Arrival at Raudfjorden (N Spitsbergen)
08:00 – Breakfast
09:00–14:00 – Field excursion – Eclogites of the Richarddalen Complex – Landing Site 5 (Fig. 1)
14:00 – Lunch
15:00 – Departure from Raudfjorden (NW Spitsbergen) to Ekmanfjorden (Isfjorden)
16:00–19:00 – Scientific sessions, Part IV
19:00 – Dinner

Day 6 (8 September 2024) – MESOZOIC MAGMATISM

08:00 – Breakfast
10:00 – Arrival at Ekmanfjorden (Isfjorden)
10:00–14:00 – Field excursion – Bloemesletta (HALIP) – Landing Site 6 (Fig. 1)
14:00 – Lunch
16:00–19:00 – Scientific sessions, Part V (Summary of the workshop)
19:00 – Dinner

Day 7 (9 September 2024) – DEPARTURE FROM SVALBARD

06:00 – Departure from Ekmanfjorden to Longyearbyen
08:00 – Arrival in Longyearbyen
08:00 – Breakfast
09:00–13:00 – Free time in Longyearbyen
13:00 – Bus transfer from the harbour to Longyearbyen Airport
14:45 – Departure from Longyearbyen – SAS flight to Oslo (SK4491)

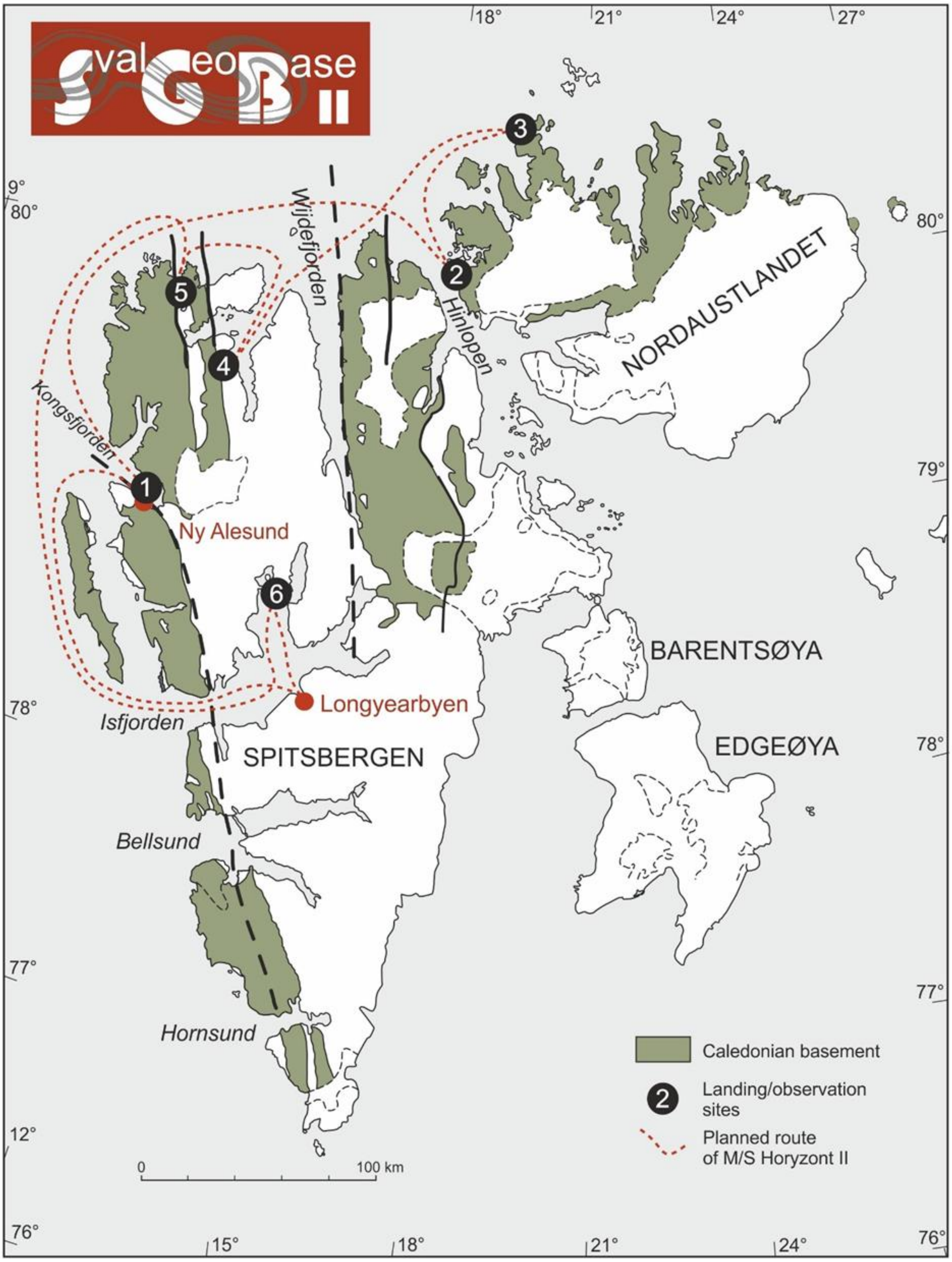


Fig. 1. Route of the Geological Workshop SvalGeoBase II 2024.

APPENDIX 3

DETAILED PLAN OF SCIENTIFIC SESSIONS*

OPENING SESSION (3 September 2024) – Longyearbyen, UNIS, Lassegrotta

16:00–16:10 – Invitation (SvalGeoBase II team)
16:10–16:35 – Svalbard Integrated Arctic Earth Observing System – SIOS (Daan Kivits)
16:35–17:00 – Svalbard Science Forum (Lena Cappelen)
17:00–17:25 – Caledonian Basement of Svalbard (Jarosław Majka)
17:25–17:50 – Post-Caledonian evolution of Svalbard (Anna Sartell)
17:50–18:00 – Safety instruction (Krzysztof Michalski)

SESSION I – Oral presentations (4 September 2024) – R/V Horyzont II

16:00–16:30 – The Eurekan West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya (Karsten Piepjohn)
16:30–17:00 – An alternative hypothesis for forming the West Spitsbergen Fold and Thrust Belt (Geoffrey Manby)
17:00–17:30 – Tectonic evolution of the Wandel Sea Basin (eastern North Greenland): insight from structural data, mineralogy, fluid inclusions, vitrinite reflectance and conodont color alteration index (Pierpaolo Guarnieri)
17:30–18:00 – The Caledonian Wilson Cycle from a North Atlantic perspective (Jarek Majka)
18:00–18:30 – Current paleomagnetic database of Svalbard (Krzysztof Michalski)

SESSION II – Oral presentations (5 September 2024) – R/V Horyzont II

19:00–19:30 – Architecture of the Caledonian foldbelt in the Western Part of the Nordaustlandet Terrane (Karsten Piepjohn)
19:30–20:00 – Palaeomagnetic data obtained from recent deglacial sediments in the Baltic Sea: modern analogues may be the key to understanding (much) older records (Ian Snowball)
20:00–20:30 – Neoproterozoic tillites of Polarisbreen Group (Nordauslandet, Svalbard) – pale omagnetic and petrographic investigations (Szczepan Bal)

SESSION III – Oral presentations (6 September 2024) – R/V Horyzont II

9:00–09:30 – Arctic Tectonics (Victoria Pease)
9:30–10:00 – A global full-plate model for the past 2 billion years (Yebo Liu)

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*Only the names of the speakers are listed in the program. The names of co-authors are presented in the abstract section of this report.

10:00–10:30 – Exploring Neogene–Quaternary magmatism and thermal springs: data acquisition in Woodfjorden 2022–2023 (Rafael Kenji Horota)
10:30–11:00 – Magnetic mineralogy vs. rock-magnetic properties of rock samples - toward filling the gap between these data sources (Krzysztof Nejbert)

SESSION IV – Oral presentations (7 September 2024) – R/V Horyzont II

16:00–16:30 – The Hadean: was it really Hell-like? (Simon Wilde)
16:30–17:00 – Geological constraints on claims for Earth's earliest life in the Eoarchean of Greenland and Labrador (Martin Whitehouse)
17:00–17:30 – Remnants of Eoarchean crust in the Napier Complex, East Antarctica (Monika Kusiak)
17:30–18:00 – In situ beta decay dating and the potential for regional geology studies (Thomas Zack)
18:00–18:30 – Arctic nanogranitoids and what we can learn from them (Alessia Borghini)

SESSION V – Oral presentations (8 September 2024) – R/V Horyzont II

16:00–16:30 – Diabasodden and its Suite - the High Arctic Large Igneous Province on Svalbard and its type locality (Anna Sartell)
16:30–17:00 – Large Igneous Provinces and the crustal filter: what happens when magma plays with sedimentary rocks? (Sara Callegaro)
17:00–17:30 – Can lamprophyres in LIPs constrain upper mantle plume dynamics? (Lars Eivind Augland)
17:30–19:00 – Summary and recommendations from the workshop

APPENDIX 4

THE LIST OF SELECTED PROJECTS RELATED TO THE SCIENTIFIC SCOPE OF SVALGEOBASE II

"A Web GIS platform to access UNIS Arctic Geology and Arctic Geophysics Virtual Field Tours"; acronym: **VR SVALBARD**; host institution: UNIS; contact: kims@unis.no, rafaelh@unis.no

Website: https://vrsvalbard.com/

"Svalbox 2.0 – Fair geoscientific data from Svalbard"; acronym: **SVALBOX 2.0**; host institution: UNIS; PI: Kim Senger, Aleksandra Smyrak-Sikora; contact: kims@unis.no

Website: https://svalbox.no/projects/svalbox-2-0/

"Integration of palaeomagnetic, isotopic and structural data to understand Svalbard Caledonian Terranes assemblage"; acronym **PALMAG**; 2012–2016; funded by the Polish National Science Centre (NSC); host institution: IG PAS; PI: Krzysztof Michalski; contact: krzysztof.michalski@igf.edu.pl

Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=172340

"Rate of tectonic plates movement in Neoproterozoic – verification of Neoproterozoic True Polar Wander hypothesis"; acronym **NEOMAGRATE**; 2022–2026; funded by the Polish National Science Centre (NSC); host institution: IG PAS; PI: Krzysztof Michalski; contact: krzysztof.michalski@igf.edu.pl

Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=519531

"Meso-Neoproterozoic Evolution of the metamorphic basement of western Svalbard"; 2014–2017funded by the Polish National Science Centre (NSC); host institution: AGH University of Krakow; PI: Karolina Kośmińska; contact: jaroslaw.majka@geo.uu.se

"Arctic Connection (NAC): is southwestern Svalbard a counterpart of the Pearya Terrane?"; 2016–2019; funded by the Polish National Science Centre (NSC); host institution: AGH University of Krakow; PI: Jarosław Majka; contact: jaroslaw.majka@geo.uu.se

Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=294776

"Mosselhalvøya thrust (Ny Friesland) a major boundary between different terranes of the Caledonian basement of Svalbard?"; 2016–2020; funded by the Polish National Science Centre (NSC); host institution: PIG-PIB; PI: Jakub Bazarnik; contact: jaroslaw.majka@geo.uu.se

Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=310382

"Exhumation dynamics of the Vestgötabreen High-Pressure Metamorphic Complex, Svalbard"; 2018–2020; funded by the Polish National Science Centre (NSC); host institution: AGH University of Krakow; PI: Christopher Barnes; contact: jaroslaw.majka@geo.uu.se

Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=375874

"The timing of Iapetus opening and its implications for understanding the break-up of Rodinia and evolution of Baltica"; 2020–2023; funded by the Polish National Science Centre

(NSC); host institution: AGH University of Krakow; PI: Jarosław Majka; contact: jaroslaw.majka@geo.uu.se
Website: https://projekty.ncn.gov.pl/en/index.php?projekt_id=446693

"Proterozoic-Paleozoic histories of North Greenland: pivotal windows for deciphering the High Arctic tectonic puzzle"; 2024–2027; funded by the Swedish Research Council (VR); host institution: Uppsala Universitet; PI: Jarosław Majka contact: jaroslaw.majka@geo.uu.se
Website: https://www.vr.se/english/swecris.html?project=2023-03843_VR#/

"The Timanian Orogeny in Northern Svalbard"; acronym: **TONeS;** 2022–2024; funded by the Research council of Norway; host institution: University of Oslo; PI: Jean-Baptiste Koehl; contact: j.b.p.koehl@geo.uio.no, krzysztof.michalski@igf.edu.pl, jaroslaw.majka@geo.uu.se
Website: https://prosjektbanken.forskningsradet.no/en/project/FORISS/337227

"A bilateral initiative for harmonisation of the Svalbard cooperation – scientific collaboration between Poland and Norway in Svalbard for a sustainable future"; acronym **HARSVAL**; 2024–2025; coordinated by the Polish National Science Centre (NSC); Activity 1.2 Joint pilot studies concerning impact of Arctic climate change on marine and coastal environment in the northern and eastern Svalbard key areas and paleogeographical and thermal evolution of Svalbard, Task 1.2.2 PALEOGEOGRAPHICAL and THERMAL EVOLUTION; host institution: University of Silesia; PI: Dariusz Ignatiuk; contact: krzysztof.michalski@igf.edu.pl
Website: https://harsval.eu/

"Deep-time Arctic climate archives: High-resolution coring of Svalbard's sedimentary record"; acronym **SVALCLIME**; application submitted to the International Continental Scientific Drilling Program (ICDP);host institution: UNIS; contact: kims@unis.no
Website: https://svalbox.no/projects/svalclime/

"Changes at the Top of the World through Volcanism and Plate Tectonics"; acronym **NOR-R-AM2**; 2020–2024; funded by the Research Council of Norway (NRC); host institution: UiO; PI: Carmen Gaina; contact: carmen.gaina@geo.uio.no, l.e.augland@geo.uio.no
Website: https://www.mn.uio.no/geo/english/research/projects/nor-r-am2-partnership/index.html

"MAgma PLays with sedimEntary rockS"; acronym **MAPLES**; 2020–2024; funded by the Research Council of Norway (NRC); host institution: UiO; PI: Sara Callegaro; contact: sara.callegaro@geo.uio.no, l.e.augland@geo.uio.no
Website: https://www.mn.uio.no/geo/english/research/projects/maples/index.html

"VISTA Centre for CO2 Storage in Volcanic-Sedimentary Systems"; acronym **VICCO**; 2025–2030; funded by the Research Council of Norway (NRC); host institution: UiO; PI: Henrik Svensen; contact: Henrik.svensen@geo.uio.no, l.e.augland@geo.uio.no
Website: https://www.mn.uio.no/geo/english/research/projects/vicco/index.html

"Poles together – missing links between Arctic and ANtarctic early Earth records"; acronym **PAAN**; 2020–2024; funded within the GRIEG competition funded by the Norwegian Financial Mechanism 2014–2021; host institution: IG PAS; PI: Monika Kusiak; contact: monika.kusiak@igf.edu.pl, l.e.augland@geo.uio.no
Website: https://polestogether.igf.edu.pl/

"Publications of the Institute of Geophysics, Polish Academy of Sciences: Geophysical Data Bases, Processing and Instrumentation" appears in the following series:

A – Physics of the Earth's Interior

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D – Physics of the Atmosphere

E – Hydrology (formerly Water Resources)

P – Polar Research

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Every volume has two numbers: the first one is the consecutive number of the journal and the second one (in brackets) is the current number in the series.