

The 35th Nordic Geological Winter Meeting 2022

Programme and Abstracts

Editors: Þorsteinn Sæmundsson, Ásta Rut Hjartardóttir,
Bjarni Gautason, Halldór Geirsson

Reykjavík, Iceland 11-13 May 2022



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Editors

Þorsteinn Sæmundsson, Ásta Rut Hjartardóttir, Bjarni Gautason, Halldór Geirsson

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Ásta Rut Hjartardóttir, Institute of Earth Sciences, University of Iceland

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Halldór Geirsson, Institute of Earth Sciences, University of Iceland



Programme and Abstracts

Editors: Þorsteinn Sæmundsson, Ásta Rut Hjartardóttir, Bjarni Gautason, Halldór Geirsson
Organizing bureau: Sena ehf.

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Welcome



Þorsteinn Sæmundsson



Ásta Rut Hjartardóttir

Dear Colleagues,

It is our great pleasure to welcome you all to Reykjavík for the Nordic Geological Winter Meeting, which is the 35th meeting in the series and the 5th to be held here in Iceland. Unlike most other "winter" meetings, this one is held in May, which is to our best knowledge the second time the meeting has been held in the springtime. We all know the reason why we had to change the timing of the meeting, and hopefully that is well behind us now.



Bjarni Gautason



Halldór Geirsson

The Nordic Geological Winter Meetings have proved to be an important venue for Nordic geoscientists to meet, share new research results and to create and strengthen friendship and collaboration. These meetings also reflect the great variety of topics that Nordic geoscientists deal with and highlight the importance of our work within the Nordic countries. It is also very motivating that scientists worldwide are showing increasing interest in these meetings.

Iceland has a very dynamic geology and is exposed to the forces of nature. We were reminded once again of that in 2020 and 2021 with a quite intensive and, for us geoscientist, very interesting episode of earthquake activity and magma movements in the Reykjanes Peninsula, which frequently were felt here in the capital. This earthquake activity was followed by a volcanic eruption in Geldingadalir in 2021, only about 30 km from downtown Reykjavík. Numerous people were able to visit the eruption site and enjoy its spectacular show of flowing lava. Many of you used the opportunity to visit the eruption site the day before this meeting.

The last decade, since we had the last meeting in Iceland in 2012, has been very eventful, both regarding eruptions, earthquake activity, mass movements, heavy storms and not least new discoveries within the geoscience. Several presentations at the conference will highlight those recent events and we look forward to sharing them with you all.

At this meeting the Nordic Geoscientist Award will be presented for the sixth time. The award was first given here in Iceland in 2012. The award is presented to a Nordic geoscientist who has, in the course of his/her career, been strongly involved in the society around us, as well as in specific fields of geosciences. The award winner will be announced at the conference dinner, and he/she will give an honorary lecture on the last day of the meeting.

The organization of a meeting like this requires more than a year of preparation, a task that many people are involved in. This time we have to say that it was complicated and a great challenge, but here we are. We would like to thank the Scientific Programme Committee for putting together an ambitious programme, the conveners for coordinating the sessions and reviewing the abstracts, the plenary lecturers for their contribution, the organizing bureau "Sena" for professional assistance, and the many sponsors who have made this event possible. Last but not least we thank sincerely all of you who participate in this meeting.

We hope that the 35th Nordic Geological Winter Meeting will be fruitful and lead to a better and deeper insight into the different fields of geosciences and stimulate further Nordic collaboration.

We wish you a pleasant stay in Iceland.

Þorsteinn Sæmundsson

Chairman of the Geological Society of Iceland and the 2022 NGWM SPC

Ásta Rut Hjartardóttir

Vice chairman of the Geological Society of Iceland

Bjarni Gautason

Co-manager of the Geological Society of Iceland

Halldór Geirsson

Co-manager of the Geological Society of Iceland



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Table of Contents

Welcome.....	3
Programme Overview	7
Social Programme	9
Programme	11
Conference Excursions	48
Plenary Abstracts	51
Oral Abstracts	57
Posters	151
Author Index	177

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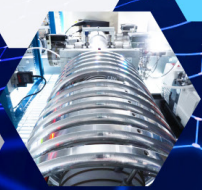
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Programme Overview

WEDNESDAY 11 May

Time		Hall 1	Hall 2	VHV-023	O-101	O-201		
08:00	9:00	Registration - Welcome note at 9:00 in the Large Hall						
09:00	09:10	Welcome - Þorsteinn Sæmundsson, Geoscience Society of Iceland						
09:10	09:20	Opening - Mr. Guðlaugur Þór Þórðarson, Minister of Environment, Energy and Climate						
09:20	09:50	Large Hall Plenary 1: Kristín Jónsdóttir						
10:00	10:15	Refreshments						
10:15	10:30	ER1	ER6	GA1/GA2	GT1	IS4	7 talks	
10:30	10:45							
10:45	11:00							
11:00	11:15							
11:15	11:30							
11:30	11:45	Lunch / posters						
12:00	13:00	Lunch / posters						
13:00	13:30	Large Hall Plenary 2: Steinar Ellefmo						
13:45	14:00	ER1	ER6	GA1/GA2	GT5	IS4	9 talks	
14:00	14:15							
14:15	14:30							
14:30	14:45							
14:45	15:00							
15:00	15:15	Refreshments						
15:15	15:30	RS4	ER6	GA1/GA2	GT2	IS4		
15:30	15:45							
15:45	16:00							
16:00	17:00							
17:00	18:30	Poster session - Háskólabíó						
		IceBreaker - Askja						

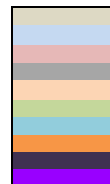
THURSDAY 12 May

Time		Hall 1	Hall 2	VHV-023	O-101	O-201		
08:30	09:00	Large Hall Plenary 3: Guðfinna Aðalgeirsdóttir						
09:15	09:30	ER5	UV2	GA1/GA2	AG1/3	IS2	5 talks	
09:30	09:45							
09:45	10:00							
10:00	10:15							
10:15	10:30							
10:30	10:45	Refreshments						
10:45	11:00	ER5	UV2	GA1/GA2	AG1/3	IS2	5 talks	
11:00	11:15							
11:15	11:30							
11:30	11:45							
11:45	12:00							
12:00	13:00	Lunch / posters						
13:00	13:30	Large Hall Plenary 4: Reginald Hermanns						
13:30	13:50	Large Hall: Making Movies						
14:00	14:15	ER5	UV4	EC4	GT4/GT6	EC2	5 talks	
14:15	14:30							
14:30	14:45							
14:45	15:00							
15:00	15:15							
15:15	15:30	Refreshments						
15:30	15:45	ER4	UV4		GT4/GT6	EC2	5 talks	
15:45	16:00							
16:00	16:15							
16:15	16:30							
16:30	16:45							
16:45	18:30	Sky Lagoon						
19:30	23:30	Conference dinner, Gamla Bló, Ingólfsstræti 2a						

FRIDAY 13 May

Time		Hall 1	Hall 2	VHV-023	O-101	O-201		
08:30	09:00	Large Hall Plenary 5: Sandra Ósk Snaebjörnsdóttir						
09:15	09:30	ER2	UV1	IM1/2/3	IS3	EC3	5 talks	
09:30	09:45							
09:45	10:00							
10:00	10:15							
10:15	10:30							
10:30	10:45	Refreshments						
10:45	11:00	ER2	UV1	IM1/2/3	IS1	EC3	6 talks	
11:00	11:15							
11:15	11:30							
11:30	11:45							
11:45	12:00							
12:00	13:00	Lunch / posters						
13:00	13:40	Large Hall Plenary 6: Nordic Geoscientist Award						
14:00	14:15	ER3	RS3	IM1/2/3	EC1	EC3	5 talks	
14:15	14:30							
14:30	14:45							
14:45	15:00							
15:00	15:15							
15:15	15:30	Refreshments						
15:30	15:45	UV3	RS2	IM1/2/3	EC1	EC3	6 talks	
15:45	16:00							
16:00	16:15							
16:15	16:30							
16:30	16:45							
16:45	17:00							

- Theme 1
- Theme 2
- Theme 3
- Theme 4
- Theme 5
- Theme 6
- Theme 7
- Theme 8
- Theme 9
- Posters



- [EC] Environment and climate
- [UV] Understanding volcanoes
- [GT] Geodynamics & tectonic evolution
- [GA] Geoscience and the society: hazards and anthropogenic impact
- [IP] Igneous and Metamorphic Geochemistry
- [ER] Earth resources
- [IS] Interdisciplinary sessions
- [AG] Applied geology
- [RS] Remote Sensing in geosciences



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Social Programme

11.05 – Wednesday

17:00 – 18:30	IceBreaker – Askja
<p>The Geoscience Society of Iceland cordially invites all delegates and registered accompanying persons to the reception. Light freshments will be served during the reception.</p> <p>The reception is at Askja which is located on campus at the University of Iceland.</p>	

12.05 – Thursday

16:45 - 18:30	Sky Lagoon
<p>A time to relax, unwind and enjoy the dramatic scenery at the oceanside geothermal lagoon.</p>	
19:30 – 23:30	Conference Dinner at Gamla Bíó (Ingólfsstræti 2a)
<p>The Conference dinner is held at Gamla Bíó, where a three course dinner will be served after a welcome drink.</p>	



NordVulk

- the Nordic Volcanological Center



NordVulk is a Nordic research center specializing in volcanology and related fields, co-financed through NordForsk by the Nordic Council of Ministers and the Icelandic government. It is located in downtown Reykjavík, at the Institute of Earth Sciences, University of Iceland.

NordVulk was established in 1974 to enhance Nordic research and educational collaboration in dynamic geology, focusing on volcanology and plate tectonics. Opportunities offered by the exceptional geological conditions in Iceland have been the basis for a Nordic collaborative program in volcanology.

NordVulk runs a fellowship programme for PhD students and early career researchers as well as a Summer School programme.

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Programme

Wednesday, May 11

08:00 - 09:00	Registration - Welcome note at 09:00 in the Large Hall	
09:00 - 09:10	Welcome - Þorsteinn Sæmundsson, Geoscience Society of Iceland in the Large Hall	
09:10 - 09:20	Opening - Mr. Guðlaugur Þór Þórðarson, Minister of Environment, Energy and Climate	
09:20 - 10:00	Large Hall Plenary 1: Kristín Jónsdóttir	
	PL-1	
	The unrest on the Reykjanes Peninsula and eruption in Fagradalsfjall 2021	
	Kristín Jónsdóttir	
	<i>Icelandic Meteorological Office, Reykjavik, Iceland</i>	
10:00 - 10:15	REFRESHMENTS – in the Foyer	
10:15 - 12:00	ER6 - Earth resources	Hall 2 /
	- Convener: Ingrid Anell, Universitetet i Oslo	
	ER6-01	
	Time constraints on hydrocarbon migration and uplift as recorded by isotopic characteristics of calcite cements in Carboniferous-Permian evaporites from the Barents Sea	
	Malcolm Hodgskiss ¹ , Aivo Lepland ¹ , Nivedita Thiagarajan ² , Erik Hammer ³ , Harald Brunstad ³ , Atle Mørk ⁴	
	¹ <i>Geological Survey of Norway, Trondheim, Norway</i>	
	² <i>California Institute of Technology, Pasadena, United States</i>	
	³ <i>Lundin Energy AS, Oslo, Norway</i>	
	⁴ <i>Norwegian University of Science and Technology, Trondheim, Norway</i>	
	ER6-02	
	Provenance of the Middle Triassic Kobbe Formation in the SW Barents Sea	
	Hallgeir Sirevaag ¹ , Christian Haug Eide ¹ , Albina Gilmullina ¹ , Leif-Erik Rydland Pedersen ¹ , Tore Grane Klausen ²	
	¹ <i>University of Bergen, Bergen, Norway</i>	
	² <i>MVest Energy AS, Bergen, Norway</i>	
	ER6-03	
	The role of organic matter production, preservation and dilution on Triassic black shale formation on the Norwegian Barents Shelf	
	Fredrik Wesenlund ¹ , Sten-Andreas Grundvåg ¹ , Victoria Sjøholt Engelschiøn ² , Olaf Thießen ³ , Jon Halvard Pedersen ⁴ , Benedikt Lerch ⁵	
	¹ <i>Department of Geosciences, UiT The Arctic University of Norway, Tromsø, Norway</i>	
	² <i>Natural History Museum, University of Oslo, Oslo, Norway</i>	
	³ <i>Equinor, Harstad, Norway</i>	
	⁴ <i>Lundin Energy Norway, Lysaker, Norway</i>	
	⁵ <i>Aker BP, Lysaker, Norway</i>	
	ER6-04	
	Geomorphology of continental rift landscapes - analyses inspired by North Sea observations	
	Alvar Braathen ¹ , Ivar Midtkandal ¹ , Per Terje Osmundsen ²	
	¹ <i>University of Oslo, Oslo, Norway</i>	
	² <i>NTNU, Trondheim, Norway</i>	
	ER6-05	
	Late Jurassic rift physiography of the Froan Basin and Frøya High: insights into the extent and longshore distribution of the shallow marine Rogn Formation	
	Lise Nakken ¹ , Domenico Chiarella ¹ , Christopher A-L. Jackson ²	
	¹ <i>Department of Earth Sciences, Royal Holloway, University of London, Egham, United Kingdom</i>	
	² <i>Department of Earth and Environmental Sciences, The University of Manchester, Manchester, United Kingdom</i>	

ER6-06

Mobilized sand and injectites in the North Sea. Importance for fluid communication in the basin and a proposed triggering mechanism.

Hilde Braut, Alexey Deryabin

NPD, Stavanger, Norway

10:15 - 12:00 **IS4 - Interdisciplinary sessions** O-201 /

- Convener: Bjarni Gautason, ÍSOR

IS4-01

Geoscience Education and Technology – Results from Two Worldwide Surveys
Henk Keers ¹, Elise Myhren Stordahl ¹, Björn Nyberg ¹, Karen Mair ²

¹ *University of Bergen, Bergen, Norway*

² *University of Oslo, Oslo, Norway*

IS4-02

Fieldwork culture in Higher Education Geology

Rie Malm ¹, Lena Håkansson ²

¹ *Department of Science Education, University of Copenhagen, Copenhagen, Denmark*

² *Department of Geosciences, UiT, The Arctic University of Norway, Tromsø, Norway*

IS4-03

How can student involvement enhance geoscience higher education?

Elena Victoria Brattebø, Maja Lian Jæger, Vilhelm Nyby, Thilde Justine Voje

Department of Earth Science, University of Bergen, Norway, Bergen, Norway

IS4-04

Troublesome knowledge and signature pedagogies in geosciences – a possibility to re-focus teaching and learning

Lena Håkansson, Jennie Lundqvist

Department of Geosciences, Arctic University of Norway, Tromsø, Norway

IS4-05

Student and staff collaboration for education development - course representatives for the 21st century

Søren B Tvingsholm, Mattias Lundmark

Oslo University, Oslo, Norway

IS4-06

How important are extracurricular activities for student employability?

Lisa Julianne Nystad

Department of Geosciences, Oslo, Norway

IS4-07

Education for Earth's future. iEarth is the Centre for Integrated Earth Science Education.

Thea Krossøy ¹, Jostein Bakke ²

¹ *Network Coordinator iEarth and Department of Earth Science, UiB, Bergen, Norway*

² *Centre Leader iEarth and Department of Earth Science, UiB, Bergen, Norway*

10:15 - 12:00 **ER1 - Earth resources** Hall 1 /

- Convener: Daði Þorbjörnsson, ÍSOR

- Convener: Ingvi Gunnarsson, Reykjavík Energy

ER1-01

Boosting innovation in the field of geothermal energy through EU funded projects

Glen Burridge

European Federation of Geologists, Brussels, Belgium

ER1-02

Sedimentary geothermal resources in China -- nature and utilization

Tingting Zheng ¹, Guðni Axelsson ²

¹ University of Iceland / GRÓ GTP, Reykjavík, Iceland

² GRÓ Geothermal Training Programme (GRÓGTP), Reykjavík, Iceland

ER1-03

Chemical composition of geothermal water and geothermal gradients in the Southern Lowlands of Iceland

Finnbogi Óskarsson ¹, Heimir Ingimarsson ¹, Sigurður Kristinnsson ¹, Árni Hjartarson ¹, Albert Þorbergsson ¹, Þráinn Friðriksson ²

¹ Iceland GeoSurvey (ISOR), Kópavogur, Iceland

² Reykjavík Energy (OR), Reykjavík, Iceland

ER1-04

Regional thermal anomalies derived from magnetic spectral analysis and 3D gravity inversion: Implications of potential geothermal sites in Tanzania

Makoye Didas ¹, Egidio Armadillo ², Gylfi Hersir ³, William Cumming ⁴, Daniele Rizzello ⁵

¹ University of Iceland, Reykjavík, Iceland

² Applied Geophysics Laboratory, University of Genoa, Genoa, Italy

³ Iceland GeoSurvey (ISOR), Grensásvegur 9, 108, Reykjavík, Iceland

⁴ Cumming Geoscience, Santa Rosa, California, United States

⁵ Tellus s.a.s., Sassello, Liguria, Italy

ER1-05

Direct mixing of geothermal water into heated groundwater to improve water quality in the district heating system of the Reykjavík capital area

Arna Pálsdóttir, Baldur Brynjarsson

Reykjavík Energy, Reykjavík, Iceland

ER1-06

H2S sequestration at geothermal sites: can we enhance the monitoring using geo-electrical methods? Insights from the GEMGAS project at Nesjavellir, Iceland.

Léa Lévy ¹, Thue Bording ², Pradip Maurya ³, Daniel Ciraula ⁴, Barbara Kleine ⁴, Thomas Ratouis ⁵, Gianluca Fiandaca ⁶, Helga Margret Helgadóttir ⁷, Halldór Ingólfsson ⁷, Friðgeir Pétursson ⁷

¹ Lund University, Lund, Sweden

² Aarhus Geoinstruments, Aarhus, Denmark

³ Aarhus University, Aarhus, Denmark

⁴ University of Iceland, Reykjavík, Iceland

⁵ Carbfix, Reykjavík, Iceland

⁶ University of Milano, Milano, Italy

⁷ ISOR, Reykjavík, Iceland

ER1-07

Are dykes and sills a feasible geothermal energy source?

Steffi Burchardt ¹, Mohsen Bazargan ¹, Einar Gestsson ², Erika Ronchin ³, Hugh Tuffen ⁴, Michael J. Heap ⁵, Jonathan Davidson ⁶, Ben Kennedy ⁶, Alex Hobé ¹, Christoph Hieronymus ¹, Elodie Saubin ⁶

¹ Uppsala University, Uppsala, Sweden

² Iceland Meteorological Office, Reykjavík, Iceland

³ Sapienza University, Rome, Italy

⁴ University of Lancaster, Lancaster, United Kingdom

⁵ University of Strasbourg, Strasbourg, France

⁶ University of Canterbury, Christchurch, New Zealand

10:15 - 12:00 **GA1-GA2** - Geoscience and the society: hazards and anthropogenic impact VHV-023 /

- Convener: Þorsteinn Sæmundsson, University of Iceland
- Convener: Reginald L. Hermanns, Geological Survey of Norway (NGU)
- Convener: Daniel Ben-Yehoshua, University of Iceland
- Convener: Costanza Morino, Université Savoie Mont Blanc
- Convener: Harpa Grímsdóttir, Icelandic Met Office

GA1-01

Recent advances in rockslide mapping in Greenland – some cases and identified knowledge gaps

Kristian Svennevig

GEUS, Copenhagen, Denmark

GA1-02

10 years of national hazard mapping in Norway - experiences and lessons learned

Odd Are Jensen ¹, Andrea Taurisano ², Amund Frogner Borge ³, Yngve Midtun ¹, Odd-Arne Mikkelsen ⁴, Martine Slåtten Sagen ², Jaran Wasrud ⁵

¹ Norwegian Water Resources and Energy Directorate (NVE), Førde, Norway

² Norwegian Water Resources and Energy Directorate (NVE), Trondheim, Norway

³ Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway

⁴ Norwegian Water Resources and Energy Directorate (NVE), Tromsø, Norway

⁵ Norwegian Water Resources and Energy Directorate (NVE), Hamar, Norway

GA1-03

Extensive paraglacial slope adjustments around Svínafellsjökull, SE Iceland. A warning for other outlet glacier valleys?

Daniel Ben-Yehoshua ¹, Þorsteinn Sæmundsson ², Reginald Hermanns ³, Sigurður Erlingsson ¹

¹ Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland

² Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

³ Department of Geoscience and Petroleum, NTNU, Trondheim, Norway

GA1-04

Has climate changes affect slope stability during the last decades in Iceland?

Þorsteinn Sæmundsson ¹, Jón Kristinn Helgason ²

¹ University of Iceland, Reykjavik, Iceland

² Icelandic Meteorological Office, Reykjavik, Iceland

GA1-05

Mitigation alternatives for natural hazards along Nordic infrastructure networks – early results from the NordicLink project

Rosa M. Palau ¹, Vittoria Capobianco ¹, Graham L. Gilbert ¹, Anders Solheim ¹, Ilona Lång-Ritter ², Adriaan Perrels ², Carolina Sellin ³, Sara Filla ²

¹ Norwegian Geotechnical Institute, Oslo, Norway

² Finnish Meteorological Institute, Helsinki, Finland

³ Chalmers University of Technology, Gothenburg, Sweden

GA1-06

Snow-avalanche hazard in Nunavik, Canada: from snow-avalanche inventory to path identification

Armelle Decaulne ¹, Najat Bhiry ², Jérémy Grenier ², Beatriz Funatsu ¹, Raphaël Loiseau ¹

¹ CNRS LETG, Nantes, France

² CEN, ULaval, Geography Dept, Québec, Canada

10:15 - 12:00 **GT1 - Geodynamics & tectonic evolution** O-101 /

- Convener: Freysteinn Sigmundsson, University of Iceland
- Convener: Sonja Greiner, University of Iceland
- Convener: Steffi Burchardt, Uppsala University
- Convener: Olivier Galland, NJORD Center, Department of Geosciences, University of Oslo

GT1-01

Volcano deformation related to the emplacement of km-scale magma bodies in the upper crust

Steffi Burchardt ¹, Emma Rhodes ¹, Tobias Mattsson ², Taylor Witcher ¹, Tobias Schmiedel ³, Erika Ronchin ⁴, Sonja Greiner ⁵, Orlando Quintela ¹, Abigail Barker ¹

¹ Uppsala University, Uppsala, Sweden

² University of St. Andrews, St. Andrews, United Kingdom

³ Technical University of Delft, Delft, Netherlands

⁴ Sapienza University, Rome, Italy

⁵ University of Iceland, Reykjavik, Iceland

GT1-02

Interaction between propagating basaltic dykes and pre-existing fractures in hyaloclastite

Sonja Heidi Maria Greiner ¹, Steffi Burchardt ², Freysteinn Sigmundsson ¹, Olivier Galland ³, Halldór Geirsson ¹, Emma Rhodes ²

¹ Nordvulk, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

² Department of Earth Sciences, Uppsala University, Uppsala, Sweden

³ NJORD Center, Department of Geosciences, University of Oslo, Oslo, Norway

GT1-03

Models of pre-eruptive processes of the Fagradalsfjall eruption in 2021

Ólafur Flóvenz¹, Rongjiang Wang², Gylfi Páll Hersir¹, Torsten Dahm², Hainzl Sebastian², Magdalena Stefanova Vassileva², Vincent Drouin¹, Sebastian Heimann², Marius Paul Isken², Egill Árni Guðnason¹, Kristján Ágústsson¹, Ágústsdóttir Þorbjörg¹, Eniko Bali³, Josef Horálek⁴, Mahdi Motagh², Thomas Walter², Eleonora Rivalta², Philippe Jousset², Charlotte Krawczyk², Claus Milkereit²

¹ ÍSOR - Iceland GeoSurvey, Reykjavík, Iceland

² Helmholtz Centre Potsdam GFZ, Potsdam, Germany

³ Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

⁴ Czech Academy of Sciences, Prague, Czech Republic

GT1-04

Un-stressing of crust prior to eruptions: Precursors to the 2021 eruption at Geldingadalir, Mt. Fagradalsfjall, in the Reykjanes Peninsula Oblique Rift, Iceland

Freysteinn Sigmundsson¹, Michelle Parks², Andrew Hooper³, Halldór Geirsson¹, Kristín S. Vogfjörð², Vincent Drouin², Benedikt G. Ófeigsson², Sigrún Hreinsdóttir⁴, Sigurlaug Hjaltadóttir², Kristín Jónsdóttir², Páll Einarsson¹, Sara Barsotti², Josef Horálek Horálek⁵, Thorbjörg Ágústsdóttir⁶

¹ Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

² Icelandic Meteorological Office, Reykjavík, Iceland

³ COMET, School of Earth and Environment, University of Leeds, Leeds, United Kingdom

⁴ GNS Science, Lower Hut, New Zealand

⁵ Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic

⁶ ÍSOR - Iceland Geosurvey, Reykjavík, Iceland

GT1-05

Coeruptive subsidence during the 2021 Fagradalsfjall eruption: geodetic constraints on magma source depths and stress changes

Halldór Geirsson¹, Michelle Parks², Freysteinn Sigmundsson¹, Benedikt G. Ófeigsson², Vincent Drouin², Cécile Ducrocq¹, Hildur María Friðriksdóttir², Sigrún Hreinsdóttir³, Andrew Hooper⁴

¹ NORDVULK, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

² Icelandic Meteorological Office, Reykjavík, Iceland

³ GNS Science, Lower Hutt, New Zealand

⁴ COMET, University of Leeds, Leeds, United Kingdom

GT1-06

Pressure increase at the magma-hydrothermal interface at the Krafla caldera, North-Iceland, 2018-2020: magmatic processes or hydrothermal changes?

Chiara Lanzi¹, Vincent Drouin², Freysteinn Sigmundsson³, Halldór Geirsson³, Gylfi Páll Hersir⁴, Kristján Ágústsson⁵, Michelle Maree Parks², Sigrún Hreinsdóttir⁶, Ásgrímur Guðmundsson⁷

¹ University of Iceland, Reykjavík, Iceland

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⁶ GNS Science, Lower Hutt, New Zealand

⁷ Asgrimur2@simnet.is, Reykjavík, Iceland

12:00 - 13:00 LUNCH / POSTERS – in the Foyer of Háskólabíó

13:00 - 13:30 Large Hall Plenary 2: Steinar Ellefmo

PL-2

Deep Sea Minerals – a future mineral reserve or just a geological curiosity waiting to be obducted?

Steinar L. Ellefmo, Kurt Aasly

Norwegian University of Science and Technology, Trondheim, Norway

13:45 - 14:45 GT5 - Geodynamics & tectonic evolution O-101 /

- Convener: Halldór Geirsson, University of Iceland

- Convener: Björn Lund, Uppsala University

GT5-01

Lateglacial and Holocene sealevel history for the island Værlandet, western Norway

John Inge Svendsen²

¹ University of Bergen, Dept. of Earth Science, Bergen, Norway

² University of Bergen, Bergen, Norway

GT5-02

Glacial Rebound and Crustal Movements affecting Coastal Engineering Projects

Sigurdur Sigurdarson, Fannar Gíslason

Icelandic Road and Coastal Administration, Reykjavik, Iceland

GT5-03

Glacially induced stress across the Arctic from the Eemian interglacial to the present - implications for faulting and seafloor methane seepage

Rémi Vachon¹, Peter Schmidt², Björn Lund², Andreia Plaza-Faverola¹, Henry Patton¹, Alun Hubbard¹

¹ *UiT - The Arctic University of Norway, Tromsø, Norway*

² *Uppsala University, Uppsala, Sweden*

GT5-04

Fault stability in northern Europe through past and future glacial periods

Peter Schmidt¹, Björn Lund², Jens-Ove Näslund³, Laura Thölix⁴, Johan Liakka³, Florence Colleoni⁵, Anne Kontula⁶

¹ *Uppsala university, Uppsala, Sweden*

² *Uppsala University, Uppsala, Sweden*

³ *Swedish Nuclear Fuel and Waste Management Company, Solna, Sweden*

⁴ *Finnish Meteorological Institute, Helsinki, Finland*

⁵ *Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico, Italy*

⁶ *Posiva Oy, Eurajoki, Finland*

13:45 - 14:45 **ER6 - Earth resources** Hall 2 /

- Convener: Ingrid Anell, Universitetet i Oslo

ER6-07

Eocene erosion and deposition from the Kolga High, Mid-Norwegian margin: Results from 3D seismic interpretation and stratigraphic well ties

Ben Manton¹, John Millett², Dmitry Zastrozhnov³, Laurent Gernigon⁴, Dwarika Maharjan¹, Benjamin Bellwald¹, Sverre Planke¹, Christian Berndt⁵, Dougal Jerram⁶, Jan Inge Faleide⁷, Stefan Buenz⁸, Reidun Myklebust⁹

¹ *VBER, Oslo, Norway*

² *VBER, Aberdeen, United Kingdom*

³ *A.P. Karpinsky Russian Geological Research Institute, St Petersburg, Russia*

⁴ *NGU, Trondheim, Norway*

⁵ *GEOMAR, Kiel, Germany*

⁶ *Dougal Earth, Solihull, United Kingdom*

⁷ *Department of Geosciences, University of Oslo, Oslo, Norway*

⁸ *CAGE, University of Tromsø, Tromsø, Norway*

⁹ *TGS, Oslo, Norway*

ER6-08

Contourites and sediment progradation along the Norwegian continental margin (65–70°N) during the Neogene–Quaternary

Stine Bjordal-Olsen¹, Tom Arne Rydningen¹, Jan Sverre Laberg¹, Amando P.E. Lasabuda¹, Stig-Morten Knutsen²

¹ *Department of Geosciences, UiT The Arctic University of Norway, Tromsø, Norway*

² *The Norwegian Petroleum Directorate, Harstad, Norway*

ER6-09

Geometric controls on clinofolds, the building blocks of sedimentary basins – from ripple to shelf-edge

Ingrid Anell¹, Alvar Braathen¹, Maria Haugen², Ivar Midtkandal¹, Stine Olsen³

¹ *Universitetet i Oslo, Oslo, Norway*

² *Asplan Viak AS, Ås, Norway*

³ *NGI, Oslo, Norway*

ER6-10

Deciphering the setting of volcanoclastic and effusive Devonian magmatism in the Orcadian basin, Orkney Islands, Scotland

Joachim R. Svebo, Mattias Lundmark, Lars Eivind Augland

Oslo University, Oslo, Norway

13:45 - 14:45 **ER1 - Earth resources** Hall 1 /

- Convener: Daði Þorbjörnsson, ÍSOR

- Convener: Ingvi Gunnarsson, Reykjavík Energy

ER1-08

Repeated Dike Intrusions as Heat Sources of Volcanic Geothermal Systems

Sigurður Ragnarsson ¹, Gunnar Gunnarsson ²

¹ University of Iceland, Reykjavik, Iceland

² Reykjavik Energy, Reykjavik, Iceland

ER1-09

Stress Modelling of the Theistareykir Geothermal System: Mapping of In-Situ and Future Stresses of an Active Geothermal Production Area in NE-Iceland

Kyle Dawson ¹, Halldór Geirsson ¹, Anette Mortensen ²

¹ University of Iceland, Reykjavik, Iceland

² Landsvirkjun, Reykjavik, Iceland

ER1-10

The next steps in the Icelandic Deep Drilling Project (IDDP) – Reaching for the energy below conventional geothermal fields

Gunnar Gunnarsson ¹, Simon Klüpfel ¹, Kolbrún Ragna Ragnarsdóttir ², Bjarni Reykr Kristjánsson ¹, Vala Hjörleifsdóttir ¹, Þráinn Friðriksson ¹

¹ OR Reykjavik Energy, Reykjavik, Iceland

² ON Power, Reykjavik, Iceland

ER1-11

The use of ground source heat in Norway - energy potential and geotechnical challenges

Atle Dagestad, Marie Bredal, John Dehls

Geological Survey of Norway, Trondheim, Norway

13:45 - 14:45 **IS4 - Interdisciplinary sessions** O-201 /

- Convener: Bjarni Gautason, ÍSOR

IS4-08

The European Federation of Geologists: The Voice of Professional Geologists in Europe

Glen Burridge ¹, Magnus Johansson ²

¹ European Federation of Geologists, Brussels, Belgium

² Geosektionen - Association of Geoscientists, Stockholm, Sweden

IS4-09

The International Continental Scientific Drilling Program (ICDP) – a Nordic perspective

Øystein Nordgulen, Henrik Schiellerup, Aivo Lepland

Geological Survey of Norway, Trondheim, Norway

IS4-10

The influence of surface cover and bed rock geology on the snow geochemistry – an example from northern Finland

Anne Taivalkoski ¹, Solveig Pospiech ², Maarit Middleton ³, Yann Lahaye ¹, Janne Kinnunen ⁴

¹ Geological Survey of Finland, Espoo, Finland

² Institute for Resource Ecology, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

³ Geological Survey of Finland, Rovaniemi, Finland

⁴ Mawson Oy, Rovaniemi, Finland

13:45 - 14:45 **GA1-GA2 - Geoscience and the society: hazards and anthropogenic impact** VHV-023 /

- Convener: Þorsteinn Sæmundsson, University of Iceland
- Convener: Reginald L. Hermanns, Geological Survey of Norway (NGU)
- Convener: Daniel Ben-Yehoshua, University of Iceland
- Convener: Costanza Morino, Université Savoie Mont Blanc
- Convener: Harpa Grímsdóttir, Icelandic Met Office

GA1-07

Protection measures for settlements in Iceland endangered by snow avalanches and landslides

Tómas Jóhannesson

Icelandic Meteorological Office, Reykjavik, Iceland

GA1-08

Long-term hazard assessment of explosive volcanic eruptions at Jan Mayen Island (Norway) and their implications for air traffic in the North Atlantic

Manuel Titos ², Beatriz Martínez Montesinos ³, Sara Barsotti ⁴, Laura Sandri ³, Arnau Folch ⁵, Leonardo Mingari ⁶, Giovanni Macedonio ⁷, Antonio Costa ³

¹ University of Granada, Granada, Spain

² Universidad de Granada, Granada, Spain

³ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Bologna, Italy

⁴ Icelandic Meteo Office, Reykjavik, Iceland

⁵ Geociencias Barcelona. Consejo Superior Investigaciones Científicas (CSIC), Barcelona, Spain

⁶ Barcelona Supercomputing Center, Barcelona, Spain

⁷ Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Sezione, Naples, Italy

GA1-09

Assessment of jökulhlaup hazard and risk for Sólheimajökull outlet glacier, southern Iceland

Bergur Einarsson, Einar Hjörleifsson, Tinna Þórarinsdóttir, Matthew Roberts

Icelandic Meteorological Office, Reykjavik, Iceland

GA1-10

The Geomorphological Legacy of the Steinsholtshlaup Rockslide and Outburst Flood in 1967

Nathan Smail, Þorsteinn Sæmundsson, Daniel Ben-Yehoshua, Greta Wells

University of Iceland, Reykjavik, Iceland

14:45 - 15:00	REFRESHMENTS – in the Foyer	
15:00 - 16:15	ER6 - Earth resources	Hall 2 /

- Convener: Ingrid Anell, Universitetet i Oslo

ER6-11

Depositional environments and sequence stratigraphy in a perennially isolated epicontinental basin: a case study from the Upper Ordovician Williston Basin, North America

Antun Husinec

St. Lawrence University, Canton, United States

ER6-12

Periplatform ooze in a mixed siliciclastic-carbonate system, Vaca Muerta Formation, Argentina

Leticia Rodriguez Blanco ¹, Gregor P. Eberli ², Ralf J. Weger ², Peter K. Swart ²

¹ University of Oslo, Oslo, Norway

² University of Miami, Miami, United States

ER6-13

Rift segment boundaries as key controls on deep-water, syn-rift stratigraphy; the Corinth Rift, Greece

Sofia Pechlivanidou ¹, Rob Gawthorpe ¹, Natacha Fabregas ¹, Mary Ford ², Richard Collier ³, Martin Muravchik ¹

¹ University of Bergen, Bergen, Norway

² Université de Lorraine IUT Nancy-Charlemagne, Nancy, France

³ University of Leeds, Leeds, United Kingdom

ER6-14

Variability of fault-controlled deltas in rifts: Examples from southeastern Corinth Rift, Greece

Natacha Fabregas ¹, Robert Gawthorpe ¹, Martin Muravchik ¹, Vincent Wicker ², Mary Ford ²

¹ University of Bergen, Bergen, Norway

² Université de Lorraine, Nancy, France

ER6-15

Fault-influence on provenance, depocenter development, drainage patterns, and facies assemblage: an example from the alluvial Upper Cretaceous Qahlah Formation in the Fanja Basin (northeastern Oman)

Camilla Würtzen ¹, Ivar Midtkandal ¹, Mark J. Mulrooney ¹, Miquel Poyatos-Moré ², Lina H. Line ³, Alvar Braathen ¹

¹ University of Oslo, Oslo, Norway

² Universitat Autònoma de Barcelona, Barcelona, Spain

³ Aker BP ASA, Oslo, Norway

15:00 - 16:00 **GT2 - Geodynamics & tectonic evolution** O-101 /

- Convener: Kristín Jónsdóttir, Icelandic Meteorological Office, Iceland

- Convener: Vala Hjörleifsdóttir, OR Reykjavik Energy

GT2-01

Towards the implementation of site effects in a site-specific seismic hazard study for Oslo (Norway)

Federica Ghione ¹, Volker Oye ², Andreas Köhler ²

¹ NORSAR and University of Oslo, Kjeller, Norway

² NORSAR, Kjeller, Norway

GT2-02

Pinballing across the faultplane: the 1.5-year-long migration of earthquakes in the Bitdalsvatnet swarm (Telemark, S Norway)

Felix Halpaap, Lars Ottemöller

University of Bergen, Bergen, Norway

GT2-03

Iceland GeoSurvey's seismic monitoring of developed geothermal fields in Iceland

Egill Árni Gudnason ¹, Thorbjörg Ágústsdóttir ¹, Rögnvaldur Lindal Magnússon ¹, Friðgeir Pétursson ¹, Anette Kærgaard Mortensen ², Vala Hjörleifsdóttir ³, Hjalti Steinn Gunnarsson ⁴

¹ Iceland GeoSurvey, Reykjavík, Iceland

² Landsvirkjun, Reykjavík, Iceland

³ OR-Reykjavik Energy, Reykjavík, Iceland

⁴ Nordurorka Ltd., Akureyri, Iceland

GT2-04

Using natural seismicity on the Reykjanes Peninsula for an enhanced understanding of the crustal structure with emphasis on the high-temperature geothermal fields within the NASPMON project.

Thorbjörg Ágústsdóttir, Egill Árni Gudnason, Rögnvaldur Lindal Magnússon, Friðgeir Pétursson

ÍSOR, Reykjavík, Iceland

15:00 - 15:30 **IS4 - Interdisciplinary sessions** O-201 /

- Convener: Bjarni Gautason, ÍSOR

IS4-11

X-ray Computed Tomography of thin section off-cuts to complement 2D e-beam microanalysis

Mathis Warlo ¹, Glenn Bark ¹, Christina Wanhainen ¹, Alan R. Butcher ², Jukka Kuva ²

¹ Luleå University of Technology, Luleå, Sweden

² Geological Survey of Finland (GTK), Espoo, Finland

IS4-13

Short-term temporal-compositional trends in monogenetic basaltic volcanism: The Coalstoun Lake volcanic field

Catherine Brown

Queensland University of Technology, Brisbane, Australia

15:00 - 16:00 **RS4 - Remote Sensing in geosciences** Hall 1 /

- Convener: Gro B. M. Pedersen, University of Iceland

- Convener: Birgir Óskarsson, Icelandic Institute of Natural History

- Convener: Gunnlaugur Einarsson, ÍSOR

RS4-01

A new 1:50.000 scale map of the Nuussuaq basin: insights into the art of photogrammetric mapping and volcanic processes

Erik Vest Sørensen ¹, Asger Ken Pedersen ²

¹ Geological Survey of Denmark And Greenland, Copenhagen, Denmark

² Natural History Museum of Denmark and Geological Survey of Denmark and Greenland, Copenhagen, Denmark

RS4-02

Mineral Mapping Using Oblique Helicopter-Borne Hyperspectral and Photogrammetric Data Acquisition

Sara Salehi ¹, Daniel Schläpfer ², Erik Vest Sørensen ¹

¹ Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark

² ReSe Applications LLC, Wil, Swaziland

RS4-03

Fagridalur volcano: Photogrammetric and ground-based geological mapping of a complex and inaccessible caldera structure

Robert A. Askew, Birgir Vilhelm Óskarsson

Icelandic Institute of Natural History, 6–8 Urriðaholtsstræti, Garðabær, Iceland

RS4-04

Monitoring of Surtsey island (S-Iceland) with close-range airborne photogrammetry

Birgir Óskarsson ¹, Guðmundur Valsson ², Joaquín Belart ²

¹ Icelandic Institute of Natural History, Garðabær, Iceland

² National Land Survey of Iceland, Akranes, Iceland

15:00 - 15:45	GA1-GA2 - Geoscience and the society: hazards and anthropogenic impact	VHV-023 /
	<ul style="list-style-type: none">- Convener: Þorsteinn Sæmundsson, University of Iceland- Convener: Reginald L. Hermanns, Geological Survey of Norway (NGU)- Convener: Daniel Ben-Yehoshua, University of Iceland- Convener: Costanza Morino, Université Savoie Mont Blanc- Convener: Harpa Grímsdóttir, Icelandic Met Office	
	GA1-11	
	What is the potential for earthquake-induced landslides in Norway?	
	Mathilde B. Sørensen ¹ , Torbjørn Haga ²	
	¹ Dept. of Earth Science, University of Bergen, Bergen, Norway	
	² Skanska, -, Norway	
	GA1-12	
	Mitigation of induced seismic risk associated with geothermal energy in urban environments in Finland	
	Annakaisa Korja, Niina Junno, Johanna Tuomisaari, Pia Bäcklund	
	<i>University of Helsinki, Helsinki, Finland</i>	
16:00 - 17:00	POSTER SESSION - in the Foyer of Háskólabíó	
17:00 - 18:30	ICEBREAKER – ASKJA	

Thursday, May 12

08:30 - 09:00	Large Hall Plenary 3: Guðfinna Aðalgeirsdóttir	
	PL-3 Glaciers in Iceland in the past, present and future Guðfinna Aðalgeirsdóttir ¹ , Finnur Pálsson ² ¹ <i>University of Iceland, Reykjavík, Iceland</i> ² <i>Institute of Earth Sciences, Reykjavík, Iceland</i>	
09:15 - 10:30	UV2 - Understanding volcanoes	Hall 2 /
	- Convener: Bergrún Anna Óladóttir, Icelandic Met Office - Convener: Þorvaldur Þórðarson, Faculty of Earth Sciences UV2-01 Fault structures in the Fagradalsfjall area and tectonic framework of the 2021 eruption in the Reykjanes Peninsula Oblique Rift, Iceland. Páll Einarsson ¹ , Vigfús Eyjólfsson ² , Ásta Rut Hjartardóttir ¹ ¹ <i>Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland</i> ² <i>Rannís, Icelandic Research Center, Reykjavík, Iceland</i> UV2-02 Degassing of thick basaltic flow during crystallisation and segregation of residual melt Nicolas Levillayer ¹ , Olgeir Sigmarsson ² ¹ <i>Institute of Earth Sciences, Reykjavík, Iceland</i> ² <i>IES, UI and LMV, CNRS, Reykjavík, Iceland</i> UV2-03 Diverse mantle components with invariant oxygen isotopes; the 2021 Fagradalsfjall eruption, Iceland Ilya Bindeman ¹ , Frances Deegan ² , Valentin Troll ² , Thor Thordarson ³ , Armann Höskuldsson ³ , William Moreland ³ , Edgar Zorn ⁴ , Alina Shevchenko ⁴ , Thomas Walter ⁴ ¹ <i>University of Oregon, Oregon, United States</i> ² <i>Uppsala University, Uppsala, Sweden</i> ³ <i>University of Iceland, Reykjavík, Iceland</i> ⁴ <i>GFZ German Research Centre for Geosciences, Potsdam, Germany</i> UV2-04 Geology of a Neogene caldera cluster in the Borgarfjörður eystri – Loðmundarfjörður area, Northeast Iceland Steffi Burchardt ¹ , Birgir V. Oskarsson ² , Ludvik E. Gustafsson ³ , Sylvia E Berg ⁴ , Morten S. Riisshuus ⁵ ¹ <i>Uppsala University, Uppsala, Sweden</i> ² <i>Icelandic Institute of Natural History, Reykjavík, Iceland</i> ³ <i>Geological Society of Iceland, Reykjavík, Iceland</i> ⁴ <i>Tyréns, Stockholm, Sweden</i> ⁵ <i>Geological Survey of the Faroe Islands, Thorshavn, Faroe Islands</i> UV2-05 Caldera volcanoes in Iceland: A record of caldera formation and eruptive history in Breiðdalur volcano, east Iceland Robert A. Askew ¹ , Catherine R. Gallagher ² , Thorvaldur Thordarson ³ , Birgir Vilhelm Óskarsson ¹ , Irma Gná Jóngeirsdóttir ³ , William C. Wenrich ³ ¹ <i>Icelandic Institute of Natural History, 6–8 Urriðaholtssræti, Garðabær, Iceland</i> ² <i>Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland</i> ³ <i>Faculty of Earth Sciences, University of Iceland, Sturlugata 7, Reykjavík, Iceland</i>	
09:15 - 10:30	ER5 - Earth resources	Hall 1 /
	- Convener: Bryndís G. Róbertsdóttir, National Energy Authority - Convener: Hjalti Franzson, Retiree ER5-01 Mineral Criticality – why critical minerals are different and why they are not. Karen Hanghøj <i>British Geological Survey, Keyworth, United Kingdom</i>	

ER5-02

The history of gold exploration in Iceland by Malmis and associates

Hallgrímur Jónasson ¹, Guðmundur Ómar Friðleifsson ², Hjalti Franzson ³

¹ Rannís, 105 Reykjavík, Iceland

² Viðilundur 10, 210 Garðabær, Iceland

³ Háaleitisbraut 123, 108 Reykjavík, Iceland

ER5-03

Sulphur isotope systematics in sulphide occurrences in the Lovisa region, SE Finland

Krister Leon Sundblad ¹, Abigail Jiménez-Franco ², Josep Roque-Rosell ³

¹ Institute of Earth Sciences, Saint Petersburg State University, Saint Petersburg, Russia

² Facultat de Geografia i Història, Universitat de Barcelona, Barcelona, Spain

³ Facultat de Ciències de la Terra, Universitat de Barcelona, Barcelona, Spain

ER5-04

Role of Cu remobilization during the formation of the epigenetic Pahtohavare Cu ± Au deposits, Kiruna mining district, Sweden

Leslie Logan, Joel B.H. Andersson, Tobias E. Bauer

Luleå University of Technology, Luleå, Sweden

09:15 - 10:30 **AG1-AG3 - Applied geology** O-101 /

- Convener: Jón Haukur Steingrímsson, Efla consulting engineers

- Convener: Atli Karl Ingimarsson, Mannvit Consulting engineers

AG1-01

Rock Mechanics Laboratory model

Lars Maersk Hansen

Institute of Geoscience, Uppsala, Sweden

AG1-02

Characterizing potential quick clay with a 3D resistivity model in the mid-Norwegian Orkdal valley

Sofie Gradmann, Vikas Chand Baranwal, Jan Steinar Rønning, Inger-Lise Solberg, Atle Dagestad, Louise Hansen, Bjørn Eskil Larsen, Ivanna Penna, Pia Sunde, Georgios Tassis

Geological Survey of Norway, Trondheim, Norway

AG1-03

Do harmful clay minerals affect adhesion between aggregate and binder?

Hafðís Eygló Jónsdóttir ¹, Erla María Hauksdóttir ², Þorbjörg Hólmgeirsdóttir ³

¹ The Icelandic Road and Coastal Administration, Akureyri, Iceland

² The Icelandic Road and Coastal Administration, Garðabær, Iceland

³ Mannvit Consulting Engineers, Kópavogur, Iceland

AG1-04

Unfavourable geological structure. A case history

Lars Maersk Hansen

Institute of Geoscience, Uppsala, Sweden

AG1-05

Gravel Wearing Course

Hafðís Eygló Jónsdóttir

The Icelandic Road and Coastal Administration, Akureyri, Iceland

09:15 - 10:30 **GA1-GA2 - Geoscience and the society: hazards and anthropogenic impact** VHV-023 /

- Convener: Þorsteinn Sæmundsson, University of Iceland

- Convener: Reginald L. Hermanns, Geological Survey of Norway (NGU)

- Convener: Daniel Ben-Yehoshua, University of Iceland

- Convener: Costanza Morino, Université Savoie Mont Blanc

- Convener: Harpa Grímsdóttir, Icelandic Met Office

GA1-13

Climate change and permafrost degradation in northeastern Canada

Najat Bhiry ¹, Armelle Decaulne ², John Molson ¹, Frédéric Manseau ¹, Jérémy Grenier ¹, Madiha Khadhraoui ¹, Danielle Cloutier ³

¹ Centre d'études nordiques, Laval University, Quebec, Canada

² UMR-6554 CNRS, Nantes, France

³ Department of Geography, Laval University, Quebec, Canada

GA1-14

Improving the resilience of linear infrastructure against climate induced natural hazards; Projects and case studies.

Anders Solheim, Rosa Maria Berastegui, Graham Gilbert, Vittoria Capobianco, Luca Piciullo, James Strout, Bjørn Kalsnes, Unni Eidsvig

NGI, Oslo, Norway

GA1-15

Permafrost and large slope instabilities – observations, models and implications

Etzelmüller Bernd ²

¹ University of Oslo, Department of Geosciences, Oslo, Norway

² UiO, Oslo, Norway

GA1-16

H2020 – PHUSICOS, Nature Based Solutions at rural mountain sites in Europe, implementation of measures and barriers experienced.

Anders Solheim, Amy Oen, Bjørn Kalsnes, Vittoria Capobianco, Farrokh Nadim, James Strout

NGI, Oslo, Norway

GA1-17

Rock slope failures along the Isfjorden and Billefjorden coastline, Svalbard: characteristics and implications for controlling factors

Dirk Kuhn ¹, Reginald L. Hermanns ², Michael Fuchs ¹, Nick Schüßler ¹, Jewgenij Torizin ¹, Tim F. Redfield ², Martina Boehme ², Raymond Eilertsen ², Dirk Balzer ¹

¹ Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

² Geological Survey of Norway (NGU), Trondheim, Norway

09:15 - 10:30 **IS2 - Interdisciplinary sessions** O-201 /

- Convener: Tobias Bauer, Luleå University of Technology
- Convener: Tero Niiranen, Geological Survey of Finland

IS2-01

3-D geologic modeling of the iron-oxide apatite (IOA) deposits from the Kiruna Mining District

Cs. Ervin Veress ¹, Inna Popova ², R. Irvine Annesley ³, E. Tobias Bauer ¹

¹ Luleå University of Technology, Luleå, Sweden

² Luossavaara-Kiirunavaara AB (LKAB), Gällivare, Sweden

³ Université de Lorraine, Nancy, Sweden

IS2-02

Defining mappable criteria for mineral systems model elements in mineral prospectivity modeling

Tero Niiranen, Vesa Nykänen

Geological Survey of Finland, Rovaniemi, Finland

IS2-03

Validating country wide cobalt prospectivity models in Finland

Vesa Nykänen, Tero Niiranen, Tuomo Törmänen

Geological Survey of Finland, Rovaniemi, Finland

IS2-04

EPOS-Norway Portal

Christian Rønnevik ¹, Jan Michalek ¹, Kuvvet Atakan ¹, Lars Ottemöller ¹, Øyvind Natvik ¹, Tor Langeland ², Ove Daae Lampe ², Gro Fonnes ², Jeremy Cook ², Jon Magnus Christensen ³, Ulf Baadshaug ³, Halfdan Kierulf ⁴, Bjørn-Ove Grøtan ⁵, Odleiv Olesen ⁵, John Dehls ⁵, Valerie Maupin ⁶

¹ University of Bergen, Bergen, Norway

² NORCE, Bergen, Norway

³ NORSAR, Kjeller, Norway

⁴ Norwegian Mapping Authority, Hønefoss, Norway

⁵ Geological Survey of Norway, Trondheim, Norway

⁶ University of Oslo, Oslo, Norway

IS2-05

EPOS ICS Data Portal

Daniele Bailo ¹, Jan Michalek ², Kuvvet Atakan ², Keith Jeffery ³, Team EPOS ICS ⁴

¹ INGV, Rome, Italy

² University of Bergen, Bergen, Norway

³ Keith G Jeffery Consultants, Faringdon, United Kingdom

⁴ EPOS-ERIC, Rome, Italy

10:30 - 10:45	REFRESHMENTS - in the Foyer	
10:45 - 11:15	IS2 - Interdisciplinary sessions	O-201 /

- Convener: Tobias Bauer, Luleå University of Technology

- Convener: Tero Niiranen, Geological Survey of Finland

IS2-06

Cartograms in geosciences: Alternative visualisations of our dynamic Earth

Benjamin Hennig

University of Iceland, Reykjavík, Iceland

IS2-07

Paleomagnetic data and the Deep-time Digital Earth program

Johanna Salminen ¹, Shihong Zhang ², David Evans ³

¹ Geological Survey of Finland, Espoo, Finland

² China University of Geosciences Beijing, Beijing, China

³ Yale University, New Haven, United States

10:45 - 12:00	UV2 - Understanding volcanoes	Hall 2 /
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- Convener: Bergrún Anna Óladóttir, Icelandic Met Office

- Convener: Þorvaldur Þórðarson, Faculty of Earth Sciences

UV2-06

Photogrammetric investigation of Vestfirðir (NW peninsula) of Iceland: New insights to the structure of the Miocene lava pile and the enigmatic lignite horizon

Erik Vest Sørensen ¹, Paul Martin Holm ²

¹ Geological Survey of Denmark And Greenland, Copenhagen, Denmark

² University of Copenhagen, Copenhagen, Denmark

UV2-07

Paleomagnetism and rock magnetism applied to volcanology – prospects for Iceland

Elisa Piispa

Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

UV2-08

Characterising ice-magma interactions during a shallow subglacial fissure eruption: northern Laki, Iceland, a case study

Catherine R. Gallagher ¹, Magnús Tumi Guðmundsson ¹, Thorvaldur Thordarson ², Bruce F. Houghton ³, Birgir V. Óskarsson ⁴, Robert A. Askew ⁴, Rosie P. Cole ¹, William M. Moreland ⁵, Valentin Troll ⁶, Guðrún Þ. Larsen ¹

¹ The Nordic Volcanological Center, University of Iceland, Reykjavík, Iceland

² Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland

³ SOEST, University of Hawai'i at Mānoa, Honolulu, United States

⁴ The Icelandic Institute of Natural History, Garðabær, Iceland

⁵ Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

⁶ Department of Earth Sciences, Uppsala University, Uppsala, Sweden

UV2-09

Early Holocene explosive volcanism in Iceland

Esther Ruth Gudmundsdóttir ¹, Guðrún Larsen ², Bergrún Arna Óladóttir ³, Jón Eiríksson ², Olgeir Sigmarsson ², Maarit H Kalliokoski ⁴, Egill Erlendsson ⁵, Sigrún Dögg Eddudóttir ⁶, Wesley R Farnsworth ⁷

¹ Nordic Volcanological Center, Institute of Earth Sciences, Reykjavik, Iceland

² Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

³ Icelandic Met Office, Reykjavik, Iceland

⁴ Department of Geography and Geology, University of Turku, Turku, Finland

⁵ Institute of Life and Environmental Sciences, University of Iceland, Reykjavik, Iceland

⁶ Department of Archaeology and Ancient History, Uppsala University, Uppsala, Sweden

⁷ GLOBE Institute, University of Copenhagen, Copenhagen a, Denmark

UV2-10

Late Quaternary Tephrochronology of Sweden: A look back and prospects for the future

Stefan Wastegård, Simon A. Larsson

Stockholm University, STOCKHOLM, Sweden

10:45 - 11:45 **ER5 - Earth resources** Hall 1 /

- Convener: Bryndís G. Róbertsdóttir, National Energy Authority

- Convener: Hjalti Franzson, Retiree

ER5-05

Volatile transport in the Virginia Formation black shale contact aureole with implications for the formation of the Cu-Ni-(PGE) sulfide deposits of the Duluth Complex, Minnesota

Ville J. Virtanen ¹, Lena Märki ², Ferenc Molnár ³, Jussi S. Heinonen ⁴, Matthieu E. Galvez ²

¹ University of Helsinki, Helsinki, Finland

² ETH Zürich, Zürich, Switzerland

³ Eötvös Loránd University, Budapest, Hungary

⁴ Finnish Museum of Natural History, University of Helsinki, Helsinki, Finland

ER5-06

Mining of raw material for low emission basalt fiber production in Iceland

Ögmundur Erlendsson ¹, Birgir Jóhannesson ², Árni Árnason ³, Hjalti Franzson ¹

¹ ISOR, Reykjavik, Iceland

² Tæknisetur ehf, IceTec, Reykjavik, Iceland

³ JEI, Jarðefnaíðnaður, Þorlákshöfn, Iceland

ER5-07

Geology, chemostratigraphy and hydrothermal alteration at the Metsämonttu Zn-Pb-Cu-Au-Ag deposit, Aijala-Orijärvi area, southern Finland: Implications for VMS exploration

Janne Hokka, Hanna Leväniemi

Geological Survey of Finland, Espoo, Finland

ER5-08

Tracing alteration mineralogy using portable X-ray diffraction (pXRD) and hyperspectral (SWIR) analysis for systematic drill core mapping: An example from the Aijala Cu-S and Metsämonttu Zn-Pb-Cu-Ag-Au deposits, Aijala-Orijärvi area, southern Finland

Irmeli Huovinen ¹, Jenniina Siira ², Jaro Kuikka ¹

¹ Geological Survey of Finland, Espoo, Finland

² Finnish Food Authority, Helsinki, Finland

10:45 - 11:00 **AG1-AG3 - Applied geology** O-101 /

- Convener: Jón Haukur Steingrímsson, Efla consulting engineers

- Convener: Atli Karl Ingimarsson, Mannvit Consulting engineers

AG1-06

Qualitative and semi-quantitative determination of low concentrated iron mono-sulfides in concrete aggregates by differential thermal and thermomagnetic analysis

Nikolas Oberhardt ¹, Nathan Church ², Kurt Aasly ²

¹ Norwegian University of Science and Technology (NTNU)/Department of Geoscience, Trondheim, Norway

² Norwegian University of Science and Technology (NTNU)/Department of Geoscience, Trondheim, Norway

10:45 - 12:00 **GA1-GA2** - Geoscience and the society: hazards and anthropogenic impact VHV-023 /

- Convener: Þorsteinn Sæmundsson, University of Iceland
- Convener: Reginald L. Hermanns, Geological Survey of Norway (NGU)
- Convener: Daniel Ben-Yehoshua, University of Iceland
- Convener: Costanza Morino, Université Savoie Mont Blanc
- Convener: Harpa Grímsdóttir, Icelandic Met Office

GA1-18

The landslides cycle in the village Seyðisfjörður, east Iceland, 14.-18. December 2020

Sveinn Brynjólfsson

Veðurstofa Íslands, Akureyri, Iceland

GA1-19

Past and present landslide investigations in the town of Seyðisfjörður

Jón Kristinn Helgason ¹, Þorsteinn Sæmundsson ², Magni Hreinn Jónsson ¹, Harpa Grímsdóttir ¹, Skafti Brynjólfsson ³, Sigurdís B. Jónasdóttir ¹, Sveinn Brynjólfsson ¹, Jón Haukur Steingrímsson ⁴

¹ Icelandic Met Office, Ísafjörður, Iceland

² University of Iceland, Reykjavík, Iceland

³ Icelandic Institute of Natural History, Akureyri, Iceland

⁴ EFLA consultant engineering, Reykjavík, Iceland

GA1-20

Landslide monitoring and early warning system in the town of Seyðisfjörður, Eastern Iceland.

Jón Kristinn Helgason, Magni Hreinn Jónsson, Harpa Grímsdóttir, Vincent Drouin, Esther Jensen

Icelandic Met Office, Ísafjörður, Iceland

GA1-21

Landslide protection measures for Seyðisfjörður following the landslide cycle in December 2020

Jón Haukur Steingrímsson

Efla consulting engineers, Reykjavík, Iceland

GA1-22

Beyond environmental monitoring : are automatic time-lapse cameras an efficient tool for temperature measurement in remote regions ?

Jérémy Grenier ¹, Najat Bhiri ¹, Armelle Decaulne ²

¹ Université Laval, Québec, Canada

² Centre National de recherche scientifique, Université de Nantes, Nantes, France

11:30 - 12:30 **NORDQUA Meeting** O-201 /

11:30 - 12:00 **GT4-GT6** - Geodynamics & tectonic evolution O-101 /

- Convener: Ásta Rut Hjartardóttir, University of Iceland

GT6-01

Rift propagation north of Iceland: A case of asymmetric plume dynamics?

Hans Christian Larsen ², Anett Blischke ¹, Sæmundur Halldórsson ³, Bryndís Brandsdóttir ³, Charles E. Lesher ⁴, Clinton P. Conrad ⁵, Eric L. Brown ⁶, Helen K. Coxall ⁷, Joost Frieling ⁸, Juliane Dannberg ⁹, Anders McCarthy ¹⁰, Bernhard Steinberger ¹¹, Carmen Gaina ⁵, Colin Devey ¹², David Peate ¹³, Garry D. Karner ¹⁴, John R. Hopper ², Bjarni Gautason ¹⁵, Sverre Planke ⁵, Ögmundur Erlendsson ¹⁶

¹ Iceland GeoSurvey, Akureyri, Iceland

² Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark

³ University of Iceland, Reykjavik, Iceland

⁴ Earth and Planetary Sciences, University of California, Davis, California, United States

⁵ Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway

⁶ Department of Geoscience - Earth System Petrology, Aarhus University, Aarhus, Denmark

⁷ Department of Geological Sciences, Stockholm University, Stockholm, Sweden

⁸ Department of Earth Sciences, University of Oxford, Oxford, United Kingdom

⁹ Department of Geological Sciences, University of Florida, Gainesville, United States

¹⁰ Department of Earth Sciences, Eidgenössische Technische Hochschule - ETH Zürich, Zürich, Switzerland

¹¹ German Research Centre for Geosciences (GFZ), Potsdam, Germany

¹² Helmholtz Centre for Ocean Research (GEOMAR), Kiel, Germany

¹³ Department of Earth & Environmental Sciences, The University of Iowa, Iowa City, United States

¹⁴ ExxonMobil Upstream Integrated Solutions Company, Spring, United States

¹⁵ Iceland GeoSurvey, AKUREYRI, Iceland

¹⁶ Iceland GeoSurvey, Reykjavik, Iceland

GT6-02

The influence of orogenic collision inheritance on rifted margin architecture and segmentation: Insights from comparing numerical experiments to the mid-Norwegian margin

Gwenn Peron-Pinvidic ¹, Loic Fourel ², Susanne Buitert ³

¹ NTNU – Norwegian University of Science and Technology

² NGU Geological Survey of Norway, Trondheim, Norway

³ RWTH Aachen University, Aachen, Germany

12:00 - 13:00	LUNCH / POSTERS - in the Foyer of Háskólabíó	
13:00 - 13:30	Large Hall Plenary 4: Reginald Hermanns	
	PL-4	
	How is the threat of rock slope failure connected to climate change? – A perspective from Norway	
	Reginald L Hermanns	
	<i>Geological Survey of Norway, Trondheim, Norway</i>	
13:30 - 13:50	Large Hall: Making Movies	
14:00 - 15:15	ER5 - Earth resources	Hall 1 /
	- Convener: Bryndís G. Róbertsdóttir, National Energy Authority	
	- Convener: Hjalti Franzson, Retiree	
	ER5-09	
	Greenland mineral exploration – comparison with petroleum history	
	Flemming G. Christiansen	
	<i>FlemmingGC, Vanløse, Denmark</i>	
	ER5-11	
	Exposure and transport histories of ore-bearing glacial erratics in complex glacial environments using Terrestrial Cosmogenic Nuclide dating.	
	Veikko Peltonen ¹ , Seija Kultti ¹ , Niko Putkinen ² , Vincent Rinterknecht ³ , Adrian Hall ⁴ , David Whipp ¹	

- ¹ University of Helsinki, Helsinki, Finland
² Geological Survey of Finland, Kokkola, Finland
³ CEREGE, CNRS, Aix Marseille, France
⁴ Stockholm University, Stockholm, Sweden

ERS-12

Geochemical and isotopic fingerprinting of Cu metal using Laser ablation mass spectrometry

Xuan Liu ¹, Heini Reijonen ¹, Ismo Aaltonen ¹, Timo Ruskeeniemi ¹, Christina Lilja ², Axel Liebscher ³, Simon Norris ⁴, Warwick Watt ⁵, Nikitas Diomidis ⁶, Yann Lahaye ¹

- ¹ Geological Survey of Finland, Espoo, Finland
² Swedish Nuclear Fuel and Waste Management Co, Solna, Sweden
³ Federal Company for Radioactive Waste Disposal, Peine, Germany
⁴ Nuclear Waste Services, Didcot, United Kingdom
⁵ Nuclear Waste Management Organization, Toronto, Canada
⁶ National Cooperative for the Disposal of Radioactive Waste, Wetingen, Switzerland

14:00 - 15:15 **EC4 - Environment and climate** VHV-023 /

- Convener: Bernd Etzelmüller, Department of Geosciences, University of Oslo
- Convener: Ivar Berthling,
- Convener: Karianne Staalesen Lilleøren, University of Oslo

EC4-01

Modelling of rock wall permafrost development in Norway post the Little Ice Age

Justyna Czekirda ¹, Bernd Etzelmüller ¹, Sebastian Westermann ¹, Ketil Isaksen ², Florence Magnin ³

- ¹ Department of Geosciences, University of Oslo, Oslo, Norway
² Department of Research and Development, Norwegian Meteorological Institute, Oslo, Norway
³ EDYTEM, Université Savoie Mont-Blanc, CNRS, Chambéry, France

EC4-02

Late Quaternary—recent geological evolution of the Qaanaaq area, North Greenland: The impact on infrastructure and construction

Thomas Guldborg Petersen, Niels Foged, Soňa Tomašková, Thomas Ingeman-Nielsen

DTU Department of Environmental and Resource Engineering, Kongens Lyngby, Denmark

EC4-03

Modelling hydrogeological processes in steep permafrost-affected rock slopes

Florence Magnin, Jean-Yves Josnin, Matan Ben-Asher, Josué Bock, Philip Deline, Ludovic Ravel

EDYTEM Laboratory, Le Bourget du Lac, France

EC4-04

Using molards as marker of permafrost degradation in cold environments

Costanza Morino ¹, Susan Conway ², Philip Deline ¹, Florence Magnin ¹, Axel Noblet ², Svennevig Kristian ³, Antoine Lucas ⁴, Alexander Strom ⁵, Stuart Dunning ⁶, Reginald Hermanns ⁷

- ¹ Laboratoire EDYTEM, Université Savoie Mont Blanc, UMR-CNRS 5204, Chambéry, France
² Nantes Université, CNRS UMR 6112, Laboratoire de Planétologie et Géosciences, Nantes, France
³ Geological Survey of Denmark and Greenland, Copenhagen, Denmark
⁴ Université de Paris, Institut de Physique du Globe de Paris CNRS UMR 7154, Paris, France
⁵ Geodynamics Research Center, JSC Hydroproject Institute, Moscow, Russia
⁶ Newcastle University, School of Geography, Politics and Sociology, Newcastle, United Kingdom
⁷ Geohazards and Earth Observation, Geological Survey of Norway, Trondheim, Norway

EC4-05

Rock glaciers and post-glacial landscape development in Finnmark, Northern Norway

Karianne Lilleøren

Department of Geosciences, University of Oslo, Oslo, Norway

14:00 - 15:15 **EC2 - Environment and climate** O-201 /

- Convener: Hrafnhildur Hannesdóttir, Icelandic Met Office
- Convener: Ívar Örn Benediktsson, Institute of Earth Sciences, University of Iceland
- Convener: Skafti Brynjólfsson, The Icelandic Institute of Natural History

EC2-01

Extent of an independent late Weichselian ice-cap above the Vestfirðir Peninsula, Northwest Iceland

Hreggviður Norðdahl ¹, Halldór G Pétursson ²

¹ *Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland*

² *Icelandic Institute of Natural History, Akureyri, Iceland*

EC2-02

Geomorphology, hydrology, and chronology of early Holocene jökulhlaups along the Hvítá River, southwestern Iceland

Greta Wells ¹, Þorsteinn Sæmundsson ¹, Dugmore Andrew ², Sheryl Luzzadder-Beach ³, Timothy Beach ³

¹ *University of Iceland, Reykjavik, Iceland*

² *University of Edinburgh, Edinburgh, United Kingdom*

³ *University of Texas at Austin, Austin, United States*

EC2-03

Formation of the Bustarfell drumlin field, NE-Iceland: Integrating sedimentological and GPR data

Nína Aradóttir ¹, Ívar Örn Benediktsson ¹, Ólafur Ingólfsson ¹, Erik Sturkell ², Skafti Brynjólfsson ³, Wesley Randall Farnsworth ⁴

¹ *Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland*

² *Department of Earth Science, University of Gothenburg, Gothenburg, Sweden*

³ *Icelandic Institute of Natural History, Reykjavik, Iceland*

⁴ *GLOBE Institute, University of Copenhagen, Copenhagen, Denmark*

EC2-04

Formation of Crevasse Squeeze Ridges – a case study from Trygghamna, Svalbard

Ólafur Ingólfsson ¹, David Ben-Yehoshua ², Ívar Örn Benediktsson ¹, Nína Aradóttir ¹, Wesley R. Farnsworth ³

¹ *Earth Science Institute, University of Iceland, Reykjavik, Iceland*

² *Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland*

³ *GLOBE Institute, University of Copenhagen, Copenhagen, Denmark*

EC2-05

Inventory of glacial curvilineations (GCLs) at the southern periphery of the last Scandinavian Ice Sheet

Aleksander Adamczyk ¹, Wojciech Wysota ¹, Jan A. Piotrowski ², Piotr Weckwerth ¹

¹ *Nicolaus Copernicus University in Toruń, Toruń, Poland*

² *Aarhus University, Aarhus, Denmark*

14:00 - 15:15 **GT4-GT6 - Geodynamics & tectonic evolution** O-101 /

- Convener: John R. Hopper, GEUS

GT6-03

3D evolution of large-magnitude extensional faults and their effect on the architecture of rifts and rifted margins

Per Terje Osmundsen ¹, Julie Linnea S. Gresseth ¹, Alvar Braathen ³

¹ *NTNU, Trondheim, Norway*

² *NGU, Trondheim, Norway*

³ *UiO, Oslo, Norway*

GT5-04

Investigating a possible onshore-offshore correlation between the Frøya High and Frøya Island, mid-Norwegian margin

Julie Gresseth ¹, Lars Riber ², Tim Redfield ³, Per Terje Osmundsen ¹, Alvar Braathen ²

¹ *Norwegian University of Science and Technology, Trondheim, Norway*

² *University of Oslo, Oslo, Norway*

³ *Geological Survey of Norway, Trondheim, Norway*

GT6-05

How Caledonian structures camouflage as Permo-Carboniferous structures in the Oslo Region, Norway

Sofie Hildegard Ryen, Anders Mattias Lundmark, Augland Lars Eivind

University of Oslo, Oslo, Norway

GT6-06

Geochronology of the norther part of the Karasjok Greenstone Belt records ~500 million years of plume induced magmatism and rifting.

Harald Hansen ¹, Trond Slagstad ², Steffen Bergh ¹

¹ *UiT The Arctic University of Norway, Tromsø, Norway*

² *Geological Survey of Norway, Trondheim, Norway*

GT6-07

Extensional tectonic geomorphology along the northeast Atlantic margin? A field-based investigation of three half-graben basins

Linda Haaland ¹, Per Terje Osmundsen ¹, Tim Redfield ², Svendby Katia ², Kim Senger ³

¹ *NTNU, Trondheim, Norway*

² *NGU, Trondheim, Norway*

³ *UNIS, Longyearbyen, Norway*

14:00 - 15:15 **UV4 - Understanding volcanoes** Hall 2 /

- Convener: Michelle Maree Parks, Icelandic Meteorological Office

- Convener: Rikke Pedersen, Nordic Volcanological Center

UV4-01

Shallow magma degassing drives short-period lava fountaining at Fagradalsfjall, Iceland

Samuel Scott ¹, Melissa Pfeffer ², Clive Oppenheimer ³, Oliver Lamb ⁴, Talfan Barnie ², Rikey Kjartansdóttir ¹, Andri Stefánsson ¹

¹ *University of Iceland, Reykjavik, Iceland*

² *Icelandic Meteorological Office, Reykjavik, Iceland*

³ *Department of Geography, University of Cambridge, Cambridge, United Kingdom*

⁴ *University of North Carolina, Chapel Hill, NC, United States*

UV4-02

Highlighting gas accumulation as a driver of recent Hekla's eruptions using the short-lived radionuclide ²²²Rn.

Garance HERVE ¹, Olgeir SIGMARSSON ²

¹ *LMV, Université Clermont Auvergne, Aubière, France*

² *IES, UI and LMV, CNRS, Reykjavik, Iceland*

UV4-03

Magma plumbing system of mass extinction-related Large Igneous Provinces: Insights from Synchrotron Light X-ray microtomography

Manfredo Capriolo ¹, Sara Callegaro ¹, Jacopo Dal Corso ², Robert Newton ³, Don Baker ⁴, Paul Renne ⁵, Malte Storm ⁶, Andrea Marzoli ⁷

¹ *Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway*

² *State Key Laboratory of Biogeology and Environmental Geology, CUG, Wuhan, China*

³ *School of Earth and Environment, University of Leeds, Leeds, United Kingdom*

⁴ *Department of Earth and Planetary Sciences, McGill University, Montreal, Canada*

⁵ *Berkeley Geochronology Center, Berkeley, United States*

⁶ *Diamond Manchester Imaging Branchline, Diamond Light Source, Oxford, United Kingdom*

⁷ *Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro, Italy*

UV4-04

A new multi-scale, multi-modal and multi-dimensional workflow for the rapid characterization of volcanic materials – a study from the 2021 La Palma eruptions

Alan Butcher ¹, Matthew Pankhurst ², Beverley Coldwell ³, Olivia Barbee ⁴, Jane Scarrow ⁵, Katy Chamberlain ⁶, Fátima Rodríguez ⁴, Alba Martín Lorenzo ³, James Hickey ⁷, Gavyn Rollinson ⁷, Ester Jolis ⁸, Sari Lukkari ¹, Ian Corfe ¹, Jukka Kuva ¹, Pasi Heikkilä ¹, Radoslaw Michallik ¹, Liu Xuan ¹, Yann Lahaye ¹, Hugh O'Brien ¹, Andrew Menzies ⁹

¹ *Geological Survey of Finland, Espoo, Finland*

² *Instituto Tecnológico y de Energías Renovables (ITER), Tenerife, Canary Islands, Tenerife, Spain*

³ *Instituto Tecnológico y de Energías Renovables (ITER), Tenerife, Canary Islands, Tenerife, Spain*

⁴ *Instituto Volcanológico de Canarias (INVOLCAN), Tenerife, Canary Islands, Spain, Tenerife, Spain*

⁵ *University of Granada, Granada, Spain*

⁶ *Teesside University, UK, Newcastle, United Kingdom*

⁷ *University of Exeter, Camborne School of Mines, UK, Falmouth, United Kingdom*

⁸ *Geological Survey of Finland, Espoo, Finland, Finland*

⁹ *Bruker Nano Berlin, Berlin, Germany*

UV4-05

Insight into a shallow magma plumbing system: examples from the exhumed Torfufell central volcano, Eyjafjarðardalur, N-Iceland

Sigurveig Árnadóttir¹, Árni Hjartarson², Þorvaldur Þórðarson³, Bjarni Gautason¹ and Anett Blischke¹

- ¹ Iceland Geosurvey, Akureyri, Iceland
² Iceland Geosurvey, Reykjavik, Iceland
³ Faculty of Earth Sciences, University of Iceland, Reykjavik, Iceland

15:15 - 15:30	REFRESHMENTS - in the Foyer	
15:30 - 16:30	GT4-GT6 - Geodynamics & tectonic evolution	O-101 /
	- Convener: Anett Blischke, ÍSOR - Convener: Ásta Rut Hjartardóttir, University of Iceland	
	GT6-08	
	Geomorphic Evolution of a Passive Margin of Korean Peninsula: Initial Uplift, Tectonic Inversion, and Divide Migration	
	Yeong Bae Seong ¹ , Dong-Eun Kim ²	
	¹ Korea University, Seoul, South Korea ² Korea Institute of Geoscience and Mineral Resources, Daejeon, South Korea	
	GT6-09	
	New apatite thermochronological data from Western Norway	
	Åse Hestnes ¹ , Joachim Jacobs ¹ , Istvan Dunkl ² , Deta Gasser ³ , Anna K. Ksienzyk ⁴ , Thomas Scheiber ³ , Ferdinand Mayer-Ullmann ¹	
	¹ University of Bergen, Bergen, Norway ² University of Göttingen, Göttingen, Germany ³ Western Norway University of Applied Sciences, Sogndal, Norway ⁴ Geological Survey of Norway, Trondheim, Norway	
	GT6-10	
	Fault outcrop analysis in porous siliciclastic rocks	
	Anita Torabi ¹ , Fabrizio Balsamo ² , Francisco, C.C. Nogueira ³ , David L. Vasconcelos ³ , Amanda, C.E. Silva ³ , Francisco H.R. Bezerra ⁴ , Jorge, A.B. Souza ⁵	
	¹ University of Oslo, Oslo, Norway ² University of Parma, Parma, Italy ³ University of Campina Grande, Campina Grande, Brazil ⁴ University of Rio Grande do Norte, Natal, Brazil ⁵ Petrobras, Rio de Janeiro, Brazil	
	GT6-11	
	Integration of different methodologies to analyze surface deformation: examples from Iceland and Mt. Etna	
	Noemi Corti ¹ , Fabio Luca Bonali ¹ , Alessandro Tibaldi ¹ , Elena Russo ¹ , Federico Pasquarè Mariotto ² , Ásta Rut Hjartardóttir ³ , Páll Einarsson ³	
	¹ Department of Earth and Environmental Sciences, University of Milan-Bicocca, Milano, Italy ² Department of Human and Innovation Sciences, Insubria University, Varese, Italy ³ Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland	
15:30 - 16:30	ER4 - Earth resources	Hall 1 /
	- Convener: Børge Johannes Wigum, HeidelbergCement Northern Europe - Convener: Steinar Ellefmo, Norwegian University of Science and Technology	
	ER4-01	
	Sustainable management of deep-sea minerals within national jurisdiction: the case of Norway	
	Sissel Eriksen Oljedirektoratet/ Norwegian Petroleum Directorate, Hafslund, Norway	
	ER4-02	
	New technology and mission concept to discover marine critical minerals	
	Pablo Sobron, Kirby Simon, Anastasia Yanchilina, Daniel Van Hoesen, Evan Eshelman Impossible Sensing, St. Louis, United States	
	ER4-03	
	Geological models for some SMS deposits in the Mohn Ridge in the Norwegian Sea.	

Harald Brekke

Norwegian Petroleum Directorate, Tveit, Norway

ER4-04

Evolution of the metal-bearing fluids at the Fåvne hydrothermal vent field, the Arctic Mid-Ocean Ridges

Sabina Strmic Palinkas ¹, Rolf B. Pedersen ², Marie Wold ², Fredrik Sahlström ¹, Siv Hjorth Dundas ², Eszter Sendula ¹, Sean H. McClenaghan ³

¹ UiT Arctic University of Norway, Tromsø, Norway

² University of Bergen / Centre for Deep Sea Research, Bergen, Norway

³ Trinity College Dublin, Dublin, Ireland

15:30 - 16:45 **UV4 - Understanding volcanoes** Hall 2 /

- Convener: Michelle Maree Parks, Icelandic Meteorological Office

- Convener: Rikke Pedersen, Nordic Volcanological Center

UV4-06

Reconstructing silicic magma intrusion and eruption in the Reyðarártindur pluton, Southeast Iceland

Emma Rhodes ¹, Steffi Burchardt ¹, Abigail Barker ¹, Sonja Greiner ², Tobias Mattsson ³, Tobias Schmiedel ⁴, Taylor Witcher ¹, Erika Ronchin ⁵

¹ Uppsala Universitet, Uppsala, Sweden

² University of Iceland, Reykjavik, Iceland

³ University of St Andrews, St Andrews, United Kingdom

⁴ TU Delft, Delft, Netherlands

⁵ Sapienza University of Rome, Rome, Italy

UV4-07

Lithological controls on sill development in sedimentary basins: Observations from the San Rafael Volcanic Field, Utah.

Martin Kjenes ¹, Christian Haug Eide ¹, Nicolas Schofield ², Anna Bøgh ¹

¹ University of Bergen, Bergen, Norway

² University of Aberdeen, Aberdeen, United Kingdom

UV4-08

Streitishvarf composite dyke, a snapshot of magma mixing and silicic magma ascent through the shallow crust

Robert A. Askew ¹, Thorvaldur Thordarson ², Godfrey Fitton ³

¹ Icelandic Institute of Natural History, 6–8 Urriðahóltsstræti, Garðabær, Iceland

² Faculty of Earth Sciences, University of Iceland, Sturlugata 7, Reykjavik, Iceland

³ School of GeoSciences, University of Edinburgh, The King's Buildings, Edinburgh, United Kingdom

UV4-09

Pit crater depressions in the Galilee, Israel: volcanic-tectonic landforms?

Amos Frumkin, Ariel Heimann

Institute of Earth Sciences The Hebrew University of Jerusalem, Jerusalem, Israel

15:30 - 16:15 **EC2 - Environment and climate** O-201 /

- Convener: Hrafnhildur Hannesdóttir, Icelandic Met Office

- Convener: Ívar Örn Benediktsson, Institute of Earth Sciences, University of Iceland

- Convener: Skafti Brynjólfsson, The Icelandic Institute of Natural History

EC2-06

The internal controls of glacier movement over a soft bed – insights from high-resolution X-ray tomography, Storglaciären, Sweden

Lena Hansen ¹, Charlotte Sparrenbom ², Erika Tudisko ², Sven Lukas ²

¹ Department of Geology, Lund University, Lund, Sweden

² Lund University, Lund, Sweden

EC2-07

Dynamic subglacial meltwater systems drive late erosion pulses beneath rapidly thawing cold-based ice sheets.

Mikis Boeckel ², Tayo Boeckel ¹, Adrian Hall ³

¹ Private Researcher, Amsterdam, Netherlands

² Norges Geologiske Undersøkelse (NGU), Trondheim, Norway

³ Department of Physical Geography, Stockholm University, Stockholm, Sweden

EC2-08

Microstructural proxies for porewater pressure fluctuations in a subglacial till under a palaeo-ice stream in NW Poland

Piotr Hermanowski ¹, Jan A. Piotrowski ²

¹ Institute of Geology, Adam Mickiewicz University, Poznan, Poland

² Department of Geoscience, Aarhus University, Aarhus, Denmark

16:45 - 19:30	SKY LAGOON
19:30 - 23:30	CONFERENCE DINNER - GAMLA BÍÓ

Friday, May 13

08:30 - 09:00	Large Hall Plenary 5: Sandra Ósk Snæbjörnsdóttir	
	PL-5 Carbfix: CO ₂ mineral storage in basaltic rocks Sandra Snæbjörnsdóttir ¹ , Sigfússon Bergur ¹ , Chiara Marieni ¹ , Deirdre Clark ² , Ratouis Thomas ¹ , Martin Voigt ¹ , Sigurdur R. Gislason ³ ¹ Carbfix, Reykjavik, Iceland ² ISOR, Reykjavik, Iceland ³ Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland	
09:15 - 10:30	EC3 - Environment and climate	O-201 /
	- Convener: Anna Hughes, University of Manchester - Convener: Monica Winsborrow, The Arctic University of Norway - UiT EC3-01 Subglacial bedform sensitivity to variable topography and geology across the deglaciated Northern Hemisphere Lauren Simkins ¹ , Marion McKenzie ² , Sarah Principato ³ , Jacob Slawson ¹ , Shujie Wang ⁴ ¹ University of Virginia, Charlottesville, United States ² University of Virginia, Department of Environmental Sciences, Charlottesville, United States ³ Gettysburg College, Gettysburg, United States ⁴ Pennsylvania State University, University Park, United States EC3-02 Marine Ice Stream retreat offshore N-Iceland documented by multibeam bathymetric and high-resolution Chirp reflection data Bryndís Brandsdóttir, Bailey O'Connell, Patricia Höfer Institute of Earth Sciences, Science Institute, University of Iceland, Reykjavik, Iceland EC3-03 Footprint of the lake-terminating Baltic Sea Ice Stream Sarah Greenwood, Rachael Avery, Björn Morén Department of Geological Sciences, Stockholm University, Stockholm, Sweden EC3-04 Cross-cutting palaeo-ice streams in NE-Iceland reveal shifting Iceland Ice Sheet dynamics Ívar Benediktsson ¹ , Nína Aradóttir ¹ , Ólafur Ingólfsson ¹ , Skafti Brynjólfsson ² ¹ University of Iceland, Institute of Earth Sciences, Reykjavik, Iceland ² Icelandic Institute of Natural History, Akureyri, Iceland	
09:15 - 10:15	ER2 - Earth resources	Hall 1 /
	- Convener: Sandra Ósk Snæbjörnsdóttir, Carbfix - Convener: Deirdre Clark, ISOR ER2-01 Reservoir potential of the Faroe Islands basalt lava flows: an analogue study of the potential for CO ₂ storage in volcanic margin basalt sequences Marija Plahter Rosenqvist ¹ , Max William John Meakins ² , Sverre Planke ³ , John M. Millett ³ , Hans Jørgen Kjøll ² , Bjørn Jamtveit ¹ ¹ The Njord Centre, University of Oslo, Oslo, Norway ² Department of Geosciences, University of Oslo, Oslo, Norway ³ Volcanic Basin Petroleum Research (VBPR), Oslo, Norway ER2-02 How to obtain a better overall geological understanding of the central Faroe Islands by usage of Construction of a geomodel in Petrel software by integrating geological and geophysical data of different scale and age. Rakul Maria Johannesen ¹ , Jana Ólavsdóttir ² , Lars Ole Boldreel ³ , Turid Hátún Madsen ² ¹ Jarðfeingi (Faroe Earth and Energy Directorate), The Njord Centre, UiO, Tórshavn, Faroe Islands ² Jarðfeingi (Faroe Earth and Energy Directorate), Tórshavn, Faroe Islands ³ Department of Geosciences & Natural Resources Management, University of Copenhagen, Copenhagen, Denmark	

ER2-03CO₂ storage on the Norwegian Continental Shelf – status and learnings

Stig-Morten Knutsen

*Norwegian Petroleum Directorate, HARSTAD, Norway***ER2-04**Evaluating CO₂ storage potential in an under-explored basin: Stord Basin, northern North Sea

Sian Evans, Alvar Braathen

University of Oslo, Oslo, Norway

09:15 - 10:30	IS3 - Interdisciplinary sessions	O-101 /
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- Convener: Berglind Sigmundsdóttir, Katla UNESCO Global Geopark

- Convener: Lovisa Guðrún Ásbjörnsdóttir, Icelandic Institute of Natural History

IS3-01

Geoheritage in Iceland, an inventory and assessment

Lovisa Ásbjörnsdóttir, Ingvar Atli Sigurðsson

*Icelandic Institute of Natural History, Garðabær, Iceland***IS3-02**

A claim for the promotion of landslides in the global geoheritage

Costanza Morino ¹, Paola Coratza ², Mauro Soldati ²¹ *Laboratoire EDYTEM, Université Savoie Mont Blanc, UMR-CNRS 5204, Chambéry, France*² *Dept. of Chemical and Geological Sciences, University of Modena Reggio Emilia, Modena, Italy***IS3-03**

Geotourism: A Strategic Opportunity for Public Engagement

Glen Burrige

*European Federation of Geologists, Brussels, Belgium***IS3-04**

How is geodiversity and geosites presented to visitors of nature reserves? A pilot study of information boards in Skåne, southernmost Sweden.

Joachim Regnéll

*Department of Environmental Science, Kristianstad University, Kristianstad, Sweden***IS3-05**

Historic quarrying of the Virolahti pyterlite – unique cultural heritage landscape in SE Finland

Paavo Härmä ¹, Olavi Selonen ²¹ *Geological Survey of Finland, Espoo, Finland*² *Åbo Akademi University, Turku, Finland*

09:15 - 10:30	IM1-2-3 - Igneous and Metamorphic Geochemistry	VHV-023 /
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- Convener: Tobias Björn Weisenberger, University of Iceland

- Convener: Kristján Jónasson, Icelandic Institute of Natural History

- Convener: Sæmundur Ari Halldórsson, University of Iceland

- Convener: Guðmundur H. Guðfinnsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Olgeir Sigmarsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Enikő Bali, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Bjarni Gautason, ÍSOR

IM1-01

The composition of apatite in the Archean Siilinjärvi glimmerite-carbonatite complex

Seppo Karvinen, Aku Heinonen, Christoph Beier

University of Helsinki, Helsinki, Finland

IM1-02

Untold Tales From the Deep Dark Crust: Importance of Lower Crustal Magmatism for the Formation of LIPs

Rune Larsen, Berg-Edland ¹, Bjørn Sørensen, E ¹, Sverre Planke ², Christian Tegner ³

¹ NTNU, Department of Geoscience and Petroleum, TRONDHEIM, Norway

² UiO, Department of Geosciences, Oslo, Norway

³ U. Aarhus, Dep. of Geoscience, Aarhus, Denmark

IM1-03

New insight into the hydrological and thermal conditions of Surtsey and relation to the time-lapse alteration.

Tobias Björn Weisenberger ¹, Simon Prause ¹, Barbara I. Kleine ¹, Rögnvaldur Magnússon ², Andri Stéfansson ¹, Magnús Tumi Guðmundsson ¹

¹ University of Iceland, Reykjavík, Iceland

² Iceland GeoSurvey, Reykjavík, Iceland

IM1-04

Petrology and geochemistry of the Sveinar-Randarhólar fissure (Central East Iceland): Insights into magmatism following post-glacial lithospheric rebound

Adam Abersteiner ¹, Christoph Beier ¹, Sæmundur Halldórsson ², Edward Marshall ²

¹ University of Helsinki, Helsinki, Finland

² University of Iceland, Reykjavík, Iceland

IM1-05

Structural control on the preservation of mantle heterogeneity during plume-ridge interaction along the southern Kolbeinsey Ridge

Christoph Beier ¹, Haase Karsten M. ², Devey Colin W. ³

¹ University of Helsinki, Helsinki, Finland

² Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany

³ GEOMAR-Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany

09:15 - 10:15 **UV1 - Understanding volcanoes** Hall 2 /

- Convener: Sara Barsotti, Icelandic Meteorological Office
- Convener: Magnús Tumi Guðmundsson, University of Iceland

UV1-01

Volcanic tremor intensity and characteristics associated with the Surtsey eruption of 1963-1967

Sara Sayyadi, Magnús Tumi Guðmundsson, Páll Einarsson

Nordvulk, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

UV1-02

Detecting crustal melts under the Reykjanes Peninsula using MT soundings to assess the risk of future volcanic eruptions

Gylfi Páll Hersir ¹, Ólafur G. Flóvenz ², Ragna Karlsdóttir ³, Egill Árni Guðnason ², Þorbjörg Ágústsdóttir ²

¹ Gylfi.pall@outlook.com, Reykjavík, Iceland

² ÍSOR, Iceland GeoSurvey, Reykjavík, Iceland

³ Ragnakarl@outlook.com, Reykjavík, Iceland

UV1-03

SO₂ flux measurements during the 2021 eruption of Fagradalsfjall

Melissa Anne Pfeffer ¹, Santiago Arellano ², Guðrún Nína Petersen ¹, Talfan Barnie ¹, Sara Barsotti ¹

¹ Icelandic Meteorological Office, Reykjavík, Iceland

² Chalmers University of Technology, Gothenburg, Sweden

UV1-04

Volcanic activity in Iceland: Magnitude, frequency, styles of activity and principal hazards

Magnús Tumi Guðmundsson ¹, Guðrún Larsen ¹, Sara Barsotti ², Þórdís Högnadóttir ¹, Gro B.M. Pedersen ¹

¹ Nordvulk, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

² Icelandic Meteorological Office, Bústaðavegi, Reykjavík, Iceland

10:30 - 10:45 **REFRESHMENTS – in the Foyer**

10:45 - 11:30	IS1 - Interdisciplinary sessions	O-101 /
	- Convener: Susan Conway, Laboratoire de Planétologie et Géosciences - Convener: Andreas Johnsson, Department of Earth Sciences at the University of Gothenburg	
	IS1-01	
	Olivine biosignatures and/or abiotic features?	
	Helge Hellevang ¹ , Kristina Dunkel ¹ , Snædis Björnsdóttir ² , Henning Dypvik ¹	
	¹ University of Oslo/Department of geoscience, Oslo, Norway ² University of Iceland/Faculty of Env. and life sci., Reykjavik, Iceland	
	IS1-02	
	Blue copper-rich speleothems in Icelandic lava tubes: strongholds to subsurface life on Mars?	
	Nina Kopacz ¹ , Joleen Csuka ² , Mickael Baqué ³ , Iaroslav Iakubivnyi ⁴ , Hrefna Guðlaugardóttir ⁵ , Ingeborg J. Klarenberg ⁵ , Mahid Ahmed ¹ , Alexandra Zetterlind ¹ , Abhijeet Singh ⁶ , Inge Loes Ten Kate ¹ , Eric Hellebrand ¹ , Brent R. Stockwell ² , Árni B. Stefánsson ⁷ , Oddur Vilhelmsson ⁵ , Anna Neubeck ⁶ , Anna Schnurer ⁸ , Wolf Geppert ⁹	
	¹ Utrecht University, Utrecht, Netherlands ² Columbia University, New York, United States ³ DLR, Berlin, Germany ⁴ University of Tartu, Tartu, Estonia ⁵ University of Akureyri, Akureyri, Iceland ⁶ Uppsala University, Uppsala, Sweden ⁷ Augnlæknastofa ÁBS, Reykjavik, Iceland ⁸ Swedish University of Agricultural Sciences, Uppsala, Sweden ⁹ Stockholm University Astrobiology Centre, Stockholm, Sweden	
	IS1-03	
	Molards as an analogue for ejecta-ice interactions on Mars	
	Susan Conway ² , Costanza Morino ¹ , Coralie Peignaux ² , Antoine Lucas ³ , Kristian Svennevig ⁴ , Frances Butcher ⁵ , Gioachino Roberti ⁶ , Meven Philippe ² , Axel Noblet ²	
	¹ Laboratoire EDYTEM, Université Savoie Mont Blanc, UMR-CNRS 5204, Chambéry, France ² Nantes Université, CNRS UMR 6112, Laboratoire de Planétologie et Géosciences, Nantes, France ³ Université de Paris, Institut de Physique du Globe de Paris CNRS UMR 7154, Paris, France ⁴ Geological Survey of Denmark and Greenland, Copenhagen, Denmark ⁵ The University of Sheffield, Department of Geography, Sheffield, United Kingdom ⁶ Minerva Intelligence Inc., Vancouver, Canada	
10:45 - 12:15	EC3 - Environment and climate	O-201 /
	- Convener: Anna Hughes, University of Manchester - Convener: Monica Winsborrow, The Arctic University of Norway - UiT	
	EC3-05	
	Sedimentary processes and paleoenvironment of the northern Barents Sea continental slope	
	Christine Tømmervik Kollsgård ¹ , Tom Arne Rydningen ¹ , Jan Sverre Laberg ¹ , Matthias Forwick ¹ , Amado P. E. Lasabuda ¹ , Katrine Husum ²	
	¹ UiT Department of Geosciences, Tromsø, Norway ² Norwegian Polar Institute, Longyearbyen, Norway	
	EC3-06	
	Characterization of glacial landforms in the SW Barents Sea using high-resolution 3D seismic reflection data	
	Henrik Henriksen Stokke ¹ , Benjamin Bellwald ² , Sverre Planke ³ , Stefan Bünz ⁴	
	¹ UiT The Arctic University of Norway, Fetsund, Norway ² Fjorgyn, Oslo, Norway ³ Volcanic Basin Energy Research, Oslo, Norway ⁴ UiT The Arctic University of Norway, Tromsø, Norway	
	EC3-07	
	Trough mouth fans as high-resolution source-to-sink archives	
	Benjamin Bellwald ¹ , Aurora Garcia ² , Christine Batchelor ³ , Rachel Barrett ⁴ , Dwarika Maharjan ¹ , Sverre Planke ¹ , Ivar Midtkandal ² , Reidun Myklebust ⁵	
	¹ VBER, Oslo, Norway ² University of Oslo, Oslo, Norway ³ Newcastle University, Newcastle, United Kingdom ⁴ University of Kiel, Kiel, Germany ⁵ TGS, Oslo, Norway	

EC3-08

Deglaciation of a high-latitude glacial trough bordering the Arctic Ocean – the Woodfjorden Trough on the NW Svalbard margin

Tom Arne Rydningen¹, Amando Putra Ersaid Lasabuda¹, Jan Sverre Laberg¹, Christine Tømmervik Kollsgård¹, Stine Bjordal-Olsen¹, Matthias Forwick¹, Monica Winsborrow², Ólafur Ingólfsson³

¹ UiT The Arctic University of Norway, Department of Geosciences, Tromsø, Norway

² CAGE, UiT The Arctic University of Norway, Tromsø, Norway

³ University of Iceland, Faculty of Earth Sciences, Reykjavik, Iceland

EC3-09

Stratigraphy of a complete glacial-interglacial cycle: The sedimentary record of the last glaciation at the North Sea Fan

Aurora Garcia¹, Benjamin Bellwald², Ivar Midtkandal¹, Sverre Planke³, Pietro Sternai⁴, Ingrid Anell¹, Reidun Myklebust⁵

¹ Universitetet i Oslo, Oslo, Norway

² Fjorgyn, Oslo, Norway

³ Volcanic Basin Energy Research (VBER), Oslo, Norway

⁴ Università degli Studi di Milano-Bicocca (Unimib), Milan, Italy

⁵ TGS, Skøyen, Norway

EC3-10

Revised Middle and Late Pleistocene interglacial and interstadial records from the glaciated eastern Fennoscandia in Finland

Matti E. Räsänen¹, Jaakko Auri², Juha Ovaskainen²

¹ Vapparintie 732, Turku, Finland

² Geological Survey of Finland, Espoo, Finland

10:45 - 11:45

ER2 - Earth resources

Hall 1 /

- Convener: Sandra Ósk Snæbjörnsdóttir, Carbfix
- Convener: Deirdre Clark, ÍSOR

ER2-05

Fault Gouge Characterization in the Øygarden complex SW Norway – Relevance for offshore CO2 storage

Anders Bjørnstad¹, Elin Skurtveit², Joachim Jacobs¹, Magnus Soldal³

¹ University of Bergen, Department of Earth Science, Bergen, Norway

² Norwegian Geotechnical Institute, Oslo, Norway

³ University of Oslo, Department of Geosciences, Oslo, Norway

ER2-06

Structural characterization and across-fault seal assessment of the Aurora CO2 storage site, northern North Sea

Nora Holden¹, Johnathon Osmond¹, Mark Joseph Mulrooney¹, Alvar Braathen¹, Elin Skurtveit², Anja Sundal¹

¹ Department of Geosciences, University of Oslo, Oslo, Norway

² Norwegian Geotechnical Institute, Oslo, Norway

ER2-08

Initial conditions at the new injection site at Nesjavellir: Intergrating multiple geoscience models to predict flow paths, mineralization and mass replenishment

Sveinborg Hlíf Gunnarsdóttir¹, Deirdre Clark¹, Iwona Monika Galeczka¹, Helga Margrét Helgadóttir¹, Kjartan Marteinsson¹, Gunnar Þorgilsson¹, Sandra Ósk Snæbjörnsdóttir²

¹ ÍSOR, Reykjavik, Iceland

² Carbfix, Reykjavik, Iceland

ER2-07

An assessment of CO2 and H2S mineralization efficiency at the Nesjavellir (Iceland) geothermal storage site

Iwona Galeczka¹, Andri Stefánsson², Barbara Kleine², Jóhann Gunnarsson Robin², Sandra Ósk Snæbjörnsdóttir³, Bergur Sigfússon³, Sveinborg Hlíf Gunnarsdóttir¹, Tobias Björn Weisenberger⁴, Eric Oelkers⁵

¹ Iceland Geosurvey, Reykjavik, Iceland

² Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

³ Reykjavik Energy, Reykjavik, Iceland

⁴ Research Centre Breiðdalsvík, University of Iceland, Breiðdalsvík, Iceland

⁵ Géosciences Environnement Toulouse (GET) - CNRS, Toulouse, France

- Convener: Tobias Björn Weisenberger, University of Iceland
- Convener: Kristján Jónasson, Icelandic Institute of Natural History
- Convener: Sæmundur Ari Halldórsson, University of Iceland
- Convener: Guðmundur H. Guðfinnsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Olgeir Sigmarsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Enikő Bali, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Bjarni Gautason, ÍSOR

IM1-06

Environmental impact of Large Igneous Provinces: does the mantle source matter?

Sebastian Tappe ¹, Andreas Stracke ², Rolf Romer ³, Axel Schmitt ⁴

¹ *UiT The Arctic University of Norway, Tromsø, Norway*

² *University of Muenster, Muenster, Germany*

³ *GFZ Potsdam, Potsdam, Germany*

⁴ *Heidelberg University, Heidelberg, Germany*

IM1-07

W, Os, and Pb isotopic evidence for an early formed deep mantle source of Karoo flood basalts

Sanni T. Turunen ¹, Jussi S. Heinonen ¹, Richard W. Carlson ², Andrea Mundl-Petermeier ³, Arto V. Luttinen ¹

¹ *Finnish Museum of Natural History, University of Helsinki, Helsinki, Finland*

² *Earth and Planets Laboratory, Carnegie Institute for Science, Washington D.C., United States*

³ *Department of Lithospheric Research, University of Vienna, Vienna, Austria*

IM1-08

Heterogeneous Karoo mantle plume and its relation to southern Atlantic Ocean hotspots

Arto V. Luttinen ¹, Richard W. Carlson ²

¹ *University of Helsinki, Helsinki, Finland*

² *Carnegie Institution for Science, Washington DC, United States*

IM1-09

Long or short silicic magma residence time beneath Hekla volcano, Iceland?

Olgeir Sigmarsson ¹, Ingibjörg Bergþórsdóttir ², Guðrún Larsen ²

¹ *IES, UI and LMV, CNRS, Reykjavik, Iceland*

² *Institute of Earth Sciences, Reykjavik, Iceland*

IM1-10

New insights on shallow intrusions from the early stage of the Oslo Rift

Sara Callegaro ¹, Henrik Hovland Svensen ¹, Thea Hatlen Heimdal ¹, Hans Jørgen Kjølil ², Andreas Olaus Harstad ³, Else Ragnhild Neumann ¹

¹ *Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway*

² *University of Oslo, Oslo, Norway*

³ *Skanska Norge AS, Bærum, Norway*

- Convener: Sara Barsotti, Icelandic Meteorological Office
- Convener: Magnús Tumi Guðmundsson, University of Iceland

UV1-06

Lava flow hazard assessment during the 2021 Fagradalsfjall eruption, Iceland: Results from MrLavaLoba lava flow modelling

Gro B. M. Pedersen ¹, Melissa A. Pfeffer ², Sara Barsotti ², Simone Tarquini ³, Mattia De' Michieli Vitturi ⁴, Berggrún Arna Óladóttir ², Ragnar Heiðar Þrastarson ²

¹ *University of Iceland, Reykjavik, Iceland*

² *Icelandic Meteorological Office, Reykjavik, Iceland*

³ *Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy*

⁴ *Department of Geology, University at Buffalo, Buffalo, United States*

GA1-08

Long-term hazard assessment of explosive volcanic eruptions at Jan Mayen Island (Norway) and their implications for air traffic in the North Atlantic

Manuel Titos ², Beatriz Martínez Montesinos ³, Sara Barsotti ⁴, Laura Sandri ³, Arnau Folch ⁵, Leonardo Mingari ⁶, Giovanni Macedonio ⁷, Antonio Costa ³

¹ University of Granada, Granada, Spain

² Universidad de Granada, Granada, Spain

³ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Bologna, Italy

⁴ Icelandic Meteo Office, Reykjavik, Iceland

⁵ Geociencias Barcelona. Consejo Superior Investigaciones Científicas (CSIC), Barcelona, Spain

⁶ Barcelona Supercomputing Center, Barcelona, Spain

⁷ Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Sezione, Naples, Italy

11:30 - 12:00	RS3 - Remote Sensing in geosciences	Hall 2 /
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- Convener: Lilja Rún Bjarnadóttir, NGU (Geological Survey of Norway)

RS3-01

Marine base maps: Multidisciplinary mapping in the Norwegian coastal zone

Sigríð Elvenes, Reidulv Bøe

Geological Survey of Norway, Trondheim, Norway

RS3-02

The EMODNET-Geology project – harmonizing geological data of the European seas

Henry Vallius

Geologian Tutkimuskeskus - EMODnet Geology, Espoo, Finland

12:00 - 13:00	LUNCH / POSTERS - in the Foyer of Háskólabíó	
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13:00 - 13:40	Large Hall Plenary 6: Nordic Geoscientist Award	
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14:00 - 14:30	RS3 - Remote Sensing in geosciences	Hall 2 /
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- Convener: Lilja Rún Bjarnadóttir, NGU (Geological Survey of Norway)

RS3-03

The age and extent of the Andøya Slide (offshore Norway) revisited

Daniel Hesjedal Wiberg ¹, Jan Sverre Laberg ², Tom Arne Rydningen ², Matthias Forwick ²

¹ NGU (Geological Survey of Norway), Trondheim, Norway

² UiT The Arctic University of Norway, Tromsø, Norway

RS3-04

High-resolution multibeam Sonar and drone mapping of the submarine ikaite columns and structures in Ikka Fjord, SW Greenland

Paul Seaman ¹, Erik Sturkell ², Richard Gyllencreutz ³, Gabrielle J. Stockmann ⁴, Halldor Geirsson ⁴

¹ Independent scientist, N/A, United Kingdom

² University of Gothenburg, Gothenburg, Sweden

³ Bolin Centre for Climatic Research, Stockholm University, Stockholm, Sweden

⁴ NOROVULK, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

14:00 - 15:15	ER3 - Earth resources	Hall 1 /
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- Convener: Eydís Salome Eiríksdóttir, Marine and freshwater research institute

- Convener: Þráinn Friðriksson, Reykjavík Energy

ER3-01

Pre-Holocene groundwater within the Icelandic crust

Árný Erla Sveinbjörnsdóttir

Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

ER3-02

Isotope hydrology (2H and 18O) of water from the arctic Ikka Fjord, SW Greenland

Bjørn Buchardt ¹, Gabrielle Stockmann ², Árný Sveinbjörnsdóttir ²

¹ University of Copenhagen, Copenhagen, Denmark

² University of Iceland, Reykjavík, Iceland

ER3-03

Isotopic composition and origin of molecular hydrogen in bedrock groundwater

Riikka Kietäväinen ¹, Joel Silvennoinen ²

¹ Geological Survey of Finland, Espoo, Finland

² University of Helsinki, Helsinki, Finland

ER3-04

Early diagenesis as a precursor for aquifers in carbonate rocks

Jean-Baptiste Regnet ¹, Jérôme Fortin ², Christian David ¹, Philippe Robion ¹, Sylvain Richoz ³, Mikael Calner ³

¹ Cergy Paris University, Paris, France

² Ecole Normale Supérieure de Paris, Paris, France

³ Lund University, Lund, Sweden

ER3-05

Understanding the flow path of reagents in groundwater remediation actions, by means of cross-borehole electrical monitoring

Léa Lévy ¹, Thue Bording ², Rasmus Thalund-Hansen ³, Poul Bjerg ³, Kirsten Rügge ⁴, Maria Hag ⁵, Nina Tuxen ⁵, Jørgen Christensen ⁶, Lars Bennedsen ⁷, Anders Vest Christiansen ⁸, Gianluca Fiandaca ⁹

¹ Lund University, Lund, Sweden

² Aarhus Geoinstruments, Aarhus, Denmark

³ Technical University of Denmark, Lyngby, Denmark

⁴ COWI, Lyngby, Denmark

⁵ Region Hovedstaden, Hillerød, Denmark

⁶ Region Syddanmark, Vejle, Denmark

⁷ Rambøll, Esbjerg, Denmark

⁸ Aarhus University, Aarhus, Denmark

⁹ University of Milano, Milano, Italy

14:00 - 15:15 **EC3 - Environment and climate** O-201 /

- Convener: Anna Hughes, University of Manchester
- Convener: Monica Winsborrow, The Arctic University of Norway - UiT

EC3-11

Pleistocene history of eastern Fennoscandia – interglacial and interstadial record

Juha Pekka Lunkka ¹, Pertti Sarala ¹, Kari Olavi Eskola ²

¹ University of Oulu, Oulu, Finland

² University of Helsinki, Helsinki, Finland

EC3-12

Reconstructing sea ice in the Iceland Sea during the last 165,000 years

Erna Ósk Arnardóttir, Esther Ruth Guðmundsdóttir, Ívar Örn Benediktsson, Jón Eiríksson

Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

EC3-13

Palaeo-environmental reconstructions from microfossil data using machine learning

Sakari Salonen, Miska Luoto

University of Helsinki, Helsinki, Finland

EC3-14

Lateglacial seasonal climate signals reconstructed from the palaeobotanical data of the Baltic states region

Liva Trasune ¹, J. Sakari Salonen ¹, Minna Väiliranta ², Emilia Tuomaala ², Normunds Stivrins ³, Leeli Amon ⁴

¹ Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

² Ecosystems and Environment Research Programme, University of Helsinki, Helsinki, Finland

³ Department of Geography, University of Latvia, Riga, Latvia

⁴ Department of Geology, Tallinn University of Technology, Tallinn, Estonia

EC3-15

Holocene precipitation seasonality along a climatic gradient from western Spitsbergen to Nordaustlandet, Svalbard

Sofia E. Kjellman ¹, Elizabeth K. Thomas ², Anders Schomacker ¹, Wesley R. Farnsworth ³, Owen C. Cowling ², Lis Allaart ⁴, Skafti Brynjólfsson ⁵

¹ Department of Geosciences, UiT The Arctic University of Norway, Tromsø, Norway

² Department of Geology, University at Buffalo, Buffalo, NY, United States

³ Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

⁴ Department of Biology - Microbiology, Aarhus University, Aarhus, Denmark

⁵ Icelandic Institute of Natural History, Akureyri, Iceland

14:00 - 15:15 **IM1-2-3 - Igneous and Metamorphic Geochemistry** VHV-023 /

- Convener: Tobias Björn Weisenberger, University of Iceland
- Convener: Sæmundur Ari Halldórsson, University of Iceland
- Convener: Kristján Jónasson, Icelandic Institute of Natural History
- Convener: Guðmundur H. Guðfinnsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Olgeir Sigmarsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Enikő Bali, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland
- Convener: Bjarni Gautason, ISOR

IM1-11

Asymmetric distribution of enriched components in the Iceland mantle

Eemu Ranta ¹, Sæmundur Ari Halldórsson ¹, Vesa Nykänen ², Riina Kaikkonen ³, Guðmundur H. Guðfinnsson ¹, Peter H. Barry ⁴, Hugh O'Brien ⁵, Maja Bar Rasmussen ⁶, Jóhann Gunnarsson Robin ¹, Edward W. Marshall ¹, Andri Stefánsson ¹, Enikő Bali ¹, Matthew G. Jackson ⁷, Karl Grönvold ¹

¹ Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

² Geological Survey of Finland, Rovaniemi, Finland

³ Oulu Mining School, University of Oulu, Oulu, Finland

⁴ Woods Hole Oceanographic Institution, Woods Hole, United States

⁵ Geological Survey of Finland, Espoo, Finland

⁶ Dept. of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark

⁷ Department of Earth Science, University of California, Santa Barbara, United States

IM1-12

Li and Pb isotopic constrains on LCT pegmatites petrogenesis in Kaustinen area, Finland

Yann Lahaye ¹, Sari Lukkari ², Pentti Grönholm ³, Joonas Kurtti ³

¹ Geological Survey of Finland, Espoo, Finland

² Geological Survey of Finland, ESPOO, Finland

³ Keliber Technology Oy, Kaustinen, Finland

IM1-13

Non-dissolved mantle zircons record hyper rapid translithospheric ascent of lamprophyres

Lars Eivind Augland ¹ Ó Anders Mattias Lundmark ¹, Maiken Rian ¹, Dougal Jerram ²

¹ University of Oslo/ Department of Geosciences, Oslo, Norway

² DougalEarth Ltd., Solihull, United Kingdom

IM1-14

Rapid source shifting of a deep magmatic system revealed by the Fagradalsfjall eruption, Iceland

Sæmundur Ari Halldórsson ¹, Edward Marshall ¹, Alberto Caracciolo ¹, Simon Matthews ¹, Enikő Bali ¹, Maja Rasmussen ¹, Eemu Ranta ¹, Jóhann Gunnarsson Robin ¹, Guðmundur Guðfinnsson ¹, Olgeir Sigmarsson ¹, John MacLennan ², Matthew Jackson ³, Martin Whitehouse ⁴, Heejin Jeon ⁴, Quinten Van der Meer ¹, Geoffrey Mibei ¹, Maarit Kalliokoski ¹, Maria Repczynska ¹, Rebekka Rúnarsdóttir ¹, Gylfi Sigurðsson ¹, Melissa Pfeffer ⁵, Samuel Scott ¹, Rikey Kjartansdóttir ¹, Barbara Kleine ¹, Clive Oppenheimer ⁶,

¹ Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

² Department of Earth Sciences, University of Cambridge, Cambridge, United Kingdom

³ Department of Earth Science, University of California Santa Barbara, Santa Barbara, United States

⁴ Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

⁵ Icelandic Meteorological Office, Reykjavik, Iceland, Reykjavik, Iceland

⁶ Department of Geography, University of Cambridge, Cambridge, United Kingdom

⁷ Dipartimento di Scienze della Terra e del Mare, Università di Palermo, Palermo, Italy

⁸ COMET, School of Earth and Environment, University of Leeds, Leeds, United Kingdom

⁹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Catania, Italy

IM1-15

Phenocrysts through time: what can we learn at a high-speed glance

Andrew Menzies ¹, Alan Butcher ², Ester Jolis ², Sari Lukkari ², Peter Sorjonen-Ward ², Osvaldo González-Maurel ³

¹ Bruker Nano Analytics GmbH, Berlin, Germany

² Geological Survey of Finland, Helsinki, Finland

³ University of Cape Town, Cape Town, South Africa

14:00 - 15:15 **EC1 - Environment and climate** O-101 /

- Convener: Halldór Björnsson, Icelandic Met Office

EC1-01

Recent climate variations in Iceland

Halldór Björnsson, Kristín Ólafsdóttir, Trausti Jonsson

Icelandic Meteorological Office, Reykjavik, Iceland

EC1-02

The role of the ocean circulation in recent climate variability in Iceland

Andreas Macrandar ², Sólveig R. Ólafsdóttir ²

¹ Marine and Freshwater Research Institute and University of Akureyri, Akureyri, Akureyri, Iceland

² Marine and Freshwater Research Institute, Reykjavik, Iceland

EC1-03

Environmental impact from acid sulfate soils in a future climate

Christian Öhrling ¹, Gustav Sohlenius ¹, Julia Zábori ², Marina Becher ¹

¹ Geological Survey of Sweden, Gothenburg, Sweden

² Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

EC1-04

Evolution of a clastic source-to-sink system across the Permian-Triassic transition: Petrography, sediment volumes and provenance of the Røye and Havert formations, Barents Sea, Norway

Melanie Kling ¹, Hallgeir Sirevaag ², Christian Haug Eide ²

¹ Universitetet i Bergen, Bergen, Norway

² Universitetet i Bergen, Norway, Bergen, Norway

EC1-05

Role of climate and human impact on fire and vegetation dynamics in one of the oldest protected forests in Europe

Niina Kuosmanen, Tuomas Aakala, Heikki Seppä

Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

14:30 - 15:15 **RS2 - Remote Sensing in geosciences** Hall 2 /

- Convener: Ragnar Prastarson, Icelandic Met Office

- Convener: Vincent Drouin, University of Iceland

- Convener: Sydney Gunnarson, Svarmi

RS2-01

The Copernicus EGMS ground motion map of Iceland

John Dehls ¹, Yngvar Larsen ², Petar Marinkovic ³, Tom Rune Lauknes ², Daniel Stødle ², Gökhan Alsan ¹, Marie Bredal ¹, Ambrus Kenyeres ⁴

¹ Geological Survey of Norway, Trondheim, Norway

² NORCE, Tromsø, Norway

³ PPO.labs, The Hague, Netherlands

⁴ LTK Satellite Geodetic Observatory, Budapest, Hungary

RS2-02

15 years of InSAR monitoring of the unstable rock slope Jettan in northern Norway

Marie Bergvik Bredal ¹, Tom Rune Lauknes ², Line Rouyet ², Ivanna Penna ¹, Louise Vick ³, Ingrid Skrede ⁴, Steffen Bergh ³

¹ Geological Survey of Norway (NGU), Trondheim, Norway

² NORCE Norwegian Research Centre AS, Tromsø, Norway

³ UiT The Arctic University of Norway, Tromsø, Norway

⁴ The Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway

RS2-03

Mapping and classifying moving slopes around Iceland using remote sensing

Vincent Drouin, Jón Kristinn Helgason, Magni Hreinn Jónsson

Veðurstofa Íslands, Reykjavík, Iceland

15:15 - 15:30	REFRESHMENTS – in the Foyer	
15:30 - 16:45	RS2 - Remote Sensing in geosciences	Hall 2 /

- Convener: Ragnar Prastarson, Icelandic Met Office

- Convener: Vincent Drouin, University of Iceland

- Convener: Sydney Gunnarson, Svarmi

RS2-04

Monitoring and forecasting quick clay slides, using ground-based InSAR radar, at Gjerdrum, Norway

Ingrid Skrede, Lene Kristensen, Ellen E. D. Haugen

The Norwegian Water Resources and Energy Directorate, Oslo, Norway

RS2-05

Near real-time photogrammetric monitoring during the 2021 Fagradalsfjall eruption: Results on volume, effusion rate, and lava transport

Gro B. M. Pedersen¹, Joaquin M. C. Belart¹, Birgir Vilhelm Óskarsson², Magnús Tumi Gudmundsson¹, Nils Gies², Thórdís Högnadóttir¹, Ásta Rut Hjartardóttir¹, Virginie Pinel³, Etienne Berthier⁴, Tobias Dürig¹, Hannah Iona Reynolds¹, Christopher W. Hamilton⁵, Guðmundur Valsson⁶, Páll Einarsson¹, Daniel Ben-Yehosua⁹¹, Andri Gunnarsson⁷, Björn Oddsson⁸

¹ *University of Iceland, Reykjavík, Iceland*

² *Icelandic Institute of Natural History, Reykjavík, Iceland*

³ *Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, Grenoble, France*

⁴ *LEGOS CNRS, University of Toulouse, Toulouse, France*

⁵ *The University of Arizona, Arizona, Iceland*

⁶ *National Land Survey of Iceland, Akranes, Iceland*

⁷ *The National Power Company of Iceland, Reykjavík, Iceland*

⁸ *The Department of Civil Protection and Emergency Management, Reykjavík, Iceland*

RS2-06

The Multi-Pairwise Image Correlation (MPIC-OPT) processing chain, an end-to-end online service for surface motion monitoring using optical imagery

Floriane Provost¹, David Michea², Jean-Philippe Malet¹, Enguerran Boissier³, Elisabeth Pointal⁴, André Stumpf⁵, Fabrizio Pacini³, Marie-Pierre Doin⁶, Pascal Lacroix⁶, Catherine Proy⁷, Philippe Bally⁸

¹ *EOST/ITES - CNRS/Université de Strasbourg, Strasbourg, France*

² *Application Satellite Survey, A2S - CNRS/Université de Strasbourg, Strasbourg, France*

³ *Terradue, Roma, Italy*

⁴ *ForM@Ter - Pôle de Données Terre Solide, Institut de Physique du Globe de Paris, Paris, France*

⁵ *GAF, Munich, Germany*

⁶ *Institut des Sciences de la Terre, CNRS UMR 5275 - Université Grenoble-Alpes, Grenoble, France*

⁷ *CNES, Toulouse, France*

⁸ *ESA/ESRIN, Frascati, Italy*

RS2-07

The jökulhlaup from the subglacial lake Grímsvötn, beneath Vatnajökull ice cap, in November—December 2021, revealing new insight in to slowly rising jökulhlaups

Eyjólfur Magnússon¹, Vincent Drouin², Finnur Pálsson¹, Krista Hannesdóttir¹, Joaquín M. C. Belart³, Gunnar Sigurðsson², Jan Wuite⁴, Tómas Jóhannesson², Benedikt G. Ófeigsson², Thomas Nagler⁴, Magnús T. Gudmundsson¹, Thórdís Högnadóttir¹, Michelle Parks², Matthew J. Roberts², Etienne Berthier⁵

¹ *Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland*

² *Icelandic Meteorological Office, Reykjavík, Iceland*

³ *National Land Survey of Iceland, Akranes, Iceland*

⁴ *ENVEO IT GmbH, Innsbruck, Austria*

⁵ *LEGOS, Université de Toulouse, CNRS, Toulouse, France*

15:30 - 17:00	EC3 - Environment and climate	O-201 /
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- Convener: Anna Hughes, University of Manchester

- Convener: Monica Winsborrow, The Arctic University of Norway - UiT

EC3-16

The character of the drainage of the Baltic Ice Lake at the outlet: a conceptual model

Mark D. Johnson¹, Christian Öhrling²

¹ *University of Gothenburg, Olofstorp, Sweden*

² *Geological Survey of Sweden, Gothenburg, Sweden*

EC3-17

Timing of deglaciation and ice-dammed lakes in Jämtland, central Swedish mountains

Carl Regnéll¹, Robin Blomdin², Bradley W. Goodfellow³, Sarah L. Greenwood¹, Richard Gyllencreutz¹, Henrik Mikko³, Gustaf Peterson Becher³, Gunnel Ransed³, Joachim Regnéll⁴, Colby Smith³, Christian Öhring³

¹ Department of Geological Sciences, Stockholm University, Stockholm, Sweden

² Department of Geography, Norwegian University of Science and Technology, Trondheim, Norway

³ Dept. of Quaternary Geology for Physical Planning, Geological Survey of Sweden, Uppsala, Sweden

⁴ Department of Environmental Science, Kristianstad University, Kristianstad, Sweden

EC3-18

Lateglacial-Early Holocene deglaciation chronology and ice sheet-dynamics along the Helgeland coast, Northern Norway

Fredrik Høgaas, Lars Olsen, Lina Gislefoss, Martin Klug, Maria Huse Kvam, Mikis Boeckel

Geological Survey of Norway, Trondheim, Norway

EC3-19

A 'new' ice margin in central Sweden

Gustaf Peterson Becher¹, Henrik Mikko¹, Colby A. Smith¹, Christian Öhring², Gunnel Ransed¹, Bradley W. Goodfellow³

¹ Geological Survey of Sweden, Uppsala, Sweden

² Geological Survey of Sweden, Gothenburg, Sweden

³ Geological Survey of Sweden, Lund, Sweden

EC3-20

Late Quaternary glacial and environmental history of the Sjuøyane archipelago, Svalbard

Anders Schomacker¹, Helena Alexanderson², Wesley R. Farnsworth³, Mark F. A. Furze⁴, Sofia E. Kjellman¹, Nina Kirchner⁵, Riko Noormets⁴

¹ Department of Geosciences, UiT The Arctic University of Norway, Tromsø, Norway

² Department of Geology, Lund University, Lund, Sweden

³ GLOBE Institute, University of Copenhagen, Copenhagen, Denmark

⁴ Department of Arctic Geology, The University Centre in Svalbard (UNIS), Longyearbyen, Norway

⁵ Department of Physical Geography, Stockholm University, Stockholm, Sweden

15:30 - 16:00 **EC1 - Environment and climate** O-101 /

- Convener: Halldór Björnsson, Icelandic Met Office

EC1-06

Complex responses of tundra vegetation to climate change: implication for ecosystem climate feedback consequences

Ingibjörg S Jónsdóttir

University of Iceland, Reykjavik, Iceland

EC1-07

Mosses and lichens emit considerable amounts of volatile organic compounds to the atmosphere

Ingvild Ryde¹, Cleo L. Davie-Martin², Tao Li³, Mads P. Naursgaard², Riikka Rinnan²

¹ Faculty of Life and Environmental Sciences, University of Iceland, Reykjavik, Iceland

² Terrestrial Ecology Section, Department of Biology, University of Copenhagen, Copenhagen, Denmark

³ Key Laboratory for Bio-resource and Eco-environment of Ministry of Education, Co, Chengdu, China

15:30 - 16:45 **IM1-2-3 - Igneous and Metamorphic Geochemistry** VHV-023 /

- Convener: Tobias Björn Weisenberger, University of Iceland

- Convener: Kristján Jónasson, Icelandic Institute of Natural History

- Convener: Sæmundur Ari Halldórsson, University of Iceland

- Convener: Guðmundur H. Guðfinnsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Olgeir Sigmarsson, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Enikő Bali, Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

- Convener: Bjarni Gautason, ISOR

IM1-16

Metal transport in volcanic gases from Vulcano, Italy

Celine Mandon¹, Andri Stefánsson²

¹ Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

² Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

IM1-17

Small length scale H₂O heterogeneity in the Icelandic mantle

Simon Matthews ¹, Oliver Shorttle ², Sæmundur Ari Halldórsson ¹, Frances Jenner ³, Eemu Ranta ¹, John Maclennan ², Bramley Murton ⁴, John F. Rudge ²

¹ Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

² Department of Earth Sciences, University of Cambridge, Cambridge, United Kingdom

³ School of Environment, Earth and Ecosystem Sciences, The Open University, Milton Keynes, United Kingdom

⁴ National Oceanographic Centre, Southampton, United Kingdom

IM1-18

Oxygen isotope analyses in melt inclusions as an archive of crustal contamination processes underneath Bárðarbunga volcano

Alberto Caracciolo ¹, Saemundur Halldórsson ¹, Eniko Bali ¹, Edward Marshall ¹, Heejin Jeon ², Martin Whitehouse ², Jaime Barnes ³, Guðmundur Guðfinnsson ¹, Maren Kahl ⁴, Margaret Hartley ⁵

¹ NordVulk, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

² Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

³ Department of Geological Sciences, University of Texas, Austin, Texas, United States

⁴ Institut für Geowissenschaften, Universität Heidelberg, Heidelberg, Germany

⁵ Department of Earth and Environmental Sciences, University of Manchester, Manchester, United Kingdom

IM1-19

Mineral-scale evidence for magma-evaporite interaction in basaltic sills from the Siberian Traps (Tunguska basin, Russia)

Sara Callegaro ¹, Henrik H. Svensen ¹, Thea Hatlen Heimdal ¹, Sverre Planke ², Dougal A. Jerram ³, Alexander G. Polozov ⁴, Frances M. Deegan ⁵, Manfredo Capriolo ¹

¹ Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

² Volcanic Basin Petroleum Research (VBPR), Oslo, Norway

³ DougalEARTH Ltd., Solihull, United Kingdom

⁴ Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry o, Moscow, Russia

⁵ Uppsala University, Uppsala, Sweden

IM1-20

Chemical evolution of the gem-beryl bearing Luumäki pegmatite in SE Finland

Radoslaw Markus Michallik

Geological Survey of Finland, Espoo, Finland

15:30 - 16:30 **UV3 - Understanding volcanoes** Hall 1 /

- Convener: Lars Ottemöller, University of Bergen

- Convener: Esther Ruth Guðmundsdóttir, Institute of Earth Sciences, University of Iceland

UV3-01

Explosive hydromagmatic eruptions during the emplacement of the North Atlantic Igneous Province: A story of volcanic ash

Ella Wulfsberg Stokke ¹, Emma J. Liu ², Morgan T. Jones ³

¹ Centre for Earth Evolution and Dynamics, University of Oslo, OSLO, Norway

² Department of Earth Sciences, University College London, London, United Kingdom

³ Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

UV3-02

IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism and Paleoclimate Implications

Sverre Planke ¹, Christian Berndt ², Ritske Huisman ³, Stefan Buenz ⁴, Jan Inge Faleide ¹, Henrik H. Svensen ¹, Reidun Myklebust ⁵, Carlos A. Alvarez Zarikian ⁶, Scientific Party The Shipboard ⁶

¹ University of Oslo, Oslo, Norway

² GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

³ University of Bergen, Bergen, Norway

⁴ UiT The Arctic University of Norway, Tromsø, Norway

⁵ TGS, Oslo, Norway

⁶ International Ocean Discovery Program (IODP), College Station, United States

UV3-03

Core-log-seismic integration of a volcano-sedimentary sequence penetrated at the Kolga High Seaward Dipping Reflectors, mid-Norway: initial results from IODP Expedition 396

John Millett ¹, Sverre Planke ², Christian Berndt ³, Carlos Alvarez Zarikian ⁴, Peter Betlem ⁵, Irina Filina ⁶, Geoffroy Mohn ⁷, Sarah Lambart ⁸, Morgan Jones ⁹, Sayantani Chatterjee ¹⁰, Dougal Jerram ⁹, Ben Manton ², Dwarika Maharjan ², David Jolley ¹, Reidun Myklebust ¹¹, EXP396 Scientists IODP ⁴

¹ *University of Aberdeen, Aberdeen, United Kingdom*

² *Volcanic Basin Energy Research AS, Oslo, Norway*

³ *Geomar, Kiel, Germany*

⁴ *International Ocean Discovery Program, College Station, United States*

⁵ *The University Centre in Svalbard, Longyearbyen, Norway*

⁶ *University of Nebraska, Lincoln, United States*

⁷ *CY Cergy Paris Université, Paris, France*

⁸ *University of Utah, Salt Lake City, United States*

⁹ *Oslo University, Oslo, Norway*

¹⁰ *Niigata University, Niigata, Japan*

¹¹ *TGS, Oslo, Norway*

UV3-04

Preliminary results of the PORO-CLIM seismic experiment: Constraining NAIP magmatic productivity through time.

John R. Hopper ¹, Stephen M. Jones ², Brian O'Reilly ³, Thomas Funck ¹, Hazel Knight ², David Rooij ⁴, Aggeliki Georgiopoulou ⁵

¹ *GEUS, Copenhagen, Denmark*

² *U. of Birmingham, Birmingham, United Kingdom*

³ *DIAS, Dublin, Ireland*

⁴ *U. of Ghent, Ghent, Belgium*

⁵ *U. of Brighton, Brighton, United Kingdom*

Conference Excursions

Day tour to the pristine Reykjanes peninsula, 10th of May

This approximately 10-hour long round-trip across the Reykjanes Peninsula highlights the most recent volcanic and tectonic events and volcanic systems of Reykjanes Peninsula. An introduction to SWIceland's unique tectonic setting and a visit to the 2021 Fagradalsfjall eruption site.

Guides:

Ásta Rut Hjartardóttir, University of Iceland

Anett Blischke, ÍSOR

Gro B.M. Pedersen, University of Iceland

Gylfi Páll Hersir

Páll Einarsson

Stops.

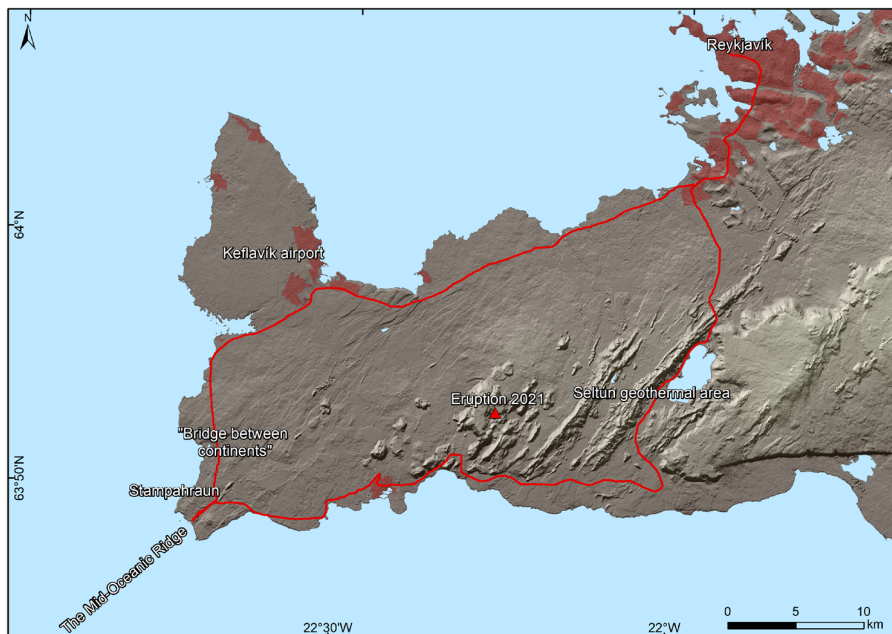
Reykjavik: Quick on-the-bus introduction to the geology of Reykjanes, plate boundary, and geothermal utilization.

Seltún: Visit to the Krýsuvík geothermal field Seltún, as a part of the Holocene Krýsuvík-Trölladyngja volcanic system.

U. Hike to the Fagradalsfjall volcanic system and 2021 eruption site. The walk duration about 4 hours or 8 km long with an elevation gain of about 250 m. We will see the newest lava in Iceland, eruptive vents that intersected the Pleistocene sub-glacial volcanic system.

Stampahraun: and the onset of the mid-oceanic ridge. This stop leads us to the tip of the southwestern most part of the Reykjanes peninsula, where the mid-oceanic ridge rises out of the sea with its fissure dominated volcanic system, lava flows and shield volcanoes. The latest activity was in 1210-1240 CE called the Reykjanes Fires, the Younger Stampahraun was formed in the beginning of that Fires, most probably in 1211 CE.

„Bridge between continents“. Visit to the plate boundary and a brief stop at the „Bridge Between Continents“, before heading back to Reykjavik. Please dress according to the weather. The day trip includes a short hike. Please come with good shoes.



Late Glacial glaciotectonics and marine limit shorelines of the Lower Borgarfjörður region (The NORDQUA excursion)

Guides:

Ívar Örn Benediktsson, University of Iceland

Þorbjörg Sigfúsdóttir, Iceland Met Office

The Lower Borgarfjörður region in West Iceland has been key for understanding the deglaciation of Iceland and the collapse of the Iceland Ice Sheet in Bølling times, as well as for deciphering Younger Dryas and Early Holocene (Preboreal) glacier dynamics. The excursion will visit marine limit shorelines and deltas in Akrafjall and Skorradalur, the spectacular Skorholtsmelar end-moraine complex, and the glaciotectonics of the Melabakkar-Ásbakkar coastal cliffs.



The Dynamic Southcoast of Iceland, 14-16th of May

Spectacular three-day trip along Iceland's Southcoast which highlights a rift valley, glaciers, presentday glacier landscapes, lavas, volcanoes, jökulhlaups and much, much more of geological interest.

Guides:

Daði Þorbjörnsson, ÍSOR

Þorsteinn Sæmundsson, University of Iceland.

Day 1

Reykjavík. Quick on-the-bus introduction to the geology of Reykjavík, including Quaternary geology and geothermal utilization.

Rauðhólar. Inside and outside view of pseudo-craters close to Reykjavík

Nesjavellir. Central volcano and a geothermal power plant

Thingvellir. Great example of continental drift, rifting tectonics and rift valley.

Drumbabót. Ancient forest which was destroyed in a flood ("jökulhlaup") from the ice-capped volcano Katla in 822 AD.

Steinshótsjökull. Short hike at the foothills of the world famous Eyjafjallajökull volcano where we explore debris and flow path of a glacial lake outburst flood caused by a rockslide in 1967.

Thórsörk (Húsadalur). We stay for the night at this beautiful place surrounded by glaciers and glacial rivers (which we will drive into on our way to the hut).

Day 2

Landeyjahöfn. Interesting harbour-design on a high-energy sand beach.

Vestmannaeyjar. Short visit to the Vestmannaeyjar islands where we will see the impacts of the volcanic eruption in 1973 on the village.

Reynisfjara. Columnar basalt and beautiful sand beach. Popular tourist attraction.

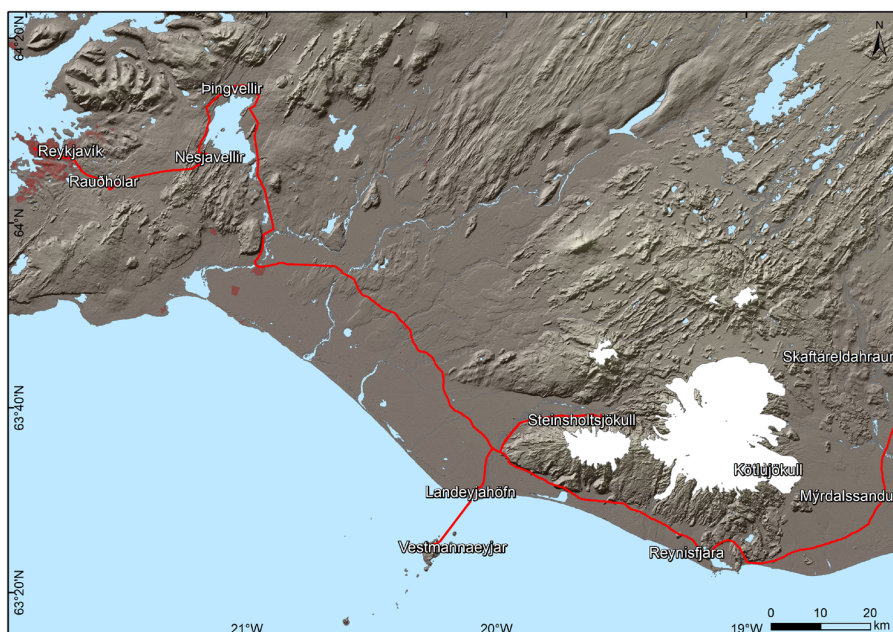
Vík. We will stay for the night in or close to the small village of Vík.

Day 3

Mýrdalssandur and Kötlujökull. Black sands formed by floods from the ice capped Katla Volcano, close encounter of the Kötlujökull glacier which is the outlet of most of the floods and pseudo craters. Skaftáreldahraun. View of the moss covered

Skaftáreldahraun which was formed in a devastating volcanic eruption in 1783-1784.

Reykjavík. In the afternoon we will return to Reykjavík and aim at be back around dinner time.



Plenary Abstracts

PL-1

The unrest on the Reykjanes Peninsula and eruption in Fagradalsfjall 2021

Kristín Jónsdóttir

Icelandic Meteorological Office, Reykjavík, Iceland

The Reykjanes Peninsula is an oblique transform zone marked with adjacent volcanic systems intersected by strike-slip earthquake faults. For the first time since modern instrumentation was installed (last 30 years) a clear, rapid uplift signal was observed on the peninsula in January 2020, interpreted as a magmatic intrusion. This event was followed by several events of further unrest. Between January to July 2020 three intrusions were detected in the vicinity of Mt. Þorbjörn and from July to August 2020 another near Krýsvík, all accompanied by increased seismic activity.

On the 24th of February 2021, a M5.7 earthquake was recorded NE of Fagradalsfjall and a dyke intrusion was detected beneath Fagradalsfjall a few days later. The intrusion continued until mid-March by which time the estimated length of the dyke was 9 km and the associated volume change 34 million cubic meters. This intrusive event triggered an unprecedented, roughly three-weeks long earthquake sequence, which extended over an area of some 350 km² and counted over 50.000 earthquakes, of which 600 were above M3. It culminated in an effusive lava forming eruption which commenced on the 19th of March 2021 at 20.35 UTC. Lava was initially erupted from a ~100 m long fissure which opened in Geldingadalur valley in Fagradalsfjall. In the final days before the onset of the eruption, the seismicity as well as all deformation signals had dramatically decreased, at that time unexpected observables shortly before eruption onset.

This was the first eruption on the Reykjanes Peninsula in 800 years, and the first one in Fagradalsfjall in over 6000 years. The eruption was characterized by lava fountaining and the extrusion of basaltic lava flows, with an initial effusion rate of ~5 m³/s. The effusive eruption was accompanied by the release of magmatic gases. Activity remained stable until the 5th of April when two new fissures opened approximately 500 m north of the initial erupting craters. In total six fissures opened between the 5th and 13th of April. After the 27th of April, lava was erupted from one main vent (the fifth opening in temporal order) which in turn formed a crater that reaches ~120 m over the pre-eruption landscape. Lava was last seen spewing from the vent on September 18th.

In total the eruption which started in the valley of Geldingadalir inside the Fagradalsfjall mountain massive produced a lava field covering about 4.9 km² and created a total SO₂ output of 0.9 Mt. The eruption progressed through different phases characterized by different emission sources, eruptive style, intensities, and associated hazards. However, in terms of intensity the eruption was small and arelatively easily accessible eruption, where the main hazards were in the near field to the thousands of visitors which had to be mindful of volcanic gasses, lava outbreaks and occasional minor lava bombs. By joining forces in monitoring and utilizing the available expertise in different institutions, the Civil Protection, Icelandic Institute of Natural History, Institute of Earth Sciences of the University of Iceland, Iceland Geosurvey, the Environmental Agency, and the Icelandic Meteorological Office, which runs the 24/7 monitoring services, a good overview was established of the evolution of the eruption and its hazards.

PL-2

Deep Sea Minerals – a future mineral reserve or just a geological curiosity waiting to be obducted?

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Introduction

Deep-marine mineral deposits are found outside the continental slope (Ecorys 2014) and are results of geological processes close to the deep ocean floor. They are typically divided into the following three types: Polymetallic Manganese Nodules (PMN), Cobalt-Rich Manganese Crusts (CRC), and Seafloor Massive Sulfides (SMS) (Hein et al. 2013).

PMNs are formed on the deep oceanic plains, where the elements precipitate from the oceanic water onto some nucleus. CRCs form similarly to PMNs but are deposited on sediment free seamounts (Glasby et al. 2015). PMN and CRC deposits contain interesting and varying grades of e.g., Ni, Cu, Ti, Co, Fe, Mn and REEs. SMS deposits form on the boundary between oceanic plates, by precipitation of sulfide minerals from mineral-laden hydrothermal solutions (M. D. Hannington et al. 1998). SMS deposits contain typically potential economic grades of Cu, Zn, Ag, Au, and in some cases Pb, and Co.

The green transition towards an energy production less dependent on fossil fuels and an increased portion of e-mobility, drives the future demand for these elements, typically found in Deep-marine mineral deposits (Månberger and Stenqvist 2018; Teske 2019). Future supply can potentially be served by urban mining and recycling, reprocessing of abandon tailing dams and waste rock deposits, and both onshore and offshore mining. The question we are asking in this regard is what role deep sea mining can play in the future supply, or the raw material mix. This requires a holistic and interdisciplinary mineral resource management approach.

Mineral Resources and Reserves

Estimations have shown that there is a significant resource potential on the deep ocean floor (Cathles 2011; Ellefmo et al. 2019; M. Hannington et al. 2011, 2017; Mizell et al. 2022; Singer 2014; Yeo et al. 2018). Following the resource classification scheme of USGS (USGS 2022), these estimations quantify however, just the amount of undiscovered and hence hypothetical or perhaps even speculative resources. More exploration is needed to understand the real geological characteristics that enables definition and classification of mineral resources and reserves, the mineable part of the resource. Assessing the potential for extraction and hence, the potential definition of reserves is a multi-objective challenge that consider geological, technical, legal, social, environmental and economic factors (PERC 2021). Recently, more emphasize has been placed on factors related to the Environment, the Society and Governance (ESGs).

Deep-marine mineralizations are located at great water depths, from nearly 1000 meter down to roughly 6000 meters. A potential future mining site will be far from shore with associated costs for crew management and could be facing challenging weather conditions, including rough sea states, icing from sea spray and sea ice.

Deep Sea Mining systems

Deep-marine mineral deposits will potentially be mined using crushing- or collection tools and stockpiled on the seafloor before lifted to sea-surface using a vertical transportation system. Further, the ore must be dewatered and stored on a production support vessel (PSV). From the PSV, the ore must be horizontally (ship-to-ship) transported to a bulk carrier for transport to onshore ore processing, smelting, and refining.

The preferred mining system is dependent on the ecosystem characteristics, ore geometry and quality variations, water depths and distance to shore, to name a few factors important for the mining setup. Two major groups of mining methods can be described as vertical and horizontal mining methods. Horizontal methods would be preferred on laterally extensive deposits. A type of horizontal mining in benches was planned for the Solwara 1 deposit (Jankowski et al. 2010). Vertical mining methods (Spagnoli et al. 2016) based on drilling, trenching, or cutting technologies, would instinctively be used on deposits with a significant vertical extension, like the TAG site (Grant et al. 2018). A vertical transport system (VTS) would schematically include a lift system (batch transport) or pumps and a riser (in case of slurry transport), a flexible jumper, infrastructure for communication, and return pipes for transporting the return water back to the ocean floor. Different concepts have been developed for VTS and their specificities are dependent on deposit type and the size and lateral extent of the deposit. Available mining technologies and -systems are in a conceptual stage, but pilot mining and new concepts emerge at high speed. Future developments will lean on technologies developed for other marine industries, like offshore oil and gas production.

Marine Mineral Resource Management

Whether a mineralization on the deep ocean floor ever can be mined is a function of a great range of factors and variables, ranging from geology to social sciences and geopolitics. These factors are very uncertain. Although a significant mineral resource potential, there is a lack of knowledge regarding specific tonnage and characteristics of the potential deposits. Details about the ecosystems and the actual impact on them from some unknown mining system is uncertain. The future framework conditions will influence the profitability, and the management of deep-sea mining projects are also uncertain.

Given the future likely increase in mineral and metal demand, the only way forward is interdisciplinary cooperation, where data, information and uncertainties are shared and communicated across discipline boundaries. Only then responsible mining for a sustainable development can be achieved.

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Glaciers in Iceland in the past, present and future

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Glaciers in Iceland are sensitive to changes in ocean and atmosphere temperatures in the North Atlantic region. Their response in terms of changes in volume can be used to infer past climate change and their future is very much dependent on the future warming, which in turn depends on the emission of greenhouse gases into the atmosphere. Glacier mass loss is observed everywhere in the world as the glaciers are adjusting to warmer climate. The volume of glaciers in Iceland (83,400 km³ in 2019) corresponds to about 9 mm of potential global sea level rise. If the ice would be evenly distributed, it would cover the island with approximately 35 m thick ice layer. The water storage in the glaciers is about 20 times the annual precipitation, and the mass turnover is large due to the maritime nature of the climate in Iceland. A record of mass change of Icelandic glaciers since the end of the 19th century i.e. the end of the Little Ice Age (LIA) in Iceland and projections for the future evolution are presented. The mass loss of -540 ± 130 Gt (-4.2 ± 1.0 Gt a⁻¹ on average) during the study period (1890/91 to 2018/19) is observed. This mass loss corresponds to 1.50 ± 0.36 mm sea level equivalent or $16 \pm 4\%$ of mass stored in Icelandic glaciers around 1890. Almost half of the total mass loss occurred in 1994/95 to 2018/19, or -240 ± 20 Gt (-9.6 ± 0.8 Gt a⁻¹ on average), with most rapid loss in the period 1994/95 to 2009/10 (mass change rate -11.6 ± 0.8 Gt a⁻¹). The future of the glaciers in Iceland depends on how much the atmosphere will warm. Vatnajökull, the largest ice cap in Iceland, may completely disappear in the coming 2-300 years if emissions continue at present rate, but if we follow the Paris agreement, and keep warming below 2°C, 30-60% of the ice cap may survive.

How is the threat of rock slope failure connected to climate change? – A perspective from Norway

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With ten known rock slope failures in the 20th century resulting in rock collapses / rock avalanches in Norway certainly the country in Europe with the highest number of such event. In addition is the mountain setting in Norway different to most Europe with fjords penetrating deep into the mountains. Therefore, seven of the rock slope failures in the 20th century were related to displacement waves s. Although, remote sensing data in the 20th century have been far less developed than they are today do pre-failure observation where available suggest that failure was preceded by decades of rock slope deformation or years of intensified rock fall activity. Related to three of these events 175 persons lost their life and houses along fjords and fjord lakes got destroyed in displacement waves (Furseth, 2006). In an additional event further eight farms got flooded in a lake that was formed by the impoundment of the valley by the rock mass, but no life losses occurred. Seven of the failures occurred from Ramnefjellet above Loen Lake, while the others at different sites in W and N Norway. None of the events was seismically triggered. However, also none of them could be

related to an especially strong weather event and the different failure events occurred in all seasons.

In a post glacial time perspective will it be impossible to ever get the full inventory of rock slope failure deposits in Norway, as multiple events occurred in steep sloped fjords where no deposits are left ashore and older postglacial deposits are often covered by subsequent events or by the sedimentation of fines in the fjords. An outstanding data set exists for the Storfjord area in western Norway for which both high resolution and seismic data exists. In this fjord region alone could 108 rock slope failure deposits be recognized. Based on deposit stratigraphy, direct dating with cosmogenic nuclide (CN) of scarp areas or deposits and dating of a sediment core could the rock slope failure stratigraphy be established. This indicates that largest events and highest frequency of events occurred in the first two millennia after deglaciation followed by a relatively constant activity of about five events per millennia throughout the Holocene that continues today (Hermanns and Longva, 2012; Böhme et al., 2015). In addition to that, was a large dataset of CN data of rock slope failure deposits that occur in valleys that have rock slope deformations today compiled from N, W and S Norway, most of them not published yet (Hermanns et al., 2017). The observed temporal trend is identical to the above data set with the largest number of deposits in the first two millennia following deglaciation. In addition, similar to the Loen site are there several mountains that experienced multiple failures in post glacial time and a temporal clustering was also documented for example for rock slope failures from Mannen, one of Norway's most active deforming rock slopes (Hilger et al., 2018).

The initiation of deformation and sliding history could so far only be defined for a dozen of deforming rock slopes with CN exposure dating of sliding surfaces (Hermanns et al., 2012; Hermanns et al. 2013, Böhme et al., 2019; Hilger et al., 2021). Of those for only two sites the deformation started prior to the last glacial maximum. Similar to the deposits, there is a large cluster of sites that started deforming in the first millennia following deglaciation. A further cluster of sites exists that started deforming in relation to the thermal maximum in the Holocene. All of the sites of the second cluster are in environments close to the permafrost boundary today. One of the sites becoming active following deglaciation is Reinbenkan/ Kruvnnut on the east side of Porsangerfjorden, northernmost Norway. CN dating suggest that this site started moving 12 kyr ago and thus 3 kyr after deglaciation. Paleo slip rates on the long-time average are nearly identical to slip rates measured today. However, during the thermal maximum paleo slip rates have been 50% higher than this average. First temporal high resolution InSAR data of corner reflectors suggest that this acceleration could be related to weather conditions over the annual cycle. Today is this site only moving from June to the end of September in which the 11 mm yearly displacement takes place.

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PL-5

Carbfix: CO₂ mineral storage in basaltic rocks

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Carbon capture and storage (CCS) plays a fundamental role in achieving the goals of the Paris agreement to limit global warming to 1.5-2°C [1]: It is estimated that over 100 Gigatonnes of Carbon dioxide (CO₂) must be captured and safely stored by 2060 [2].

To date, the most common approach of CCS is to inject pure CO₂ into sedimentary basins, where the injected CO₂ is trapped in porous rocks below an impermeable cap rock, preventing it from migrating to the surface. Over time, the CO₂ dissolves into the formation water, and reacts to form stable carbonate minerals, referred to as mineral trapping. As the injected CO₂ progresses from the gaseous to aqueous and finally mineral form, it becomes more immobile and thus the storage becomes less reliant on a secure caprock. Mineral trapping in such systems may be limited, however, by the low reactivity of silicate minerals in sedimentary rocks and a lack of silicate-bound divalent metals needed for the mineralisation process, and can take thousands of years [3]. Despite the urgent need for rapid deployment of widespread carbon storage sites, experience demonstrates that low public acceptance, high upfront investment costs and uncertain future liabilities have hindered the implementation of conventional carbon storage worldwide.

Mineral storage of CO₂ has been proposed as a safe and low-cost alternative. The idea of mineral storage of anthropogenic CO₂ was first proposed in the 1990's [4]: Mineral carbonation

is a part of the natural carbon cycle, where the carbon moves from one terrestrial reservoir to another. Within the natural cycle, carbon has thousands to millions of years residence time in rocks, which is by far largest carbon reservoir on Earth. Mineral storage of CO₂ will, however, only be practical if it is possible to accelerate this process at large enough scales to address the current global challenge

Carbfix has demonstrated the rapid mineralisation of CO₂ through injection of dissolved CO₂ into reactive rock formations, such as mafic or ultra-mafic rocks, with over 95% of the injected CO₂ mineralised within 2 years at ambient temperatures [4]. By dissolving the CO₂ in water prior to or during injection, solubility trapping is achieved immediately, adding to the security of the method. Furthermore, the CO₂-charged fluid promotes the release of divalent metals from the subsurface bedrock, which combines with the injected CO₂ and forms stable carbonate minerals. By mineralising the injected CO₂, it is permanently fixed and there is a negligible risk of it returning to the atmosphere. Mineral storage of CO₂ offers a vast storage potential and unlocks large regions in the world where CCS has until now not been considered possible. The largest potential lies offshore within the sub-marine basaltic crust, but suitable formations are also widespread onshore [4].

Carbfix has since 2014 injected over 80,000 tonnes of CO₂ from the Hellisheidi geothermal plant in SW-Iceland into the basaltic reservoir. Since 2020, Carbfix has commissioned two new injection sites, including injection of CO₂ captured directly from the atmosphere in collaboration with the Swiss green-tech company Climeworks. Carbfix is involved with four injection projects to be commissioned in 2022. Emphasis is currently being placed on making this technology more cost effective and exploring its limits in terms of geological properties and injection methods for more widespread deployment of CO₂ mineral storage - with the intention to bring the technology towards climate relevant scale.

Oral Abstracts

Themes

Environment and Climate (EC)

Understanding volcanoes (UV)

Geodynamics & tectonic evolution (GT)

Geoscience and the society: hazards and anthropogenic impact (GA)

Igneous and Metamorphic Geochemistry (IP)

Earth resources (ER)

Interdisciplinary sessions (IS)

Applied geology (AG)

Remote Sensing in geosciences (RS)

AG1-01

Rock Mechanics Laboratory model

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Rock Mechanics Laboratory model

A model on how rockbolts work by developing a zone of compressional stress in a fractured rock mass was initiated by Tom Lang, Snowy Mountains Authority, Australia, and was further developed by Dr Evert Hoek (www.rocsience.com).

For use in courses in rock mechanics at the Institution of Geosciences, Uppsala University, the model has been further improved by installing pressure gauges with manometers along the sides of the model box. By means of the manometers, one can demonstrate the compressional stress development in the fractured rock mass (represented by railway aggregate, 32-64 mm), when bolts are tightened with nuts and washers.

A conceptual understanding of how a rock mass behaves during underground rock excavation can be obtained by loosening the bolts in a certain order, such as row by row of bolts.

AG1-02

Characterizing potential quick clay with a 3D resistivity model in the mid-Norwegian Orkdal valley

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Several recent quick clay landslides have raised awareness for the need to better spatially map and understand Quaternary deposits throughout the country, especially marine clays with occurrences of quick clay.

We perform an integrated study of the Quaternary deposits of the Orkdal valley in mid-Norway using geophysical, geotechnical and geological approaches. The study aims to evaluate new ways to better map and comprehend the valley fill deposits in an area previously flooded by the sea following the last deglaciation. Electric resistivity, which is well suited to characterize marine deposits and potential quick clay, is key in this study. A 3D resistivity model of the subsurface is derived from a helicopter frequency EM (HEM) survey, flown with 200 m dense flight line spacing over the Orkdal valley. A full 3D inversion of the frequency-domain data results in a model reaching to depths of up to 150 m. This model nicely shows the distribution of low-resistivity marine clays, potential leached clays, glacio- and fluvial deposits as well as bedrock. The inversion results are tested against and locally refined by several ground electrical profiles. Geotechnical drillings that aim at detecting quick clay occurrences are included in the comparison and data interpretation. The different methods are in very good agreement and complement each other well. Furthermore, we link the potential distribution of quick clay derived from the HEM data with a terrain analysis to identify areas of potential landslide hazard.

This comprehensive study demonstrates how HEM can improve the 3D understanding of quaternary deposits and – combined with other methods such as ground geophysics (ERT and GPR) and ground observations – provide a more detailed picture of the subsurface and lay the basis for detailed geohazard analysis.

AG1-03

Do harmful clay minerals affect adhesion between aggregate and binder?

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Adhesion test is a mechanical test done in a laboratory and is performed on aggregates to assess its suitability as a surface dressing. The test referred to in this study is a special wet mix test which is only used in Iceland to test adhesion properties for aggregates for cutback surface dressing.

During routine tests in 2019 it was noted that aggregates from the same site and same production showed significantly different results between aggregate and adhesion binder, depending on which bituminous binder (adhesive promoter) was used.

This led to more detailed examination of petrographic description (PD) in relation to other test methods. The main concern was the classification of aggregates that were starting to show signs of alteration is subjective. The result was that the PD is not always a reliable tool to assess the suitability of aggregates for surface dressing.

This raised questions whether harmful clay minerals were present and had a negative effect on adhesion between aggregate and binder.

To address this question, methylene blue dye was used. In general, the assumption is made that clay minerals, like smectite, pick up the dye.

Two test methods were selected. The first method is the methylene blue test (MB test), which is a standard test method EN 933-9.

In the second method, thin sections of aggregate samples were prepared and treated with methylene blue. Analysis in thin section is useful to assess alteration of aggregates and other features visible at microscopic level. By using thin sections treated with MB the distribution and quantification of the assumed harmful minerals can be evaluated.

For this research samples were collected from several quarries and pits. All aggregates were produced with primary and secondary crushers and washing screen.

Two sets of subsamples were prepared. For one set material less than 2 mm in size was prepared for MB test. The second set was subjected to adhesion test and grains randomly collected for analysis in thin sections.

Preliminary results indicate that MB test may be used to identify potentially harmful aggregates by a simple test method.

AG1-04

Unfavourable geological structure. A case history

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In the South part of Stockholm, highway junctions are under construction. A mast for major high voltage power transmission

has its foundation on rock, a gneissic metagreywacke, with many weak surfaces in the foliation featuring sulphides, graphite and altered mica. The strike of the foliation is nearly parallel to a road cut close to the mast and the foliation dips some 45 degrees towards the highway. Such a structure is prone to planar failure and a subsequent rock slide, which in this case would jeopardize transmission of power, with severe economic consequences. In the same area, some 400 metres away, a very large rock slide of this type, caused by the said foliation, occurred about two decades ago, during excavation of a foundation pit for a building. The presentation describes how the road cut was excavated and supported with rock anchors, in order to prevent a failure.

AG1-05

Gravel Wearing Course

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Gravel wearing course (GWC) is a combination of gravel, sand and fines. Without the right proportions, it will perform poorly.

The most suitable geological formations for producing GWC is glacial till, rockslides, landslides and scree formations as they contain all particle sizes, i.e. ranging from fines to boulders.

Fines are important factor in GWC. They can be divided into 2 fractions: silt and clay. In Icelandic road construction the term clay is frequently used to describe the entire fraction smaller than 0,063 mm. But that's not entirely true as this is both silt and clay sizes. Silt is larger than clay and clay is less than 0,002 mm in size. In GWC the particle size clay is important but even more important are the clay minerals.

Some clay minerals have a special quality as they can absorb moisture and store it. It depends entirely on the clay mineral how well it can obtain the moisture. Smectite is one of these clay groups that has this property. It has a high degree of cohesion, and it can absorb water in considerable quantities and store in the interlayer space.

Fine substances such as silt, and rock and mineral fragments of clay size do not have this property. They are like flour when it is dry and completely lack plastic properties.

Icelandic fines of the grain size clay are generally not plastic as they are primarily rock and mineral fragments. But plastic clay can be found in Iceland. In rockslides f.e., is the clay originated from interbeds found in between rock layers, but there are also secondary clays minerals in the rock itself from which the rockslide descended. In the younger part of Iceland, fines are commonly rich in silt fraction, the remaining clay fraction is composed of rock and mineral fragments but lacks the clay minerals for the cohesive purpose.

When producing GWC, fines with especially some amount of clay, have to be added in the crushing process. It is not a simple task as fines are difficult in processing when wet as they get stuck on to everything.

One of the requirements for gravel wearing course in Iceland is amount of clay content. Of total fines it is recommend 10-30%. My question is: do we need all that clay, or do we just need the right clay?

AG1-06

Qualitative and semi-quantitative determination of low concentrated iron mono-sulfides in concrete aggregates by differential thermal and thermomagnetic analysis

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Oxidation of iron-sulfides in crushed concrete aggregates may trigger expansive reactions, initiating early deterioration and reduction of concrete structures. Incipient oxidation of the non-stoichiometric iron mono-sulfide pyrrhotite [Fe_{1-x}S] is considered paramount in this degradation reaction. Which specific polytypes trigger structural expansion at which concentrations are not definitely known. The maximum limit value for the total sulfur content in concrete aggregates is cautiously set to 1 wt.% (NS-EN-12620). According to the Norwegian standard, materials containing between 0,1 wt. % and 1 wt. % total sulfur should be analyzed for the presence of pyrrhotite by differential thermal analysis (DTA). If pyrrhotite is present in samples the acceptance level for total S is reduced to 0,1 wt.%. These low acceptance limits presumably lead to increased disposal rates and loss of high-quality aggregates.

Differential thermal analysis (DTA) is an indicative measurement for the presence of pyrrhotite and composes the deciding method for acceptance or rejection of aggregates in Norway. Exothermal peaks of pyrrhotite, provoked by oxidation during heating, are often closely associated in the temperature range 480° to 525°C. Other sulfide peaks may interfere in that range. This can lead to ambiguous results for samples where pyrrhotite is commonly communized with other sulfides.

An alternative method for the identification and semi-quantification of pyrrhotite in concrete aggregates was approached in this study. Thermo-magnetic analyses on bulk powder samples. Quantification was attempted by using synthesized samples of anti-ferromagnetic NC- and ferrimagnetic 4C mono-sulfide references blended, in different content. The reference samples were then compared to natural aggregate samples with known pyrrhotite concentrations.

Differentiation of antiferromagnetic and ferrimagnetic polytypes is possible due to thermomagnetic transitions and known low-temperature behavior of the mineral and semi-quantification may be achieved by compiling mass normalized susceptibility data.

Thermomagnetic susceptibility measurements can be used for the precise detection, discrimination, and semi-quantification of pyrrhotite polytypes in concrete aggregates. Instrumental specific detection limits for the MFK1-kappabridge are 0,05 wt.%, for both 4C- and NC-type pyrrhotite. Minor amounts (< 0,5 g) of a bulk powder sample, in the same fraction as used for DTA, are analyzed and results are obtained in less than 2 hours, making this method applicable and cost-effective also for industrial use.

EC1-01

Recent climate variations in Iceland

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Iceland has a maritime, cold tempered climate with significant long term variability. Cold conditions in the late 19th century only saw a significant amelioration in the 1920's followed by a robust mid-20th century warm period. After a short return to colder conditions in the 60's Iceland has experienced considerable warming since the last decade of the 20th century, first in the West and North West of Iceland, and then the center of warming shifted to East Iceland. Although the warming has slowed somewhat in the last 10 year, records temperature and precipitation has still been observed in some years, with notable events of heavy precipitation and significant weather impacts. This talk will cover climate changes in Iceland in the last century and place these in context with simultaneous regional changes. It also discusses the more recent changes, both in terms of temperature, precipitation and winds in terms of regional changes and expected climate change.

EC1-02

The role of the ocean circulation in recent climate variability in Iceland

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Iceland enjoys a much warmer climate than the average for its latitude. A major reason for this is the warm ocean currents in the Atlantic south of Iceland. Recently, several studies have been published on heat fluxes carried by ocean currents in the northern North Atlantic as well as heat fluxes through the interface between the ocean and the atmosphere. This has included heat fluxes across the ridges from Greenland to Scotland and in particular heat fluxes associated with the transport of Atlantic water through Denmark Strait. In general, in the area where Atlantic water is flowing, the ocean temperature exceeds the air temperature. This results in a heat flux from the ocean to the atmosphere, so the air temperature therefore depends to a high degree on the ocean temperature. The temperature in the Atlantic water south of Iceland increased by about 1°C from 1996 until the end of that century. Simultaneously, the salinity increased by roughly 0.1 PSU indicating that the change was due to advection. At the same time, the air temperature in southern Iceland showed a similar temperature rise in harmony with the temperature change in the ocean. The heat flux with the North Icelandic Irminger Current through Denmark Strait was also found to increase. The high temperature was consistent until 2017 when some decrease in both temperature and salinity was observed and those conditions have prevailed since then. New updated results on transport and heat fluxes with the North Icelandic Irminger Current through Denmark Strait will be presented. When considering impacts of global warming in the ocean as well as on land, in and around Iceland, it is necessary to take the temperature changes that occur because of changes in the ocean circulation into account.

EC1-03

Environmental impact from acid sulfate soils in a future climate

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Acid sulfate soil (AS-soil) can cause significant economic and environmental issues due to its ability to lower pH and mobilize elements to surface waters. The problems arise when the soils are oxidized, which commonly occurs as a result of land use; ditching and excavations. Furthermore, periods with low groundwater levels can cause soil oxidation and following periods with high runoff can affect surface waters negatively. It is assumed that such periods will be more common in the future. We used analyses from climate scenarios and water balance, as well as AS-soil maps to assess future environmental impact.

With machine learning techniques, we have produced probability maps of AS-soil along the Bothnian coast of Sweden, where these soils are common. The work is currently made within an Interreg Botnia-Atlantica project called KLIVA but was initiated during three earlier EU-collaboration projects, in partnership with the Geological Surveys of Finland and Norway, the County Administrative Board in Sweden, and others. The maps are compared with results from the hydrological runoff model HYPE regarding different IPCC scenarios.

The map predicts the distribution of three classes: 1) No AS-soil, 2) Active AS-soil, and 3) Potential AS-soil. The model was produced by using data from field observations, and several environmental covariates such as maps of Quaternary deposits, and most importantly a high-resolution elevation model from which several derivatives was extracted. The modelled map shows that active AS-soils are common in flat areas with fine-grained sediments close to the sea level where the groundwater level has been lowered by ditches. Potential AS-soils are common in peat covered wetlands and is found in larger geographical area compared to active acid soils. Models from all climate scenarios shows an increase of runoff during autumn and winter, where the increase in winter is the largest. Spring runoff is clearly estimated smaller. The summer results are more uncertain but indicate less runoff – more drought.

The described future conditions could lead to increased oxidation and the formation of active AS-soil. If these dry periods are followed by high water flow, a significant acid shock might occur. Consequently, there is a risk that AS-soils in the future may periodically, to an increased extent, adversely affect surface waters. The map data from SGU can be used to highlight areas where the geohazard from AS-soils, in a changing climate, are the greatest.

EC1-04

Evolution of a clastic source-to-sink system across the Permian-Triassic transition: Petrography, sediment volumes and provenance of the Røye and Havert formations, Barents Sea, Norway

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The eruption of the Siberian Traps Large Igneous Provinces at the Permian Triassic transition led to (I) extreme global warming, (II) increased continental weathering, (III) oceanic stagnation and acidification and (IV) mass extinction. Climate and depositional environments across the world were significantly affected, e.g., as the sedimentation rate increased worldwide. In the Barents Sea, the Permian Triassic transition is expressed as a continuous sedimentary record that changes from carbonate-dominated, low-siliciclastic Permian deposits to high-siliciclastic Triassic deposits. However, the sedimentary changes affected by the environmental change at the Permian-Triassic transition, and the implications for sediment transport from source-to-sink, have so far not been investigated. This interval is sampled by several exploration- and stratigraphic wells on the Finnmark Platform and imaged by a dense grid of seismic lines. Therefore, it serves as an excellent area to investigate the response of source-to-sink systems to such an extreme climatic change.

The goal of this project is to investigate how the Triassic climatic changes were expressed in source-to-sink systems, using provenance, facies analysis, petrography, and sediment volumes. Herein we present preliminary petrography results and sediment volumes from the Changhsingian-aged carbonates of the Røye Formation and the Induan-aged sandstones of the Havert Formation. The detrital grain properties, such as size, rounding, sphericity, angularity, and mineralogy, exhibit no overall shift across the transition although the sedimentation rate increases extremely (~100 times). The upper Permian contains spiculate mudstones, limestones, and sparse sandstones on Finnmark Platform and is covered by Lower Triassic mudstones and interbedded sandstones, which deposited as turbidites and in the shoreface and delta plain. In order to determine how the signal from the catchment changed in relation to the great climatic changes, it is of high importance to examine changes within provenance and sediment volumes across the Permian-Triassic transition.

EC1-05

Role of climate and human impact on fire and vegetation dynamics in one of the oldest protected forests in Europe

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Fire is naturally an integral part of the northern boreal forests dynamics and climate has been considered as one of the main drivers of the long-term fire and vegetation dynamics. However, anthropogenic activity has greatly affected the fire history in Fennoscandia, especially during the last millennia and the effective fire suppression practically led to the absence of a

natural fire regime in boreal forests in Finland. The warming climate may increase the risk of severe fire events regardless of the fire management. Therefore, it is important to understand the long-term interactions between climate, human impact, fire and vegetation dynamics in boreal forest ecosystems.

One of the oldest protected areas in Europe is located in Central Finland and provides an opportunity to investigate the change from natural fire and vegetation dynamics to human controlled fire regime and vegetation dynamics. The site is known to have been under slash-and-burn cultivation until the beginning of the 19th century and the last known burnings were done in the 1840s after which the site has been left to natural succession. The site was partly protected in 1911 and it was included into the national old-growth forest reserve protection program in 1994.

In order to investigate the role of climate and human impact in the long-term fire and vegetation dynamics during last 2000 years two peat cores were collected from small forest hollows from the Kuusmäki old-growth forests protected area. Macroscopic (> 150 µm) charcoal and *Neurospora*-fungal spores are used to reconstruct the fire history and pollen analysis is performed to reconstruct the long-term vegetation dynamics in the study area. Climate variable is derived from modelled climate data.

The preliminary results demonstrate an increase in charcoal abundance from 16th century suggesting increased fire activity and a more intensive period of slash and burn cultivation in the area until the beginning of the 19th century. The absence of charcoal during the last century suggests absence of fire after the cessation of slash and burn cultivation. These results together with the role of climate and human impact in vegetation dynamics will be further discussed in the presentation.

EC1-06

Complex responses of tundra vegetation to climate change: implication for ecosystem climate feedback consequences

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The rapidly warming Arctic climate may induce vegetation changes that mediate ecosystem functioning with positive climate feedback consequences. In general, plant growth is stimulated by warming that may result in vegetation change and "greening". However, such responses are not uniform across the tundra biome, or across habitats within sites, and in some areas the vegetation has even been "browning" rather greening. Studies of vegetation and ecosystem responses to long-term warming experiments across the tundra biome have revealed complex responses to warming, both direct and indirect, where the extant plant communities and their resilience to warming play a major role. Here I present some results from such long-term experiments both in Svalbard and Iceland. The results show that the presence of deciduous shrubs appears to be a critical driving factor for major vegetation changes (greening) with substantial ecosystem consequences, while high Arctic plant communities and other plant communities without deciduous shrubs are more resilient. Furthermore, climate related extreme events may have negative impact on the vegetation.

ORAL
EC1

Mosses and lichens emit considerable amounts of volatile organic compounds to the atmosphere

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One important ecosystem-climate feedback process is driven by atmospheric trace gases known as biogenic volatile organic compounds (VOCs), which are often highly reactive and affect atmospheric chemistry. Biogenic VOC emissions, of which the greatest source is terrestrial vegetation, are generally considered to be higher in magnitude and more reactive than anthropogenic VOC emissions. High temperature increases in the Arctic regions compared to lower latitudes, caused by climate change, are expected to increase plant VOC emissions, which has the potential to drive positive and negative climate feedbacks, via interactions with greenhouse gases and formation of secondary organic aerosols, respectively. VOC emission profiles vary greatly between plant species and most studies have focused on agricultural plants and trees. Mosses and lichens are vastly understudied components of terrestrial vegetation despite being of increasing importance with increasing latitude.

In this study, we aimed to measure the chemical profiles of VOC emissions from moss and lichen species common in Subarctic tundra biomes. We chose to investigate the moss species, *Hylocomium splendens*, *Pleurozium schreberi*, *Sphagnum warnstroffii*, and *Tomentypnum nitens*, and the lichen species *Cladonia arbuscula*, *Cladonia mitis*, *Cladonia pleurota*, and *Nephroma arcticum*. We measured VOC emissions using an enclosure techniques and analysis with two complementary methods, i.e., gas chromatography-mass spectrometry (GC-MS) and proton-transfer-reaction time-of-flight mass spectrometry (PTR-TOF-MS), to obtain a more complete picture of the emission profiles.

Our data demonstrates that the moss and lichen VOC emissions were in the same order of magnitude as the leaf biomass-based VOC emissions for common vascular tundra plants. VOC emissions were dominated by low molecular weight (LMW) VOCs, such as acetone and acetaldehyde, as well as hydrocarbons (HCs) and oxygenated VOCs (oVOCs). Thereby, this study shows that LMW VOCs, obtained by the less commonly used PTR-TOF-MS, contribute substantially to ecosystem emissions. Our data also shows inter-specific variation in emission rates and compound blends. For example, the highest and lowest emission rates between mosses were found for *S. warnstroffii* and *H. splendens*, respectively. Furthermore, the VOC blends of the moss species, *P. schreberi*, *S. warnstroffii*, and *T. nitens*, were clearly distinct. For lichens, *N. arcticum* was clearly distinct from the *Cladonia* spp., as it had a different VOC blend, higher emission rates of HCs, oVOCs, and lower LMW VOC emission rates. These results indicate that moss and lichen VOC emission rates and blends might be connected to genetic species relatedness.

To conclude, our results stress that we cannot generalize and model VOC emissions across mosses and lichens as a single unit. Furthermore, the high variation in the emission rates and compound blends points towards a need to continue investigations of inter-species variations and environmental controls of moss and lichen VOC emissions.

Extent of an independent late Weichselian ice-cap above the Vestfirðir Peninsula, Northwest Iceland

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Extended raised shorelines and fragments of terminal moraines around the Vestfirðir Peninsula have been mapped and surveyed in order to be able to reconstruct the extent of an independent late Weichselian ice-cap situated above the peninsula. Altitude and extent of distinct and separate sets of raised shorelines clearly show that late Weichselian crustal subsidence and uplift was closely controlled by the extent (weight) of the Northwest Icelandic Ice-cap. The three sets of raised shorelines were formed during periods with temporary equilibrium between glacial isostatic adjustment and global eustatic change, notably occurring at ~14.7, 12.1 and 11.2 cal. ka BP. during the deglaciation of Vestfirðir Peninsula. Lateral extent of three sets of raised shorelines is such that the most elevated and earliest set of raised shorelines has the least lateral extent and are found only in outermost parts of the fjords of the Vestfirðir Peninsula while less elevated and younger sets of shorelines have greater lateral extent and can be traced farther into the fjords. It is our conclusion that different and decreasing size of the Northwest Icelandic Ice-cap controlled and limited both altitude and lateral extent of the three sets of shorelines and, thus, allowing us to approximately determine the extent of the Northwest Icelandic Ice-cap at three occasions. An example showing coincidence between extent of a specific shoreline and position of a glacier terminus is retrieved from the Arnarfjörður fjord. A multibeam image of the inner parts of the fjord shows terminal moraines on the floor of the fjord close to where the lateral extent of a set of raised shorelines is truncated. Occurrences of truncated shorelines is used to define the extent of outlet glacier from the Northwest Icelandic Ice-cap at three occasions during the late Weichselian deglaciation of the Vestfirðir Peninsula. The Northwest Icelandic Ice-cap was separated from the main Icelandic Ice-Sheet during early stages of late Weichselian deglaciation at ~14.7 cal. ka BP and remained as an independent ice-cap until its final deglaciation about 10.0-9.0 cal. ka BP.

Geomorphology, hydrology, and chronology of early Holocene jökulhlaups along the Hvítá River, southwestern Iceland

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Glacial outburst floods (jökulhlaups) have significantly modified landscapes across Earth throughout the Quaternary and are a contemporary geohazard in glaciated regions worldwide. Iceland experiences more frequent jökulhlaups than nearly anywhere on Earth, though research has focused on floods triggered by subglacial volcanic and geothermal activity. However, floods from ice-marginal lakes may be a better analogue for most global jökulhlaups because both occur during rapid global warming. As the Icelandic Ice Sheet retreated in the early Holo-

cene, meltwater lakes accumulated at ice margins and periodically drained in jökulhlaups. One such lake formed in the Kjölur highland region and drained near the present-day course of the Hvítá River in southwestern Iceland, leaving behind abundant geomorphologic evidence including anastomosing bedrock channels, 50-m-deep canyons, and boulder deposits. Yet, only one previous publication has investigated these events.

This project uses a suite of field mapping, geochronological, paleohydraulic, and modeling techniques to better constrain flood timing and dynamics. This talk interprets new lines of jökulhlaup geomorphologic evidence, presents estimates of flood magnitude, and discusses ongoing cosmogenic nuclide dating analysis to reconstruct flood chronology. It synthesizes these results to introduce hypothesized scenarios of ice margin position, glacial lake evolution, and jökulhlaup drainage during the final stages of Icelandic Ice Sheet deglaciation. Finally, it discusses the Hvítá jökulhlaups as a case study for ice-marginal lake drainage processes, helping to close a research gap in Iceland and advance understanding of links between climate change, glacier response, and hydrology in other Arctic and alpine regions.

EC2-03

Formation of the Bustarfell drumlin field, NE-Iceland: Integrating sedimentological and GPR data

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Recently mapped drumlins and other streamlined subglacial bedforms (SSBs) in NE-Iceland reveal cross-cutting flow sets of palaeo-ice streams that were active during and following the Last Glacial Maximum (LGM). The Bustarfell drumlin field is located within the Vopnafjörður-Jökuldalsheiði flow set in NE-Iceland and consists of 77 drumlins. The internal architecture of two drumlins was investigated using sedimentological analysis and ground penetrating radar (GPR with 50 and 100 MHz antennas), to illuminate processes that contribute to drumlin formation, the glacial history and ice dynamics in NE-Iceland. The drumlins studied were found to be composed of subglacial traction till, with interbedded glaciofluvial sediments, showing signs of deformation. On the stoss side of one of the drumlins, two till units were identified, separated by a thick unit of deformed glaciofluvial sand and gravel layers. The core of glaciofluvial material suggests that the drumlin formation is best explained by the sticky spot hypothesis where well-drained patches in the subglacial bed retarded the ice flow locally through increased basal drag and encourage till deposition. Furthermore, our GPR data indicates that a combination of erosional and depositional processes are responsible for drumlin formation. The stratigraphy and formation of the Bustarfell drumlins suggest that the glaciofluvial sediments were deposited proglacially during deglaciation, possibly in the Bølling-Allerød interstadial, and that the drumlins were formed during a subsequent readvance during the Younger Dryas (YD). The sedimentological and GPR data are complimentary and integrating these data is considered a useful approach to investigate the internal architecture and formation of subglacial bedforms. However, the need for integrating GPR data with stratigraphical work and testing of different GPR parameters is highlighted.

EC2-04

Formation of Crevasse Squeeze Ridges – a case study from Trygghamna, Svalbard

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Crevasse squeeze ridges (CSR's) are landforms that have been described exclusively from the forefields of surge-type glaciers and ice-stream conduits. The process controlling the CSR formation have been discussed since the landform was first defined in the mid-1980's. This work describes sediment ridges that are arranged in rectilinear networks and are predominantly orientated oblique to former ice-flow direction in glacier forefields in Trygghamna, western Svalbard. In order to understand the geomorphic context of these landforms, detailed maps were produced via remote sensing and field mapping. Additionally, stratigraphic investigation into several CSR's in cross-sections highlight ridge architecture, sedimentology and structures in relationship to surrounding landforms and sediments. Findings suggest that CSR's form from saturated basal till being squeezed into basal crevasses during surges and are subsequently transported englacially before deposition after surge culmination. A conceptual model for the formation and preservation of CSR's is proposed. The results do not only further contemporary understanding of CSR's in surge-type glacier settings but may also apply to large-scale surging lobes or ice stream shut-down settings.

EC2-05

Inventory of glacial curvilineations (GCLs) at the southern periphery of the last Scandinavian Ice Sheet

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Glacial curvilineations (GCLs) are enigmatic landforms recently discovered in the southern peripheral area of the last Scandinavian Ice Sheet (SIS). They consist of multiple parallel, winding ridges several meters high and up to several kilometers long, systematically arranged in groups of common geomorphic appearance. GCLs create spectacular landscapes whose origin generates much controversy. Expanding from the first GCLs finding in central Poland, we present an inventory of other GCLs occurrences along the SIS margin in Poland, Germany and Denmark based on the analysis of high-resolution LiDAR digital elevation models (Adamczyk et al. 2021). We document a total of 59 glacial curvilineation fields. Each of these fields consists of smaller units called GCL swarms. The fields differ strongly in areal coverage (between 1 and 358 km²), number of swarms (between 1 and 21) and number of individual landforms (between 2 and 255). All GCL fields occur in tunnel valleys terminating at the ice margin, typically at various topographical levels. Our findings, interpreted in the context of glacial geological processes, support the origin of GCLs as erosional remnants of antecedent landscapes carved by channelized subglacial meltwater flows.

Reference: Adamczyk, A., Wysota, W. & Piotrowski, J.A. (2021): Inventory of glacial curvilinearities (GCLs) at the southern periphery of the last Scandinavian Ice Sheet. *Geomorphology* 108094, <https://doi.org/10.1016/j.geomorph.2021.108094>.

EC2-06

The internal controls of glacier movement over a soft bed – insights from high-resolution X-ray tomography, Storglaciären, Sweden

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Since the 1980s it has been recognised that glacier beds are not passive components over which the ice merely flows, but are part of a coupled ice-bed system where the unlithified substrate responds to the applied stress by deforming and in this way can contribute to glacier motion. However, the exact nature in which the sediment responds during subglacial deformation and especially with changing water pressures is extremely poorly understood. In this project, we aim to gain new insight into the internal controls of subglacial processes, more specifically the 'stick-slip' mechanism.

To achieve this aim, we use a combination of standard sedimentological analyses and advanced geotechnical testing to characterise the properties of bulk and undisturbed sediment samples of subglacial traction till collected at Storglaciären, Sweden, taken in the summer of 2021. We will present results from undisturbed and deformed sediment samples that show the internal composition and microstructural properties based on their true three-dimensional arrangement. High-resolution 3D imaging (x-ray tomography) enables us to first show the arrangement of particles, shear planes etc. in true 3D (undisturbed stage). In a second step, we aim to replicate the actual displacement following a 'stick-slip' cyclic in triaxial tests. A third step of renewed 3D-imaging of the deformed sample is used to visualise the internal deformation after the triaxial test.

Our first results indicate that the internal controls, such as sediment properties and the effect of fluctuating water pressure, have a large influence on subglacial processes. Such knowledge is crucial to be able to predict the future response in changes in the 'external' control such as a warming climate and ultimately sea level rise.

EC2-07

Dynamic subglacial meltwater systems drive late erosion pulses beneath rapidly thawing cold-based ice sheets.

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Cold-based ice sheet interiors are conventionally regarded as non-erosive. Yet subglacial conditions may be transformed during deglaciation by the arrival of large volumes of melt-

water at the ice sheet bed. The development of a dynamic meltwater drainage system and the onset of basal sliding have potential to increase erosion rates in bedrock and sediment. Here, we examine the impact of late deglacial thawing on the Rogen plateau, located near the former ice divide of the Fennoscandian Ice Sheet. We provide new maps of glacial and glaciifluvial landforms which we combine with existing data on Quaternary sediments and landforms. Cross-cutting and overlapping relations allow for an event sequence to be established of the deglaciation period. In the Early Holocene (11 ka), an ice lobe onset zone developed at the Rogen plateau. In places where meltwater reached the bed and where pressures rose to overpressure, it caused fracture dilation in horizontally bedded sandstones and rock brecciation. The onset of sliding and application of drag resulted in the mobilization of bedrock sheets. The establishment of meltwater corridors led to fluidisation of sediments at the bed, dissection and modification of ribbed moraines and formation of murtos and hummocky corridors. During final stagnation of the ice sheet, meltwater drained through channels forming axial eskers. The sequential development of landforms is in line with subglacial drainage development recognized beneath the former Fennoscandian and Laurentide ice sheets. Glacial ripping during deglaciation generated 317 km² of boulder spreads, locally with depths up to 4 m. The average erosion depths by removal and reworking of sediment is 0.9–1.1 m across areas below 900 m elevation. This study shows that when the cold-based interiors of ice sheets become briefly activated by large subglacial meltwater delivery late in deglaciation, there can be significant reworking and erosion of rock and sediment.

EC2-08

Microstructural proxies for porewater pressure fluctuations in a subglacial till under a palaeo-ice stream in NW Poland

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Subglacial processes under contemporary and past ice sheets attract a lot of attention, yet our understanding of the ice/bed interface remains fragmentary. Till micromorphology informs about its formation and deformation and therefore helps to decipher the nature of the subglacial processes and the origin of some active-ice landforms. Such landforms are especially abundant under fast-flowing ice streams where interactions between ice, water and the soft bed control the glacier dynamics and the land-forming processes.

In this study we investigated microstructures and clast microfabrics in tills generated under the Odra palaeo-ice stream, one of the most prominent land-based ice streams of the southern Scandinavian Ice Sheet. Specifically, S-matrix microstructures were mapped and interpreted in 17 thin sections, and 15 till blocks were investigated for X-ray microtomography (μ CT). All samples were collected in trenches excavated in three drumlins. The most frequent microstructures were microshears indicating brittle deformation, and circular structures reflecting ductile deformation. The long axes of clasts mapped by μ CT revealed weak clustering strengths and, occasionally, bimodal fabric pattern. There was no consistency in μ CT fabrics in the vertical profiles, from one trench to another, and between the drumlins.

Our data indicate a spatial and temporal complexity of the subglacial processes likely modulated by porewater pressure fluctuations. Successions of brittle and ductile deformation events contributed to substantial homogenization of the till.

However, the geometry of some microstructures suggests that only a thin layer of the till, in the range of centimetres, was experiencing deformation at any point in time. Finally, the lack of correspondence between the microclast orientations and the trend of the drumlin field suggests that the till pre-dates the drumlin formation, which is consistent with earlier studies in this area.

EC3-01

Subglacial bedform sensitivity to variable topography and geology across the deglaciated Northern Hemisphere

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Properties of the terrain on which ice sheets rest have received great attention in the glaciological community as they are important for determining ice-flow velocities, lateral and basal stress gradients, and ice-margin positions. Streamlined subglacial bedforms observed in deglaciated landscapes provide the opportunity to assess the sensitivity of ice-sheet flow behavior to regional and local bed characteristics across broader spatio-temporal scales than is possible for contemporary glacial systems. While many studies of streamlined subglacial bedforms rely on manual mapping and qualitative (i.e., visual) assessment, we utilize multiple semi-automatic mapping techniques to identify thousands of erosional and depositional bedforms, formed during the Last Glacial Maximum and following deglaciation, from LiDAR-based digital elevation models across geologically and topographically diverse deglaciated sites in the Northern Hemisphere. Using this large geomorphological dataset, we empirically test the importance of subglacial terrain on bedform morphology and ice-flow behavior. Similarities in bedform metric distribution regardless of regional topography and bed lithology indicate all bed types can support similar landform generating processes. Ice flow within confined topography (i.e., valleys) with easily erodible beds host the most elongate bedforms yet the widest range in bedform elongation and surface relief, suggesting higher ice-flow velocities occur within confined topographic settings despite spatially heterogeneous landform-generating processes. In contrast, regions not constrained by kilometer-scale topography with lithified sedimentary beds contain bedforms with the highest density and packing, smallest change in surface relief, and smallest elongation, indicating more spatially uniform and organized interactions at the ice-bed interface and consistency in ice-flow velocity. Regardless of genesis, we ultimately find a relatively higher sensitivity of bedform elongation and thus ice-flow speed and/or persistence to regional topography, while bedform density is more sensitive to bed lithology. On a relatively local scale, isolated topographic highs of varying sizes have different impacts on streamlined subglacial bedform signatures. Localized ice-flow diversion occurs around topographic highs with a "bump" volume of greater than 10 km³, indicating the scale of isolated highs is critical to the assessment of ice-flow organization. We interpret an increase in density, number, and elongation range of bedforms downstream of the topographic highs as evidence for strain heating and flow acceleration increases subglacial meltwater production, sediment transport, and variability in bedform production and/or maturity. The assessment of thousands of streamlined subglacial bedforms for the purposes of identifying ice-flow sensitivity to regional

and local bed properties ultimately indicate that the landform footprint of former ice sheets across the deglaciated Northern Hemisphere are morphologically similar and topography plays a larger role in landform product and ice flow than bed lithology.

EC3-02

Marine Ice Stream retreat offshore N-Iceland documented by multibeam bathymetric and high-resolution Chirp reflection data

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Marine glacial landforms on the N-Iceland insular shelf demonstrate that offshore ice streams during the Last Glacial Maximum extended further to the north than previously inferred. The insular shelf is draped by ice-marginal and subglacial sedimentary features, megascale glacial lineations (MSGLs), moraines, eskers, and V-shaped, till ridge features, not previously described in literature, possibly representing a push moraine or lateral crevasse-squeeze ridges. The offshore glacial landforms reflect the past ice flow directions of at least four major ice streams, from Skagafjörður into Skagafjarðardjúp, from Eyjafjörður into the southern Eyjafjarðaráll basin, from Bárðardalur into Skjálfandi and Skjálfandadjúp Basins, and from the Northern Volcanic Zone into the Öxarfjörður Basin. Megaflutes are orientated parallel to the direction of the major basins and the Kolbeinsey Ridge indicating that the ice streams were topographically constrained. The highly reflective V-shaped ridges within the more sediment starved Eyjafjarðaráll Basin are characterized by elongated "V-shape" formations with an average width of 300-500 m and an average length ranging from 400-1500 m, at a depth of 320-450 meters b.s.l. opening towards the flow direction of the main ice stream. The ridges change direction gradually, along with the basin curvature, from NNW-SSE in the southern part of the basin rotating to NNE-SSW, parallel to a 10 km long lateral moraine, which most likely separated two main ice streams. Asymmetrical broad domes interpreted as grounding zone wedges, up to 100 km offshore, suggest that the deglaciation was episodic, with periods of standstill. Large normal faults within the Eyjafjarðaráll and Skjálfandadjúp Basins cut through the glacial features, reflecting tectonic activity throughout Holocene, also represented by current seismicity. Further mapping of the insular shelf is needed to refine models of ice streams from the Iceland Ice Sheet.

EC3-03

Footprint of the lake-terminating Baltic Sea Ice Stream

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Since the early development of ideas of former glaciation in Scandinavia, it has been hypothesised that the Baltic Sea hosted an ice stream that drained the core of the Fennoscandian Ice Sheet. Landforms and sediments in the lateral and distal terrestrial periphery reveal its lobate form, far-travelled basal sediments, and local zones of elongate subglacial landforms indicative of ice streaming out of the offshore realm. Model

simulations suggest that streaming ice filled the Baltic basins and was responsible for draining vast volumes of the ice sheet. However, very limited data have been available from the Baltic bed itself, with which to directly support ice streaming: the Baltic Ice Stream has been inferred rather than directly reconstructed, and its spatial and temporal behaviour is virtually unknown.

Recent seabed data have shown that an ice stream operated in the Gulf of Bothnia, albeit limited in spatial extent and, likely, belonging to the late stages of deglaciation. Here, using a combination of moderate- and high-resolution bathymetric data from the entire Bothnia-Baltic seafloor, we present the landform imprint of ice flow and retreat in the Baltic Sea following the Last Glacial Maximum. We find strong geomorphological support for ice streaming conditions, and we use deglacial landform assemblages to characterise the style of and controls upon grounding line retreat. Predominantly terminating in a large proglacial lake during deglaciation, we contrast the behaviour of the Baltic Ice Stream with the peripheral land-terminating ice sheet sectors and with continental shelf, fully marine-based ice stream counterparts.

EC3-04

Cross-cutting palaeo-ice streams in NE-Iceland reveal shifting Iceland Ice Sheet dynamics

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During and following the Last Glacial Maximum (LGM), ice streams are thought to have regulated the past Iceland Ice Sheet (IIS) by discharging ice and sediment from the ice sheet interior towards the margin at the shelf edge. Previous reconstructions of ice streams within the IIS have produced contradictory assessments of ice sheet dynamics and location of ice divides. Here, we reconstruct palaeo-ice streams in NE-Iceland based on detailed mapping of streamlined subglacial bedforms (SSBs) and other glacial lineations. The morphometrics, distribution and orientation of the SSBs indicate the flow-sets of several cross-cutting palaeo-ice streams and the location and migration of ice divides, while high density and packing of SSBs possibly suggest the axial zones of the ice streams. North-trending flow-sets suggest that during maximum glaciation and ice-sheet thickness, ice flow within the study area was largely unaffected by underlying topography allowing ice to flow northwards across valleys and fjords. This ice flow direction correlates with the orientation of previously identified troughs on the north-eastern shelf and indicates that an E-W orientated ice divide was located to the south of the study area. During deglaciation and ice sheet thinning, a N-S orientated ice divide was located to the west of the study area, and palaeo-ice streams became confined to valleys and fjords, so that associated flow-sets crosscut the older ones. The absolute ages of these flow-sets are uncertain, but the simplest interpretation is that the older ones pertain to the LGM and the younger ones to the following deglaciation. Samples for ³⁶Cl cosmogenic exposure ages are expected to shed light on ice stream retreat and the deglaciation of the IIS. This study sheds light on the dynamics and evolution of palaeo-ice streams within the IIS and highlights the importance of further efforts to understand the subglacial processes responsible for the formation of the streamlined subglacial bedforms as well as to constrain the evolution of shelf glaciation and chronology of ice stream retreat.

EC3-05

Sedimentary processes and paleoenvironment of the northern Barents Sea continental slope

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The northern Barents Sea continental slope is a key area for understanding both the behavior and dynamics of the northern parts of the Svalbard-Barents Sea Ice Sheet and the oceanography of the Eurasian part of the Arctic Ocean. Therefore, we are investigating the Kvitøya Trough Mouth Fan and adjacent slope with the aim of reconstructing the sedimentary processes and paleoenvironment in this area.

Interpretations of the seabed morphology are made by analyzing the IBCAO 4.0 bathymetric grid (Jakobsson et al., 2020) combined with newly acquired swath-bathymetry data and high-resolution sub-bottom profiles (CHIRP). In addition, lithostratigraphy and radiocarbon dating of microfossils from six sediment cores (0.43 to 5.45 m long) make the basis for reconstructing the sedimentary processes and their timing.

Results from the bathymetry reveal that the Kvitøya Trough Mouth Fan extends to a water depth of at least 3500 m. Gul-lies on the fan, with maximum depths of 40 m and widths of 1000 m, are interpreted to reflect erosion by glacier-influenced gravity flows initiated at or near the shelf break. The morphology of the continental slope to both sides of the fan is smooth above 1000 m water depth, interpreted to represent contouritic sediment deposited from along-slope-flowing ocean currents. Below, the continental slope is characterized by up to 10 km long slide scars and maximum 500 m deep and 5000 m wide channels, interpreted to represent the dominance of erosion from sediment failure and gravity flows, respectively. Three main lithofacies reflecting several sedimentary processes have been distinguished based on the lithostratigraphic analysis, and radiocarbon dates indicate their timing.

We investigate the interplay between the ocean current regime and the glacial dynamics in the study area by discussing the results from the geomorphological mapping, the sediment property analysis, and the radiocarbon dating.

Jakobsson, M., Mayer, L.A., Bringensparr, C. et al. The International Bathymetric Chart of the Arctic Ocean Version 4.0. *Sci Data* 7, 176 (2020). <https://doi.org/10.1038/s41597-020-0520-9>

EC3-06

Characterization of glacial landforms in the SW Barents Sea using high-resolution 3D seismic reflection data

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The characterization of marine glacial landforms identified in the shallow subsurface is limited by data resolution. Conven-

tional 3D seismic and multi-beam echo sounder bathymetry covers most of the SW Barents Sea. Using such data allows for meter-scale observations of the seafloor, but the approach is limited to a resolution of 10's of meters in the subsurface. Building on previous research on high-resolution 3D data, this study uses the highest resolution 3D seismic data available in the SW Barents Sea to image glacial landforms below the resolution of conventional seismic data.

The presented results have been obtained through the interpretation of a depth migrated high-resolution P-Cable 3D seismic dataset with a vertical resolution of $\text{\textcircled{D}}3$ m and bin size of 3.1 by 3.1 m. Key horizons forming the Quaternary package, including the Upper Regional Unconformity (URU), intra-glacial reflections, and the seafloor, reveal a complex glacial history and record the interactions between glacial processes, faults, and fluids. Mega-scale glacial lineations (MSGL) and iceberg ploughmarks, with widths from 10 to $\text{\textcircled{D}}300$ m, are observed at multiple stratigraphic intervals. Corrugation ridges, with heights between 0.75 to 4.5 m and spaced between 12 to >100 m apart, can be seen within selected MSGL and ploughmarks. Slope failure along steep (up to $\text{\textcircled{D}}15^\circ$) ploughmark walls is documented on the seafloor. The submarine moraines, the most abundant landforms observed within the glacial package, includes steeply dipping shear bands that are associated with negative-amplitude anomalies close to the URU in selected areas. Interaction between glaciogenic features, faults, and fluid flow is well exemplified by hill-hole pairs observed on the URU.

The study provides new insights into the glacial history of the SW Barents Sea through the description of three distinct seismic units, the characterization of at least four ice-flow directions, and the imaging of meter-scale deglacial landforms. We thereby illustrate the importance of high-resolution data for understanding glacial landforms and the interaction between glacial processes, faults, and fluid flow in the shallow subsurface.

EC3-07

Trough mouth fans as high-resolution source-to-sink archives

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Trough mouth fans comprise the largest sediment deposits along glaciated margins, and record Pleistocene climate changes on a multi-decadal time scale. Sedimentation related to climate warming in polar regions and new challenges associated with the energy transition highlight the urge for better knowledge of these depocenters. Here, we present sedimentation models for the two largest of these depocenters – the Bear Island Fan on the western Barents Sea margin and the North Sea Fan on the northern North Sea margin – which are analogues for large glacial fans along the Antarctic and Greenland margins. We use extensive high-quality 3D reflection seismic cubes ($37,200 \text{ km}^2$) as well as conventional 2D reflection seismic lines, and combine these datasets with lithological and geophysical borehole logs.

The stratigraphy of trough mouth fans is dominated by contourites, glaciogenic debris flows, meltwater turbidites, and megaslides, which together result in a thickness exceeding 2 km. 1) Neogene to early Quaternary-age contourites are characterized

by continuous and high-amplitude reflections in the seismic data. The contourites of the late Quaternary, in contrast, have a more transparent seismic facies, and onlap the escarpments shaped by the megaslides. The lithology of the contourites varies from fine clays to coarse sands. 2) Meltwater turbidites are identified as high-amplitude reflections characterized by 4-100 m deep channels and sourced from multiple regions along the paleo-shelf break. The well-connected turbidite channels are 90-2100 m wide, and can be traced for distances of >100 km. These channels are both deeper and wider in the North Sea Fan compared to the Bear Island Fan. The lithology of these deposits has yet to be cored. 3) Glaciogenic debris flows are transparent packages of sediments, with a lens-shaped expression in the seismic profiles and lobe-shaped geomorphology in planar view. The grain size of glaciogenic debris flows is typically more mud-dominated than for contourites, but glaciogenic debris flows do include sandy beds at selected intervals. Glaciogenic debris flows are more dominant in the high-latitude Bear Island Fan compared to the mid-latitude North Sea Fan. 4) Megaslides consist of high-amplitude, deformed sediment that is constrained by steep headwalls and sidewalls. The megaslides within these two trough mouth fans have mainly occurred since the Late Pleistocene and fail along contouritic basal layers.

The contourites were fed by fluvial systems on the East Shetland Platform and the Norwegian mainland, and are, in turn, often trapped by megaslide escarpments or deeper structural elements. The rapid glacial deposition of debris flows and turbidites delivered large sediment volumes to gently-dipping slopes, which then failed as megaslides. Trough mouth fans are potentially excellent depocenters to study the interaction between along-slope and down-slope processes in high-resolution, both in space and time. We suggest that contourites are most active during interglacial periods, while turbidites and debris flows are more common during glacial periods. The timing of the megaslides, however, still includes large uncertainties. Meltwater contribution seems to be a more dominant factor for sedimentary processes in mid-latitude glacial fans than in their high-latitude counterparts.

EC3-08

Deglaciation of a high-latitude glacial trough bordering the Arctic Ocean – the Woodfjorden Trough on the NW Svalbard margin

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Global warming and sea-level rise following the Last Glacial Maximum (LGM) resulted in an overall retreat of shelf-break terminating glaciers and ice sheets worldwide. The nature of these retreats is well documented for lower latitudes, such as the shelves surrounding Britain and offshore Norway. The continental shelves at higher latitudes are, however, less investigated, as they are generally hard to reach due to challenging sea-ice conditions. This applies also to the continental shelf north of Svalbard, neighboring the Arctic Ocean, where only about 20–30 % of the Svalbard shelf is covered by multibeam swath-bathymetry data (estimated from Jakobsson et al., 2020).

Acquiring high-quality data sets in such key areas in the Arctic is crucial to understand how the major ice masses reacted to global climate changes in the past. We present mapping results from the outer part of the 60 km long and 40 km wide Woodfjorden Trough on the northwestern part of the Svalbard continental shelf. The trough is distinctively flat ($<0.1^\circ$) and shallow, ranging from about 150 to 250 m water depth from the inner part to the shelf break. Our multibeam swath-bathymetry and high-resolution CHIRP data show a complex seabed morphology consisting of trough-parallel ridges, as well as abundant trough-transverse wedges, ridges, and furrows. The trough-parallel ridges are commonly up to some meters high, 50–100 m wide, and 1–2 km long. The trough-transverse wedges are flat-topped features that are between 1–2 km wide and 30–50 m high, while the trough-transverse ridges are approximately 100 m wide and 3 m high. The largest furrows are up to 1500 m wide, 30 m deep, and more than 10 km long. The landforms show a complex superposing character.

The mapped morphology is a characteristic glacial landform assemblage within glacial troughs, interpreted to represent glacial lineations, grounding zone wedges, moraine ridges and iceberg ploughmarks. This testifies to periods of fast-flowing ice masses on the shelf, and a dynamic retreat of the glacier front including several still-stands and advances during overall retreat. However, the bathymetric profile of the trough and the high number of grounding zone wedges and moraines is atypical, as glacial troughs are commonly overdeepened and dominated by mega-scale glacial lineations superposed by one or a few grounding zone wedges and/or smaller retreat moraines. We will discuss these morphological differences in cross-shelf troughs, as well as the controlling parameters for the deglaciation dynamics of the Woodfjorden Trough.

EC3-09

Stratigraphy of a complete glacial-interglacial cycle: The sedimentary record of the last glaciation at the North Sea Fan

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Trough mouth fans are major submarine depocentres that form in front of ice streams that advance onto the continental shelf. They provide extensive records of past glaciations and ice sheet dynamics, and understanding their deposits and sedimentary processes is key when interpreting glaciated margins. In this study, we use high-quality 3D reflection seismic data with a vertical resolution of 2 m and a bin size of 6.25 x 18.75 m extending over 14000 km² at the uppermost North Sea Fan. The aim is to document the seismic stratigraphy, sedimentary processes and glacio-marine landforms shaped during different paleo-geographical configurations prevailing since Marine Isotope Stage 6 (last 130 ka). Using facies analyses and seismic geomorphology the sequence is subdivided into eight seismic units (U1-8), separated by high-amplitude continuous reflections. The uppermost stratigraphy of the fan is characterized by >400 m of prograding strata, spanning from the top of the Tampen Slide at its deepest to the seabed on the more shallow shelf, accounting to 7160 km³ of sediments. The lowermost two units, U1 and U2, are characterized by continuous reflections with increasing amplitude contrasts near the Tampen Slide headwall. U1 is a tabular body and covers the entire study

area, while U2 is lenticular and limited to the northern part, confined by a secondary headwall. Units U3-6 are characterized by a combination of chaotic, transparent, structurally deformed or parallel to sub-parallel seismic facies. They are limited by high-amplitude reflections with erosional features with varying dimensions from <10 - 2100 m wide and 3 - 100 m deep. Isolated, straight channels more than 100 km long reflect significant erosion. The uppermost unit, U7, is characterized by transparent facies close to the paleo-shelf, and parallel and slightly undulated continuous reflections downslope, with commonly-expressed pockmark fields, as well as narrow and shallow channels at its base. U8 occurs laterally to U7, but restricted to the shelf. It is characterized by a thin package with few reflections creating a wedge-shaped morphology; eroding into it, multiple iceberg ploughmarks, iceberg pits and mega-scale glacial lineations are identified. The units are interpreted as being deposited by processes linked to different stages of the glacial cycle. Units U1 and U2 are dominantly deposited by contour currents, active just after the failure of the Tampen Slide (U1, ~130 ka), and during the onset of the last glaciation (U2). Units U3 – 6 are the products of meltwater turbidites, which created mainly short-lived channels during warmer periods, and glacial debris flows, when the ice stream reached the shelf edge or nearby during an interval of 4 kyr (23-19 ka). Deposition of the suspended load created meltwater discharge coupled with ice rafted debris is responsible for the build-up of U7, representing the full retreat of the ice. Lastly, U8 is the product of deposition of subglacial tills. These new results on depositional products in relation to glacial-interglacial cycle stages demonstrate the variability of active processes during a rapid sedimentation period of the Weichselian Glaciation at the North Sea Trough Mouth Fan.

EC3-10

Revised Middle and Late Pleistocene interglacial and interstadial records from the glaciated eastern Fennoscandia in Finland

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The Middle to Late Pleistocene palaeoenvironmental record from the repeatedly glaciated central and eastern Fennoscandia is poorly known. The majority of the glacial and warm interval records have been interpreted to represent only the last, Weichselian, glacial cycle (119-11.7 ka).

We have revised the crucial part of the existing stratigraphic documentation in central and southern Finland by interpreting the stratigraphic information in a glacial sequence stratigraphic context. Our findings (Räsänen et al. 2021) show that a considerable part of the depositional record extends further back in time and is more complete than previously published.

One depositional record may reach the Middle Pleistocene Holsteinian Interglacial (≈MIS 11), 424-374 ka ago, and a large number of records are tentatively attributed to the Middle Pleistocene sc. Röpertsdorf-Schöningen Interglacial (≈MIS 7) 243-191 ka ago. During this possible Röpertsdorf-Schöningen Interglacial, the Gulf of Bothnia hosted larger alkaline and smaller dystrophic lakes surrounded by boreal pine forests in a continental climate with warmer summers and colder winters than today. The Eemian (≈MIS 5e) 131-119 ka sea coastal records show detailed evidence of the widespread intermixing of continental fresh and marine waters. During the Early Weichselian Brörup Interstadial (≈MIS 5c) 109-96 ka, central and southern Finland seem to have supported open birch forest

tundra, later invaded by spruce; not boreal pine forest as earlier thought. The early birch vegetation faced a tundra phase which may be the Montaigne cooling event c. 103 ka ago. The revised palaeoenvironmental interpretation shows that the development in Fennoscandia during the three discussed warmer intervals is well in line with the central European vegetational development. Our palaeoenvironmental interpretations concerning Røpersdorf-Schöningen and Brörup warm intervals are preliminary and will need further investigations. No indisputable Middle Weichselian (≈MIS 3, 57-29 ka) sedimentary record seems to have been recorded in the studied area.

Reference:

Räsänen, M.E., Auri, J., Ovaskainen, J., 2021. Revised Middle and Late Pleistocene interglacial and interstadial records from the glaciated eastern Fennoscandia. *Quat. Sci. Rev.* 251, 106716. <https://doi.org/10.1016/j.quascirev.2020.106716>.

EC3-11

Pleistocene history of eastern Fennoscandia – interglacial and interstadial record

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New and old data from till-covered Pleistocene sediment sections in Finland are collected to a database and assessed to shed light on glacial and non-glacial history of the eastern part of Fennoscandia and adjacent areas. The results show that the areas where sediments older than the last deglaciation (i.e. younger than the Younger Dryas stadial) occur are located mainly in Lapland, western coastal area of the Gulf of Bothnia and the Finnish Lake District area, north of the Younger Dryas Salpausselkä zone.

Litho-, bio-, and morphostratigraphical records combined with geochronological data suggest that the Pleistocene overburden above the Precambrian crystalline bedrock was mostly deposited between the late Saalian (MIS 6) and the late Weichselian (MIS 2) stages. Although there are sites in which pre-Eemian interstadial and interglacial sediments are reported, there are no conclusive evidence which indicates interglacial or interstadial sediments older than the Saalian (MIS 6-10).

The most representative Eemian marine interglacial sediments are well preserved at the Mertuanoja stratotype site, western central Finland, whereas the Eemian terrestrial sediments are best preserved at Sokli, eastern Lapland and Tepsankumpu, western Finnish Lapland. The Early Weichselian interstadial sites are numerous in eastern Fennoscandia. Based on the dating results, it seems that interstadial sediments correlative to the Brörup interstadial (MIS 5c) are best preserved while there are far less sites found, if any, where the Odderade (MIS 5a) sediments occur. According to the stratigraphical and dating results, ice-free interstadial conditions also prevailed in eastern Fennoscandia during the MIS 3 interstadial events and prior to the extensive Younger Dryas ice advance phase, after which the Scandinavian Ice Sheet deglaciated from the area.

EC3-12

Reconstructing sea ice in the Iceland Sea during the last 165,000 years

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Detailed information on past climate and oceanographic changes are stored within the sediments on the ocean floor. Various proxies from marine sediments are used to decipher palaeoenvironmental conditions. Core IS-4C from the Iceland Sea has been investigated for palaeoceanographic and climate changes. The main focus is on IRD, which provides information on e.g. past iceberg trajectories, ocean currents and sea ice coverage. Additional investigated proxies were oxygen isotopes, foraminifera, element proxy data and lithology. The sediment core spans the last 165,000 years, a time period covering more than a full glacial-interglacial cycle. The results show high variability in IRD composition during the penultimate glaciation compared to the last glacial maximum (LGM) and high amplitude variations in IRD flux and ocean temperature with a strong correlation between the two. The novelty of the study is a multi-proxy analysis and the description and definition of IRD groups. To maximize the utilization of the defined IRD, each group have been photographed and geochemically analysed for easier application. The locations of the core plays a crucial part because of the many outer factors contributing to the sediment input to the area. Core IS-4C was extracted from an oceanographic sensitive area north of Iceland, where a mix of cold Polar Water and warm Atlantic Water affect the area.

EC3-13

Palaeo-environmental reconstructions from microfossil data using machine learning

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Palaeo-environmental reconstructions prepared from microfossil proxy data (e.g., pollen, diatoms, chironomids, foraminifera) have wide-ranging applications, including palaeoclimate research and the study of human impact in ecosystems. Such reconstructions are generally underpinned by calibration datasets consisting of assemblages of the studied biological proxy sampled from surface sediments, joined by modern-day environmental observations. A variety of numerical methods have been used to construct proxy–environment calibrations, including parametric transfer functions (e.g., Weighted Averaging) and the Modern-Analogue Technique (i.e., matching of fossil assemblages with most similar modern assemblages).

Recently, new approaches based on machine-learning (ML) algorithms have emerged in the preparation of microfossil proxy calibrations. The use of ML in palaeo-environmental research builds on earlier applications in modern-world ecology, where ML has been successfully employed to model species–environment relationships, generally with the intent of predicting likely ecosystem responses to future environmental change. Even though the purpose of these studies is distinct from palaeo-environmental inquiry, in both cases the research is underpinned by an analogous modelling step, describing modern-world taxon–environment relationships. This observation motivated a research project funded by the Academy of Finland (2014–2018) to explore the applications of ML in palaeoclimatology.

During this project, we assessed ML approaches with three microfossil proxies – pollen, chironomids, and diatoms – using European, North American, and African calibration datasets which varied widely in sample count (ca. 70–2000), spatial scale (regional to continental), and reconstructed environmental variable (atmospheric temperature and moisture; water depth, pH, conductivity, and colour). We assessed the methods using a range of cross-validation schemes with the modern calibration

datasets, as well as down-core reconstructions prepared from Holocene and Last Interglacial fossil data.

Our experiments mostly focused on a family of ML methods based on ensemble models of regression trees (including Bagged Trees, Random Forests, Rotation Forests, Extremely Randomized Trees, and Boosted Trees). Work in modern-world ecology has identified important conceptual strengths of regression tree ensembles in modelling, including their ability to identify complex responses, ability to focus on best indicator taxa in a taxon-rich but noisy data, and sensitivity to rare taxa. These methods were complemented by a second family of ML methods, artificial neural networks (both traditional and Extreme Learning Machine implementations), as well as non-ML methods traditionally employed with microfossil proxies.

Especially with large, (sub)continental-scale calibration datasets relating pollen and chironomids to climate variables, we found regression tree ensembles (particularly Boosted Trees, Random Forests, and Extremely Randomized Trees) to offer significant cross-validated performance advantages over classical calibration methods. However, this outcome was not universal, and particularly with small, regional datasets (< 200 samples) we repeatedly found classical methods based on linear or unimodal taxon response models to outperform ML methods. By contrast, the performance advantage of ML over traditional methods tended to increase for variables with a moderately weak influence on the studied proxy. Importantly, the regression tree ensembles remained robust in cross-validation schemes which forced the models to predict with a constrained pool of modern samples, mimicking the challenges faced in reconstruction from fossil samples lacking good modern-world analogues.

EC3-14

Lateglacial seasonal climate signals reconstructed from the palaeobotanical data of the Baltic states region

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A weakened state of the Atlantic meridional overturning circulation (AMOC) as a result of freshwater influx into the Northern Atlantic and the climatic impact of a possible disturbance are major climate-change “wildcards” of the 21st century. The late-Quaternary palaeoclimate record includes multiple instances of AMOC slowdown and allows the assessment of associated climate signals. The Younger Dryas event (ca. 12.8–11.7 ka) and its interaction with atmospheric blocking processes over the Fennoscandia have been connected with a distinct rise in temperature seasonality in Northern Europe through cooling of winter and warming of summer. This study compares changes in mean air temperature of January and July in detail with the aim to distinguish possible climate signal patterns for coldest and warmest seasons during the Younger Dryas. In total 13 sites from the Baltic states and the surrounding area consisting of plant macrofossil sequences are examined using both classical and novel species-based climate reconstruction approaches applicable with plant macrofossils. These include the classical mutual-climate-range method and the recently developed, conceptually related CRACLE algorithm, which we tested us-

ing a range of geographic calibration regions. In addition, we tested palaeoclimate reconstructions using minimum temperature limits for plant species calculated from high-resolution climate and plant-occurrence data available from Finland. Plant macrofossils, usually identified at genus or species level, represent local vegetation and environment in contrary with, e.g., pollen data, while facing a high risk of false absences, due to proxy-related characteristics (large size and mass of the remains and possible high decomposition rates). Nevertheless, climate reconstructions from these proxies show contrasting results of temperature trends for winter and summer seasons and can either support or reject the warm-summer hypothesis, depending on the employed reconstruction approaches. Hence, our results also point out the significance of choice of the modern calibration regions and of species assemblages as important factors influencing the results.

EC3-15

Holocene precipitation seasonality along a climatic gradient from western Spitsbergen to Nordaustlandet, Svalbard

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Climatic warming, diminishing sea ice, and increasing freshwater fluxes have an immense impact on the Arctic hydrological cycle. Modeling suggests that Arctic precipitation may increase by more than 50% this century, affecting freshwater budgets, ecosystems, slope processes, and glacier mass balance. Quantifying the variability in precipitation seasonality during past warm periods helps us understand the mechanisms causing precipitation change over long timescales. We use the hydrogen isotope ratios ($\delta^2\text{H}$) of *n*-alkanoic acids in lake sediment cores from Svalbard to reconstruct changes in Holocene precipitation seasonality and summer humidity. Svalbard is located where heat and moisture from the North Atlantic meet dry and cold polar air and water masses, causing a high sensitivity to changes in oceanic and atmospheric circulation and large contrasts in climate between different parts of the archipelago. We present four plant wax $\delta^2\text{H}$ records along a climatic gradient from relatively warm, wet western Spitsbergen to relatively cold, dry Nordaustlandet. We interpret the $\delta^2\text{H}$ of mid-chain (C_{22}) *n*-alkanoic acids, derived from aquatic plants, to reflect the $\delta^2\text{H}$ of lake water. Lake water $\delta^2\text{H}$ is affected by the water residence time and can reflect either summer or mean annual precipitation $\delta^2\text{H}$. The $\delta^2\text{H}$ of long-chain (C_{28}) *n*-alkanoic acids, mainly produced by terrestrial plants, reflects soil water $\delta^2\text{H}$, which in turn reflects growing season precipitation $\delta^2\text{H}$ and leaf water evaporative ^2H -enrichment. Heftyvatnet, close to the west coast of Spitsbergen, has a summer-biased $\delta^2\text{H}$ signal, and preliminary results suggest relatively stable summer climate throughout the Holocene. Jodavannet, Northern Spitsbergen, has modern lake water $\delta^2\text{H}$ indicating a winter-biased aquatic $\delta^2\text{H}$ signal, possibly reflecting lack of summer precipitation in this arid central part of Spitsbergen. Austre Nevlingen, 50 km north of Jodavannet, has lake water $\delta^2\text{H}$ reflecting mean annual precipitation $\delta^2\text{H}$. Leaf wax data from both Jodavannet and Austre Nevlingen suggest that the most prominent Holocene

precipitation changes occurred in winter. Finally, Kløverbladvatna, Nordaustlandet, has lake water $\delta^2\text{H}$ reflecting mean annual precipitation $\delta^2\text{H}$, but relatively ^2H -enriched mid-chain $\delta^2\text{H}$ values in the Middle to Late Holocene suggest a different moisture source or different plant wax sources compared to the other lakes. This presentation will summarize results from each of these lakes and assess the implications for Holocene precipitation seasonality change across Svalbard.

EC3-16

The character of the drainage of the Baltic Ice Lake at the outlet: a conceptual model

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We present a conceptual model for the 11.6 cal. ka BP drainage of the Baltic Ice Lake in the outlet area based on a new geomorphological map as well as new sedimentological information. We combine this new information with a review of the previous work on this well-studied area. The model includes the premise of remnant ice in the Långan valley as suggested by previous workers and indicates the drainage began subglacially. Cobbly sediment on northeast Billingen formerly interpreted as beach sediment is interpreted to be a subglacial lag deposit. The ridge at Timmersdala is composed of drainage sediment from the initial phases of the drainage, deposited in a subglacial tunnel that emptied out on to central Klyftamon. Continued drainage widened the tunnel by frictional melting, eventually lifting and fracturing the ice. A clay-draped scarp along the Långan valley is interpreted as due to subglacial meltwater erosion following initial lifting of the ice tongue. Pendant bars, expansion bars and boulder sheets on central and southern Klyftamon formed during the drainage event. Cobbly and bouldery drainage sediment in the bars, which is massive and poorly sorted, was deposited as bedload from sediment-charged water. Imbrication, bar orientation, and changes in grain size and Cambrian-clast content indicate flow to the west–northwest. Most sediment in the bars was derived from erosion on Klyftamon, but Cambrian rock from Billingen is present, delivered directly by the floodwaters directly and/or from debris-rich icebergs from the broken-up remnant ice. This flood event is distinguished from other Quaternary megafloods by being sediment-supply limited and having a short, subaerial floodway (20 km).

EC3-17

Timing of deglaciation and ice-dammed lakes in Jämtland, central Swedish mountains

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Jämtland is arguably the most classical region for the study of ice-dammed lakes in Sweden, with a rich research history going back 150 years. In the late 19th century, early workers concluded that, in the late stages of the last deglaciation, extensive glacial lakes were dammed between the eastward retreating Scandinavian Ice Sheet and the water divide within the mountains to the west. However, over time, interpretations of the deglaciation in Jämtland have changed. Most notably, around the middle of the 20th century, divergent opinions arose concerning the nature and extent of the ice-dammed lakes; Were they open lakes or just marginal lakes in valleys largely filled with stagnant ice?

Using high-resolution LiDAR-data, shorelines and other landforms relating to ice-dammed lakes have now been mapped over larger areas and in greater numbers than previously known, enabling a far more detailed reconstruction of the last deglaciation. Based on our mapping, we present the extents and relative ages of ice-dammed lakes in Jämtland and demonstrate how they were an intricate part of the deglacial dynamics. The landform evidence indicates an actively retreating ice margin in an open lake system. By radiocarbon dating the ice-dammed lake sediments we can now also, for the first time, present absolute ages directly related to their requisite ice-damming positions. Thus, the dates constrain both the timing and rate of deglaciation for the area. In addition, we use the shorelines' present-day tilts to inform about patterns and magnitudes of postglacial isostatic uplift; information otherwise lacking from the continental interior but of particular importance for modelling former ice sheet volumes and understanding the crustal response to ice sheet loading and unloading. We illustrate that reconstructing the extents and timing of ice-dammed lakes can greatly improve our understanding of the final decay of the Scandinavian Ice Sheet and provide potential analogues for the predicted future behaviours of modern ice sheets.

EC3-18

Lateglacial-Early Holocene deglaciation chronology and ice sheet-dynamics along the Helgeland coast, Northern Norway

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We present results from a Quaternary geology mapping project carried out along the coast of southern Nordland county, Northern Norway. Here we have mapped eight Quaternary map sheets (scale 1:50 000, each map sheet covering ~650 km²) from studying digital aerial photographs, LiDAR data and carrying out fieldwork over several seasons. Bathymetric and seismic surveys conducted in the adjacent fjords, have extended the geomorphological and subsurface mapping offshore.

The mapping reveals several sets of moraines and ice-marginal deposits that allow for the reconstruction of ice-marginal sub-stages related to the overall deglaciation of the Scandinavian Ice Sheet – both outside and inside the prominent Younger Dryas (YD) ice-marginal zone. A ≥ 15 km ice sheet readvance during the cold YD resulted in the deposition of a near continuous zone of moraines in the study area. In the fjords, the main outlet glaciers readvanced across several hundred meters deep troughs to deposit moraines and grounding-zone wedges at fjord sills. Some of the moraines tower more than a hundred meters over the surrounding seafloor and are associated with large glacial debris flow fans. The mapping also reveals elongated streamlined landforms that points to dynamic and fast-flowing outlet glaciers, particularly during the YD.

About 70 radiocarbon dates of marine shells located in till, glaciomarine sediments and raised littoral deposits provide chronological constraints on the regional deglaciation history and glacial dynamics. The outer coastline is believed to have become ice-free prior to c. 14.5 cal. ka BP. From c. 14.5 cal. ka BP to the end of the YD (c. 11.5 cal. ka BP), the ice sheet margin appears to have been fluctuating near the outer coast, as dated marine shells found in till suggest ice-free periods prior to readvances at 14.2 cal. ka BP and in the YD. The magnitudes of the ice margin fluctuations are not fully known, however. Deglaciation from the YD position took partly place in fjords with palaeodepths up to 800 m, which likely facilitated rapid frontal retreat through extensive calving. Despite this, mapped moraine substages inside the YD ice-marginal zone reflect glacial stillstands or small readvances even during the Early Holocene. The radiocarbon dates indicate that the palaeofjord heads were deglaciated by c. 11-10.8 cal. ka BP.

EC3-19

A 'new' ice margin in central Sweden

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We have mapped a series of landforms in central northern Sweden that we interpret as ice-marginal. Furthermore, we hypothesize that they formed during Marine Isotope Stage (MIS) 3 based on the regional geometry of the landforms, crosscutting relationships, and existing chronological data.

Several localities in central and northern Sweden show interstadial sediments with early MIS 3 ages. Consequently, these sediments pre-date the late Weichselian glaciation and, accordingly, were deposited by an earlier ice-sheet. However, an associated regional earlier ice-sheet margin has not been clearly defined. In comparison, in far-northern Sweden, the Veiki moraine (i.e., ice-walled lake plains) zone is assumed to be associated the ice margin of an ice-sheet retreating from an MIS 4 maximum. Recently, a moraine in the southern part of the Swedish mountains has been OSL-dated to an early stage of the MIS 3 interstadial. This moraine could be contemporaneous with the Veiki moraine zone to the north, based on the similar ages. However, there has been no evidence of any MIS 3 ice-margin between these localities; a distance of almost 600 km.

We have interpreted ice-marginal landforms in central northern Sweden connecting these two pre-late Weichselian ice margins. Our ice margin interpretation is generally based on landforms indicative of an ice-marginal dead-ice environment, including Veiki moraines, dead-ice hollows, and hummock tracts. We also associate spottily distributed end moraines with this hypothesized ice-margin. Our reconstruction indicates that the ice margin consisted of lobate forms that were 100s of km wide. Finally, crosscutting relationships indicate that the interpreted ice margin has been overridden by a late Weichselian ice sheet (MIS 2). This ice-margin reconstruction provides valuable information on the dynamics of the Scandinavian ice sheet in a region for which such evidence has previously been sparse.

EC3-20

Late Quaternary glacial and environmental history of the Sjuøyane archipelago, Svalbard

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Sjuøyane (English: 'The Seven Islands') are the northernmost part of the Svalbard archipelago, located north of Nordaustlandet, NE Svalbard. Little is known about their glaciation history, deglaciation, relative sea-level change and postglacial environments. Here we present problems, potentials, and preliminary results from two Quaternary geological field expeditions to Sjuøyane.

Geological sections along the coast of several of the islands provide an insight into the Quaternary stratigraphy. Two coarsening-upwards marine sedimentary sequences were identified. This agrees with previous studies that interpreted these sediments as evidence of a pre-Late Weichselian and a Late Weichselian glaciation. Radiocarbon and luminescence ages indicate a glacial event before ~40 ka. The postglacial marine limit sits at 18 m a.h.t. in Isflakbukta, Phippsøya. Above that, we identified an upper pre-Last Glacial Maximum marine limit marked by a clear bedrock erosional notch with wave-eroded bedrock, large water-worn boulders, and rounded cobbles.

Ages from raised beaches and deltaic sediments at Parryøya suggest that the island was ice free at c. 11.2±0.3 cal. ka BP. Samples for cosmogenic exposure dating were collected to reconstruct the last deglaciation of the area. 'Kill-ages' of vegetation emerging from small glaciers and snow fans indicate a Late Holocene climate deterioration.

We mapped the bathymetry of Isvatnet, Phippsøya and collected two 34 cm and 38 cm-long lake sediment cores. Both cores consist of a lower unit of grey silt and silty clay overlain by gyttja with a high content of bryophytes. The oldest radiocarbon age of the cores is c. 7.3 cal. ka BP.

The ultimate goal of this study is to better understand the history and behavior of the northern margin of the Weichselian Svalbard-Barents Sea Ice Sheet. Being the northernmost land area on Svalbard, Sjuøyane are strategically well located for this purpose.

EC4-01

Modelling of rock wall permafrost development in Norway post the Little Ice Age

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Slope destabilization due to atmospheric-warming-induced permafrost degradation is one of the global warming risks in Norway, where around one tenth of potentially unstable slopes are underlain by widespread permafrost. More knowledge about permafrost distribution in steep slopes in Norway is required for investigation of links between permafrost thawing and geomorphological activity, such as frost weathering and gravitational processes. In the present study, we assess spatio-temporal permafrost development in rock walls in Norway over the last 120 years. We model ground temperature evolution in the monitored rock walls in the Western Norway, the Jotunheimen, central-southern Norway, and the Northern Norway using the two-dimensional (2D) conductive heat flow model CryoGrid 2D. Sporadic to cold permafrost is reproduced in the simulations and results indicate that 20 m rock wall temperature increased by 0.2 °C decade⁻¹ on average since the 1980s. Hence, if the atmospheric warming rate will remain the same, rock wall permafrost in Norway at -1 °C at 20 m depth will likely thaw at this depth by 2070. Additionally, we show how permafrost distribution and/or warming rates are influenced by: 1) rock wall geometry and size, 2) snow conditions, 3) surface offsets arising from the incoming shortwave solar radiation, 4) snow conditions in the rock wall vicinity, 5) thermal conditions in the nearby blockfield-covered plateaus or glaciers.

EC4-02

Late Quaternary—recent geological evolution of the Qaanaaq area, North Greenland: The impact on infrastructure and construction

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Understanding the distribution of frost-sensitive soils in Arctic regions is critical to ensure long-lasting, sustainable infrastructure in arctic regions. In many coastal areas rapid sea-level changes during the late- and post-glacial periods have created a complex succession of marine and glacial sediments. This may be further complicated by glacial deformation. This study aims to describe the distribution of frost-sensitive, fine-grained soils in a high arctic coastal setting near the town of Qaanaaq, North Greenland. In this study, we have integrated geomorphological mapping, sedimentological descriptions of >20 boreholes down to a depth of 20 m and radiocarbon dating of shell material recovered from the boreholes. Based on the interpretation of boreholes and landscape, we describe the sedimentary slope where Qaanaaq is located as Holocene to recent marine sediments locally overlain by alluvial sediments. A significant difference in the soil behaviour is observed where buildings located on alluvial sediments are less affected by frost heave. A central discovery of the study is the presence of glacially reworked marine material ca. 20 m above msl with shells dated to ca. 42 Ka BP. This indicates that the area was not glaciated during this period, and that marine sediments may be redistributed along the coast by glaciers. Furthermore, we describe the deglaciation of the area surrounding Qaanaaq, where ice retreat is controlled by landscape topography, which gives rise to early ice retreat in the deep fiord south of Qaanaaq, and later ice retreat in the Qaanaaq area.

EC4-03

Modelling hydrogeological processes in steep permafrost-affected rock slopes

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Water infiltration and circulation in bedrock fractures is a potentially key-process in permafrost degradation and rock slope failure triggering. However, hydrological and hydrogeological processes in steep permafrost-affected rock slopes are difficult to investigate because of their non-linearity and anisotropy.

In this communication, we will present preliminary results and perspectives of the WISPER project ("Water and Ice related thermo-mechanical processes in the fractures of Steep alpine bedrock PERmafrost", funded by the French National Agency for Research) that aims to improve the understanding of water-related processes in steep permafrost-affected rock slopes.

We will introduce the first coupling of thermal and hydrological models applied to steep permafrost-affected rock slopes in a high Alpine granite peak (the Aiguille du Midi, Mont Blanc massif, 3842 m a.s.l.). Four case-studies with a simplified fracture network and various levels of saturation and hydrological forcings have been tested. They confirmed that water infiltration in fractures may accelerate permafrost degradation within them only, and within the rock mass as well, depending on the level of saturation. Furthermore, these simulations demonstrate that water infiltration may also lead to a deeper extent of the permafrost body than originally thought, prompting a rethink of permafrost occurrence at sites where permafrost was considered as non-existent. Finally, these thermo-hydrological simulations serve as a promising tool to assess the role of hydrostatic pressures in triggering rock failure by implementing the results to parameterize mechanical models.

Current challenges are related to the quantitative estimation of infiltrating water, notably water produced from snow melting, and to understanding the role of fracture geometry in the acceleration of permafrost degradation and in the development of hydrostatic pressures.

EC4-04

Using molards as marker of permafrost degradation in cold environments

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This study explores the possibility to use the landform called "molard" as a marker of permafrost degradation in arctic, sub-arctic and mountain environments. Molards in permafrost

terrains are cones of loose debris that result from thawing of blocks of ice-rich sediments mobilised by a landslide. Such molards cannot form without ground ice, which cements the source material, allowing it to behave like solid during transport. Once the ground ice has thawed, its cementing action is lost, inducing collapse of the material into molards. We reconstruct the permafrost, geological, geographical settings of 52 landslides characterised by molards, compiling data available in the literature. We apply quantitative terrain analysis using high-resolution DEMs to describe, quantify and compare their topographic characteristics, morphometry, dynamics, and molards distribution and density. Our results show that landslides with molards can occur in terrains characterised by various permafrost distribution, from continuous to isolated. These landslides show a variety of morphological and morphometric characteristics, source materials often composed of loose debris or rheologically weak bedrock, and their molard distribution reflects the dynamics of the landslide. In this study, we show that molards are an indicator landform of permafrost degradation under different permafrost, geomorphological and geological conditions, and that they can be used to decipher landslide dynamics in cold environments.

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EC4-05

Rock glaciers and post-glacial landscape development in Finnmark, Northern Norway

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Since 2015 we have mapped and monitored parts of the coastal areas in Finnmark, Northern Norway, and have produced detailed geomorphological maps of some key areas in the proximity of Hopsfjorden. In this area, rock glaciers are numerous and prominent features in the landscape, indicative of long periods with permafrost conditions following the early Weichselian deglaciation as modelled by e.g. Patton et al. (2017). Also in Finnmark, increasing temperatures over the last century affect the possibility of maintaining frozen ground, and in these coastal areas the air temperatures has risen with ca. 2 °C from below to above 0 °C in the recent decades. This temperature change led to degrading permafrost and rock glaciers, and can possibly result in slope failures.

The rock glaciers have probably been active in several different time periods during the late Pleistocene and the Holocene, from an early cold phase to the recent warming, with colder time periods like the Neoglaciation and the Little Ice Age in between. We observe that the rock glaciers are now transitioning from active towards relict landforms, with velocity rates in the mm to cm per year-range. Exactly which processes the measured rock glacier dynamics represent are difficult to interpret, most likely there is a combination of different processes; seasonal creep, rockslides, rock fall, snow avalanches, etc.

We also notice that at least one recently released rockslide (after 2008) have surface structures resembling the creeping surfaces of rock glaciers, and hypothesize that several of the rock glaciers in the area could have formed by secondary creep in rockslide masses deposited in permafrost environments under paraglacial adjustment or under changing ground temperature conditions.

This area display a variety of slope landforms at different activity stages, some dependent on permafrost, others solely on seasonal frost processes. The long exposure to periglacial conditions, recent warming and geomorphological changes make this area an excellent field analogue for colder areas, e.g. Svalbard, which will undergo similar changes in a recent future.

ER1-01

Boosting innovation in the field of geothermal energy through EU funded projects

Glen Burrige

European Federation of Geologists, Brussels, Belgium

Geothermal energy is a powerful low-carbon technology which can play a major role in society's quest to move towards more secure, clean, and efficient energy sources. The European Commission funds a range of projects in the field of geothermal through its Horizon Programme of research and innovation, which aims at securing Europe's global competitiveness, while boosting economic growth and creating jobs.

The European Federation of Geologists (EFG) and its consortium partners have been involved in 4 geothermal projects to date within this Programme: CROWD THERMAL, REFLECT, CHPM2030 and the upcoming CRM-geothermal.

CROWD THERMAL, a project co-ordinated by EFG, aims to empower the European public to directly participate in the development of geothermal projects with the help of alternative financing schemes and social engagement tools. In addition to a set of core services for the promotion and alternative financing for geothermal developments, one of its major outputs is a framework for a Social License to Operate.

At the other end of the spectrum, the REFLECT research project is focused on geothermal facilities and improving their efficiency and economic viability by preventing issues caused by fluid chemistry and solids deposition. The European Fluid Atlas it will produce will provide extremely useful information on geothermal fluid properties across Europe.

Both CHPM2030 and CRM-Geothermal are concerned with pioneering novel technologies that draw on the productive side of carried solids in the geothermal fluids and that, in some locations, will allow co-production of both energy and strategic metals in a single interlinked, geothermal process.

Specifically, the upcoming CRM-geothermal project, starting mid-2022, will build on and enlarge the REFLECT Geothermal Fluid Atlas by collecting new data and sampling wells for their critical raw materials (CRM) content in both Europe and East Africa. The technological developments will be accompanied by environmental and social impact assessments that will help provide guidance on good governance for the future of the industry.

These four EU-funded projects collectively aim to harness the latest in geothermal innovation with a view to improving operational efficiency, project economics and viability, social acceptance and the sector's environmental footprint.

Establishing this know-how can help open up the potentially huge, untapped, resource that is geothermal energy and deploy solutions that could help Europe fulfil the strategic objectives of the EU Green Deal as well its Agenda for Sustainable Development.

Sedimentary geothermal resources in China -- nature and utilization

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Utilization of low-temperature (<150°C) geothermal water plays an increasingly important role in direct use and provides an alternative energy source to fossil fuels in China. In contrast to the limited distribution of high-temperature geothermal reservoirs in the world, low-temperature geothermal reservoirs are widely distributed and have huge potential for direct use, especially geothermal reservoirs located in sedimentary basins. Such reservoirs are dominated by conductive heat transfer from terrestrial heat flow. In China, the heat flow in sedimentary basins is quite variable, with above average heat flow of 55 - 90 mW/m² in the middle and east parts of China, and below average heat flow of 30 - 50 mW/m² in the northwest part. Due to the relatively low background heat flow, sedimentary geothermal reservoirs, which are found in the depth range of ~1000 - ~4000 m, are mainly low temperatures (~50 - 150°C). Despite their low temperature, sedimentary geothermal reservoirs offer enormous potential as geothermal resources, due to their great buried depth and thick layers. The total extractable geothermal resources in the major sedimentary basins in China are estimated to equal 5.3×10^{18} kJ, which is 89% of the total estimated geothermal resources in the country. This is equivalent to about 180 billion tons of standard coal, constituting a large potential for reducing CO₂ emissions. Utilization of sedimentary geothermal resources in China is mainly direct rather than electricity generation. Before 2014 the main use was for bathing, but district heating took over first place after 2014. Based on the lithology of the sedimentary formations, there are two main types of productive sedimentary reservoirs, one type composed of Palaeogene - Neogene porous sandstone and the of Cambrian - Ordovician karstified carbonate rocks. Compared to the carbonate reservoirs, sandstone reservoirs usually have a shallower burial depth with lower reservoir temperatures. The carbonate reservoirs are usually at a great depth below the sandstone aquifers with thick caprock. Therefore, the average reservoir temperature of carbonate rock is relatively higher. As the demand for direct use of sedimentary geothermal resources in China has been increasing in recent years, their sustainable utilization has become a requirement for local geothermal production. Rejection of the return water back into the underground has become an effective means to this end. However, in contrast to the high reinjection rates possible in carbonate reservoirs, sandstone reinjection is more difficult, which makes reinjection a challenge. Therefore, extensive research focusing on solving the sandstone reinjection problem has been undertaken with many successful cases.

Chemical composition of geothermal water and geothermal gradients in the Southern Lowlands of Iceland

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The Rangárveitur district heating utility provides hot water to the towns of Hella and Hvolsvöllur and the surrounding rural

area in the Southern Lowlands of Iceland. The Rangárveitur utility currently produces from two low-temperature geothermal fields, Kaldárholt and Laugaland, but due to increasing demand it is foreseen that the utility will need to expand beyond these fields in the coming years. Although geothermal energy is abundant in the Southern Lowlands, many of the known fields either lack sufficiently high temperature or sufficient production capacity to be of interest for the utility.

In order to identify the geothermal fields that might be of most interest for the expansion of the Rangárveitur utility, information on the temperature and composition of geothermal water from 90 wells and hot springs, as well as measured geothermal gradients in 112 wells was compiled and reviewed systematically.

The results show a rather clear-cut geographical distribution both in terms of water composition and temperature, both of which show correlation with the production capacity of the geothermal fields. The fields in the easternmost part of the study area, east of the Þjórsá river, generally produce large volumes of warm water (30-70°C) with low salinity and deuterium values that suggest local precipitation. The fields in the western part of the study area, west of river Þjórsá, have lower flow rates but produce hotter (70-90°C) water, which is more saline and shows mixing with pre-Holocene water. The geothermal fields in the northern part of the study area, north of river Stóra-Laxá, produce large quantities of boiling geothermal water with low salinity and deuterium values corresponding to highland precipitation.

The geothermal gradient results largely agree with the results of water chemistry; the measured gradients are generally rather low (< 120°C/km) in the easternmost part, east of river Þjórsá, but higher (>200°C/km) in the western and northern parts of the study area. For comparison, the local background value for the geothermal gradient has been estimated to be 80-85°C/km. A few exceptions to these general trends are observed, and those should be examined further.

In this study, eight geothermal fields with proven geothermal resources were highlighted and five more options were identified as promising but in need of further research.

Regional thermal anomalies derived from magnetic spectral analysis and 3D gravity inversion: Implications of potential geothermal sites in Tanzania

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Tanzania is one of the several countries intersected by the East African Rift System (EARS) which is endowed by a geothermal potential that has been explored only to a limited extent. Here we present the first heat flux map over the region based on the Curie point depth (CPD) estimation from aeromagnetic data. We have estimated the base of magnetic sources as a proxy for the CPD from the radially average power spectra of the total magnetic field using the centroid and the de-fractal methods. Our results show that the CPDs range ca. 11 to 43 km and are comparable with the global CPD estimates but with more

detail in our estimates. The heat flow has then been computed assuming a constant heat conductivity. In order to evaluate the results against crustal thickness, we have inverted the gravimetric regional field constrained by existing Moho depth from seismic receiver functions. Our analysis has revealed high heat flow values (over 100 mW/m²) along the EARS and at the Proterozoic collision boundaries that have been reactivated by the EARS. In general, the high heat flow anomalies coincide with the known surface geothermal manifestations and shallow Moho depth in the range ca. 30 to 35 km. A high heat flow anomaly is also found in the central part of the Tanzanian craton, likely related to the mantle plume imaged by seismic tomography. The most interesting areas for geothermal exploration in Tanzania, according to our results, are the EARS triple junction in the Rungwe volcanic province, the north Tanzania divergent zone and the areas of the Proterozoic collision boundaries reactivated by the EARS.

ER1-05

Direct mixing of geothermal water into heated groundwater to improve water quality in the district heating system of the Reykjavik capital area

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The Hellisheiði Geothermal Power Plant has produced hot water for the Reykjavik capital area since 2010. The power plant is co-generative, producing electricity in steam turbines and hot water for district heating through heat exchange between the geothermal fluid and cold groundwater. The cold groundwater is saturated with oxygen when it is pumped out of the ground and becomes supersaturated after going through the heat exchangers. Deaeration of the water is necessary after passing through the heat exchangers as the presence of dissolved oxygen in the water causes corrosion in the carbon steel pipes of the district heating system. The deaeration process is both physical and chemical and takes place in a set of deaerators. The chemical deaeration is achieved with the injection of a small amount of steam. Geothermal steam contains hydrogen sulfide (H₂S) which reacts with the remaining oxygen after the physical deaeration as well as maintaining a high enough H₂S level in the water in the district heating system to react with any oxygen that may be introduced into the system. However, H₂S is acidic and thus steam injection lowers the pH of the heated groundwater. From the commencement of hot water production at the Hellisheiði Geothermal Power Plant, keeping a steady pH and H₂S level has been problematic. To keep from corroding the pipes in the district heating system in Reykjavik the pH must be above 8,0. The average from the start of production is 7,9 and the pH has in certain instances been measured at 7,0.

A project to adjust this chemical balance in the heated groundwater started as a research project in 2018 and came into operation on a full scale in February 2022. In this project a small amount of the separator water (the liquid part of the geothermal fluid after steam and water have been separated) is mixed with the heated groundwater after deaeration. The separator water contains 20-30 mg/kg of H₂S and has a pH of ~9.2. It is fairly buffered compared to the heated groundwater and becomes dominating in the mixture even though the mixing ratio never exceeds 2%. Through this mixing the pH and H₂S can be adjusted simultaneously to an appropriate level. In addition to adjusting the chemical balance this mixing increases the production of hot water at the Hellisheiði Geothermal Power Plant

by 20-40 l/s at peak capacity, reduces the need for geothermal water re-injection, and the steam injection can be lowered significantly, resulting in more available steam for electricity production.

ER1-06

H₂S sequestration at geothermal sites: can we enhance the monitoring using geo-electrical methods? Insights from the GEMGAS project at Nesjavellir, Iceland.

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Hydrogen sulfur (H₂S) emitted from geothermal exploitation is an air pollutant: high concentrations of H₂S are corrosive and toxic. A solution to decrease H₂S emissions is to re-inject it into basaltic rocks. Laboratory studies show that the interaction between H₂S-enriched fluids and basaltic rocks results in the precipitation of pyrite and other minerals such as smectite. This solution has been applied at the Hellisheiði geothermal plant since 2014: both H₂S and CO₂ are captured from the non-condensable gases stream and injected into basaltic rocks. The success of mineralization is usually documented by tracer tests and chemical monitoring in wells located downgradient. We present here insights from the on-going GEMGAS project funded by Rannis, where the possibility to enhance the documentation of H₂S mineralization, using geo-electrical monitoring, is investigated.

Petrophysical laboratory measurements and field investigations at Krafla (Iceland) suggest that the formation of pyrite and smectite can be characterized by their resistivity and induced polarization (IP) signals and detected in volcanic rocks using geo-electrical methods. The GEMGAS research project (Geo-Electrical Monitoring of H₂S Gas Sequestration) aims at developing a new methodology for H₂S mineralization monitoring, using the special electrical properties of pyrite. A long-term goal of this research is to bridge the gap between reactive transport models and geophysical monitoring, where all type of data and knowledge are used together in the assessment of sequestration success.

A test injection of H₂S into shallow wells (200-500 m) at the Nesjavellir geothermal site started in January 2021 and has been on-going continuously since then. We use this opportunity to investigate the capabilities of five different geo-electrical methods to image H₂S sequestration in basalts: transient electromagnetic (TEM) soundings, self-potential (SP), surface electrical resistivity tomography and induced polarization (ERT/IP), casing-to-surface ERT/IP and borehole logging.

We first share our experience on how surface instruments can perform in such a context and summarize the lessons learnt from 3-year of geo-electrical field work at Nesjavellir. We discuss in particular the following challenges and how we dealt with them: buried infrastructure, retrieving information at the depth of interest and measuring systems changing position from year to year.

Then we present results from the two methods where electrodes are below the surface (logging and casing-to-surface). We focus in particular on the borehole logging, which has so far been carried out in 2020 (baseline), 2021 (injection + one month) and 2022 (injection + one year). Boreholes NN4, NN3 and NN7, where H₂S injection takes place, are investigated. We analyze the clear increase of IP signal observed in boreholes NN4 and NN3 and put that into perspective with independent knowledge. We compare the logging results to geology (cutting analyses and gamma-logs), porosity (neutron logs) as well as to the expected flow paths for the injected fluids, based on Nesjavellir conceptual model.

Finally, we will discuss why we think methods with subsurface electrodes are the way forward for H₂S, as well as for CO₂ in certain contexts, sequestration monitoring.

ER1-07

Are dykes and sills a feasible geothermal energy source?

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Geothermal exploration usually targets large magmatic intrusions as heat sources due of their longevity, size, and thus amount of stored energy. However, such large intrusions are usually located at several kilometers depth in active volcanic areas, while networks of numerous small intrusions (sills and dykes) are frequent even at shallower depths. To evaluate the geothermal potential of such small intrusions, we use geological data on the arrangement, size, temperatures, and host rocks of sills and dykes in the eroded Breiðuvík caldera in Northeast Iceland, which serves as an analogue to the active Krafla volcano. We use this data to constrain 2D finite element models of dykes and sills that consider heat transfer in porous host rocks of different permeabilities. We compare the cooling times and thermal impact of single, larger dykes and sills with those of arrays of contemporaneous small dykes and sills. Our modelling results show that small intrusions cause considerable thermal anomalies in their immediate vicinity. While larger intrusions produce larger-magnitude and longer-lasting anomalies, arrays of smaller sills and dykes emplaced close in time can create more widespread thermal anomalies that may be viable economic targets for decades after their emplacement.

ER1-08

Repeated Dike Intrusions as Heat Sources of Volcanic Geothermal Systems

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The Hengill geothermal system in SW Iceland, 30 km East from Reykjavik, is an important energy source for the Capital

Region. Reykjavik Energy's subsidiary ON Power operates two co-generation power plants in the area with total installed capacity of 423 MW_e and 500 MW_{th}. It is located within the rift zone of the Mid Atlantic ridge crossing Iceland from SW to NE. The nature of the heat sources of the geothermal system are not known. As a part of the company's ongoing research of illuminating the deeper parts of the system and its heat sources. A modelling study was performed with the aim of further study the hypothesis, that volcanic geothermal systems like the Hengill system, can be formed due to repeated shallow dike intrusions. As earlier studies have indicated. In numerical modelling of geothermal reservoirs, the heat sources are generally assumed to be below the model depth and accounted for by appropriate boundary conditions. The iTOUGH2 – EOS1sc module for water under sub- and supercritical conditions has made it possible to use the iTOUGH2/TOUGH2 simulators to model hydrothermal systems above the critical point of water. Allowing model depths to be increased and hot formations like dikes or plutons to be considered as a part of the model domain. A TOUGH2 model with the depth of 4 km and a permeability structure similar to what is seen in the Hengill system was made. Repeated dike intrusions reaching different depths were modeled, ranging from 1.2 to 3.0 km.b.s.l. The dike intrusions were assumed to be 2 km long and 25 m wide which is wide enough to fill up a space generated by the divergent plate boundaries over 1,250 years. The Results show that repeated dike intrusions under lithostatic pressure and with temperature of 900°C, reaching 2.5 km.b.s.l or higher, can form temperature structures as seen in the Hengill system in about 5-10 thousand years. If the diking intersects with the permeable part of the system. With the permeable structure used in the model it means that repeated diking reaching 2.5 km.b.s.l or higher can form high temperature geothermal systems. Given the assumptions made in the modelling process geothermal systems located on divergent plate boundaries, with permeability structure similar to the Hengill system, can be formed by repeated shallow dike intrusions reaching near to, or into the permeable part of the system. The diking will influence the location and lifetime of supercritical or superheated zones in the system compared to a system with a larger deeper heat source.

ER1-09

Stress Modelling of the Theistareykir Geothermal System: Mapping of In-Situ and Future Stresses of an Active Geothermal Production Area in NE-Iceland

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The Theistareykir Geothermal Field in NE-Iceland is a powerful high-temperature geothermal resource that has been explored for several decades to evaluate and develop its geothermal potential. With the recent development of the Theistareykir Power Plant (Theistareykjavirkjun), long term monitoring of the geothermal resource and its response to geothermal production is valuable for future utilization and potential expansion.

Stress change in geothermal systems is a critical parameter to monitor while exploiting geothermal resources. Stress change in the fracture network can lead to increased permeability, but critical stressing of existing faults can ultimately promote critical failure. Having a detailed stress model of a geothermal system can help quantify the stress rates induced in the region throughout the operational lifespan of the power plant. While countrywide stress models for Iceland are available, a detailed

stress model of the Theistareykir region has never been compiled. Due to its location along the active plate boundary within Theistareykir Central Volcano and in proximity to Krafla Central Volcano and the Husavík-Flatey Transform Fault, stress contributions from individual sources need to be isolated.

An overall stress model of the Theistareykir Geothermal Field was developed containing yearly stress contributions from plate spreading and volcanic sources applied to receiver faults and fractures with varied orientations. Further forward modeling was performed to determine the stress-state after major geological events in the region, such as a major earthquake on the Husavík-Flatey Fault, dike intrusions, or volcanic uplift to determine the future impact they could have on the geothermal area. The model is compared with primary datasets such as GNSS velocities, InSAR, seismicity, and borehole televiewer logs to verify model coherence with existing data.

We find that from the three dominating fault directions in the region, the primarily N-S trending faults have the highest susceptibility to positive coulomb stress changes. In contrast, ENE-WSW and WNW-ESE trending faults have more complex stress patterns that are highly spatially dependent. Forward modeling predicts that future geological or tectonic events have the capability to drastically change the stress state, with the most potent being a major earthquake on the Husavík-Flatey Fault. The results of stress modeling along the Tjarnar by seismic data in the pre-production period.

This study aims to evaluate the in-situ and future stress state of the Theistareykir Geothermal Area, and to be a resource for future decisions taken during the operation of the power plant. Future studies can build upon this for use in drilling, stability evaluations, or surveying for geothermal resources in similar volcano-tectonic settings.

ER1-10

The next steps in the Icelandic Deep Drilling Project (IDDP) – Reaching for the energy below conventional geothermal fields

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The next generation of high-enthalpy geothermal production is utilizing deeper near magmatic geothermal resources and tap into the roots of the geothermal systems to enlarge the geothermal production fields downwards. One of the projects that aim to drill deeper into hotter formations is the Iceland Deep Drilling project (IDDP). The three biggest power companies in Iceland, HS-Orka, Landsvirkjun and OR-Reykjavík Energy are working together with domestic and international partners on the project. Two wells have already been drilled, IDDP-1 in Krafla, N-Iceland, and IDDP-2 in Reykjanes, SW-Iceland. The third well, IDDP-3, is currently being planned in the Hengill Area, SW-Iceland.

To be able to produce energy from the hot deep layers in volcanic geothermal systems, several important challenges must be solved. Firstly, the roots of the geothermal systems are not fully understood. The depth range of the water circulation, the fluid chemistry, the depth of the heat sources, and the nature of the heat transfer between the heat source and the water circulation is not exactly known. The goal of the IDDP project is partly to gather important information on the conditions at

greater depths in a geothermal system, and to find out how to harness the energy there.

Another important goal of the IDDP project is to address the technical challenges of drilling into deep, hot formations and mine the heat from there. The two wells that already have been drilled in the IDDP project both have had problems with casing failures and corrosive fluid chemistry. Corrosive fluid has also been found in other deep hot wells in Iceland.

The main technical challenges are related to extreme temperature changes in the well bore. The well is relatively cold when the casings are installed and cemented. The well subsequently warms up and reaches the formation temperature and during production, casing is exposed to even higher temperatures. Those changes in temperature induce high stresses in the casing, that can cause it to fail. Corrosive fluid can also jeopardize well integrity. Thus, finding a cost-effective solution for mitigating thermal induced stresses in casing and preventing corrosion, is essential for drilling deep wells.

Solving those challenges will open a new frontier in geothermal power production. Huge resources below current geothermal reservoirs will be accessible for sustainable production of clean energy.

ER1-11

The use of ground source heat in Norway - energy potential and geotechnical challenges

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The use of ground source heat in Norway - energy potential and geotechnical challenges

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During the last decade, the extraction of low-temperature ground source heat from bedrock wells using closed-loop heat pump systems has become a significant part of the renewable energy supply in Norway. Between 2000-4000 energy wells have been drilled yearly, mainly single wells for private household heating, but also large well fields supplying housing cooperatives, hospitals and office buildings with both heating and cooling. During the summer season, excess heat from cooling is typically stored in the subsurface, warming up the ground for boosted heat extraction during the cold season. Given the energy crises in Europe, which have resulted in an all-time high price for electric power in the Southern part of Norway, a significant increase in projects using the subsurface for heat/cold storage are foreseen. Studies by the Norwegian Water Resources and Energy Directorate (NVE) show that today's installed capacity of 3 TWh/year could, from a cost/benefit perspective, be increased to over 30 TWh/year, which corresponds to over 20 % of the yearly hydropower production in Norway. In addition to the cost and energy-saving potential, ground source energy is a stable renewable energy source delivered on-site, not vulnerable to changing wind and sun conditions. It also has a lower impact on nature than onshore wind and hydropower installations.

However, in several cases in the last years, there have been reports of severe settlement damage on buildings and infra-

structure following energy well installations. These have raised concerns about the damage potential from the drilling of wells. We show that all the reported cases are in areas with thick marine clay deposits, indicating that the well drilling process and/or the well installation may alter the stability of the clay. In some cases, our evidence suggests that energy wells in bedrock may act as vertical drains for groundwater, resulting in a drop in the groundwater table, lowering pore pressure in the overlying clay deposits and subsequent ground settlement. The use of InSAR time series of ground movements (available through the Norwegian Ground Motion service: www.insar.ngu.no), has shown to be of great value to sort out possible causes of ground settlement, especially in areas with limited or no historical ground measurements. InSAR data have also been used in several court cases recently as evidence of land subsidence due to ground constructions such as sheet piling, excavations, and well drillings. It is foreseen that many similar cases will emerge in the coming years, both in Norway and abroad, as more wells are being drilled, and InSAR data become available and more widely used in the scientific and engineering community and society in general.

Keywords: Norwegian ground source heat potential, bedrock energy wells, marine clay, land subsidence, settlement damages, InSAR time series

ER2-01

Reservoir potential of the Faroe Islands basalt lava flows: an analogue study of the potential for CO₂ storage in volcanic margin basalt sequences

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Volcanic margin basaltic sequences present large-scale potential storage sites for CO₂ which may offer permanent low-risk storage as carbonates. On the Faroe Islands, NE Atlantic, such volcanic sequences have been uplifted and can be studied in the field. In this study, we characterize the porosity and permeability of the onshore deposits and relate this to the potential for offshore CO₂ storage in the North Atlantic Igneous Province.

We have conducted outcrop studies and accessed onshore borehole data from the Faroe Islands. Virtual outcrop models, photos, and samples were collected in the field. The density log from the Glyvursnes-1 borehole, along with grain density estimates, was used to calculate and compare two end-member porosity logs, and laboratory analysis of borehole and field samples, by use of optical microscopy, Scanning Electron Microscope (SEM) and micro-CT (computer tomography) image analysis were used to characterize the pore networks in the rocks.

The studied Malinstindur and Enni formations of the Faroe Islands Basalt Group reveal mixed volcanic sequences comprising simple and compound-braided lava flows and volcanoclastic beds. The individual flow lobes consist of upper and lower crusts, either brecciated or vesicular, with thicknesses ranging from 0.20 m to 13 m, the upper crusts being the thickest. The crusts are separated by low-vesicularity cores with thicknesses from 0.5 m to 25 m. Most of the pores are filled with secondary zeolite and clay minerals. The porosities of the flow crusts and hyaloclastites measured from micro-CT image analysis range from 0.5% to 36.2%, with primary porosities (found by adding the volume of mineralized pore space to the current porosity)

up to 44.9%. The highest current porosities are measured for the unmineralized brecciated upper flow crust samples while the highest primary porosities are estimated for the brecciated hyaloclastite samples. Simulated permeabilities of the CT scans reach up to Darcy-scale. However, this can quickly be reduced to microdarcy-levels if secondary mineralization of the pores is prevalent. The volcanoclastic interbeds are estimated from the porosity logs to have potentially high porosities (5% to 35%) in the lower Enni Formation. However, the optical microscopy and SEM studies reveal a high content of clay and zeolite cementation, reducing the permeabilities in most of these beds. Micro- and macroscale fractures, from cooling of the lava flows and from later tectonic deformation, may increase the permeability of the volcanic sequences. However, this could not be easily addressed using small scale laboratory samples. In conclusion, the current presence of high porosity and high permeability crusts and the indication of high primary porosity crusts in the Faroe Islands basalt give hope for finding good reservoir units in less altered offshore basalt sequences, e.g., on the Vøring volcanic margin. The brecciated basalt flow crusts show the highest CO₂ reservoir potential, while the red beds and flow cores are more likely to work as caprocks or baffles.

ER2-02

How to obtain a better overall geological understanding of the central Faroe Islands by usage of Construction of a geomodel in Petrel software by integrating geological and geophysical data of different scale and age.

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Mapping is essential for understanding any geological settings, and on the Faroe Islands organized mapping based on detailed fieldwork, has been carried out since 1940'ies. Data form the basis for all mapping and therefore data are essential but how can data obtained during a large time span and from various sources be used in the digital 21'th century? Are such old data relevant for present day research questions, and can they reveal potential sites for CO₂ storage?

In this study, we showcase that a large array of data sources can be combined into a geomodel in the state-of-the-art software Petrel to address these questions for the central part of the Faroe Islands. By uniting information across scales and methods, we provide new insight into geological disagreements and unknowns in the published literature.

First, we map the Malinstindur Sneis Unconformity (MSU) across the island of Streymoy by integrating lithological logs, surface boundaries and digital surface models. By doing so, we resolve a disagreement on the level of the MSU, showing that it is located 89 meters lower in the stratigraphy than the most recent publication state.

Further, we follow the same unconformity across the Skopunarfjørður by adding well logs, seismic, bathymetry and photogrammetry. Here several different structures have been hypothesized to be present to consolidate well correlation be-

tween the three adjacent islands. However, by including these additional data in our geomodel, we correlate the layer boundaries without any sign of a dextral strike-slip fault or dome as shown in recent publications.

The results clearly show that compilation of existing data and the modelling possibilities with today's software, new insight can be gained from existing data. Our findings also highlight the importance of basing mapping on data with variable scales.

ER2-03

CO₂ storage on the Norwegian Continental Shelf – status and learnings

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Carbon capture and storage – CCS – is an important emissions reduction technology that can be applied across the energy system.

Norway has extensive experience with storage of CO₂ in geological structures. Important projects are the storage in the Neogene Utsira Formation in the North Sea since 1986, and storage in the Late Triassic to Mid Jurassic Realgrunnen Group in the Barents Sea since 2008. The Longyearbyen CO₂ lab project 2007-2017 (Spitsbergen / Svalbard) have also added important knowledge to the understanding of geological CO₂ storage.

The first licence for CO₂ storage on the Norwegian Continental Shelf (NCS) was awarded early 2019. This acreage is part of a Norwegian, partly state funded, CCS project called "Langskip / Longship". As of early March 2022, two additional areas – one in the North Sea and one in the Barents Sea - have been offered for CO₂ storage on the NCS.

The assessment of geological storages for CO₂ follows many of the same approaches as known from petroleum play- or prospect evaluations. However, some key differences are the methods and principles for estimation of storage capacity, the importance of monitoring – for efficient injection and safe storage, and the increased attention to ensure and to document the presence of sealing rocks.

The geological storage of CO₂ is typically part of a comprehensive, and sometimes complex value chain, and it is vital that the subsurface evaluation is performed and timed to other parts of these still rather new CCS technologies and -businesses.

ER2-04

Evaluating CO₂ storage potential in an under-explored basin: Stord Basin, northern North Sea

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Carbon capture and storage (CCS) will be an essential component of the energy transition, enabling decarbonisation of fossil-fuel intensive industries, and ensuring a reliable energy supply with low or negative emissions. Globally, many CCS projects are currently in development, with subsurface reservoirs providing safe, long-term storage options for captured CO₂. Norway has committed to implementing a full-scale CCS

value chain by 2024 via its 'Longship' project. In line with this, the Northern Lights partnership drilled the first CCS appraisal well on the Norwegian Continental Shelf in 2020 (Eos), targeting a suitable subsurface trap structure on the Horda Platform in the northern North Sea. However, in order to meet ambitious climate targets, CCS infrastructure must be rapidly upscaled to accommodate exponentially increasing volumes of CO₂. Regional studies have shown that it may be possible to store a large amount of CO₂ on the Norwegian Continental Shelf, but we now need detailed geological characterisation to rank and de-risk potential new storage sites.

The Stord Basin is located in the northern North Sea, south of the Horda Platform where current CCS activity is focussed. It is relatively under-explored due to its lack of hydrocarbon prospectivity, but may provide viable opportunities for CO₂ storage in saline aquifers. In this study we generate a model for the tectono-stratigraphic evolution of the Stord Basin, and use this to evaluate the basin potential for structural, stratigraphic, and residual trapping. We then discuss the potential risks associated with the potential storage sites identified using currently available data. We show that despite the lack of identifiable structural traps at depths suitable for CO₂ storage, sand-rich units within the Upper Triassic to recent strata provide good stratigraphic and residual trapping opportunities.

ER2-05

Fault Gouge Characterization in the Øygarden complex SW Norway – Relevance for offshore CO₂ storage

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Pre-existing structures such as faults are common within the North Sea sedimentary basin. These faulted reservoirs provide significant closures for subsurface storing of CO₂. An understanding of fault rocks is therefore crucial for evaluating the long-term storage stability of CO₂ storage sites. When injecting CO₂ into a faulted or fault-bound reservoir, the increasing pore pressure can lead to an increased risk of fault reactivation followed by changes in permeability and strength. The Smeaheia area, a potential CO₂ storage site at the Horda Platform is juxtaposed with the basement rocks of Øygarden Complex (ØC) to the east by the Øygarden Fault System (ØFS). The fault-related reactivation risk of the Smeaheia site towards the eastern ØFS is therefore closely linked to the characteristics of fault rocks that is present within the faulted crystalline basement rocks of the ØC. Fault gouge, a clay-rich material found within the core of shallow brittle faults, is of particular interest, as this material can act as an impermeable seal preventing fluid flow. Fault gouges also represent the mechanically weakest material found within the fault core. Despite fault rocks and fault gouges being of high importance for CO₂ storage evaluation, the amount of data from intact offshore fault rocks is limited. In this work we test the friction and cohesion of well characterized fault gouges from the ØC by using accessible surface-exposed onshore faults. Fault rocks are characterized by grain size distribution and mineralogy using both powdered clay analysis (XRD) and thin sections (optical microscopy). The fault rock samples are subjected to direct shear box experimentation at effective normal stresses ranging from 0.1 to 1.5 MPa to determine the friction angle and cohesion of the material. A total of six faults from the ØC were sampled, in addition to the well-documented Lærdal-Gjende Fault for comparison purposes. The tested sam-

ples have friction angles ranging from 17 to 32 and cohesion values ranging from 44 to 200 kPa. The structural characteristics of the faults and the local host-rock composition will be used to systemize the results, with the final aim to increase our understanding of the geological and mechanical properties of fault rocks derived from the Øygarden Complex, which juxtaposes the Smeaheia site.

ER2-06

Structural characterization and across-fault seal assessment of the Aurora CO₂ storage site, northern North Sea

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Faults play an essential role in de-risking potential CO₂ storage sites because they can act as conduits or barriers to fluid flow, thus affecting the migration of injected CO₂. Currently, the Northern Lights project is planning to store CO₂ in the Aurora storage site located in the northern North Sea. To contribute to the evaluation of the Aurora storage site, we create a detailed structural geomodel and perform structural characterization and assessment of across-fault seals that intersect and displace the Lower Jurassic storage aquifer and seal pair.

We find that the storage aquifer and seal are laterally extensive and dip to the south. First-order faults, including the block-bounding Svartalv Fault Zone, within the Aurora storage site, are predominately N–S striking, W-dipping, with throws greater than the thickness of the primary seal (>85 m). Second-order faults strike N–S to NW–SE, display varying dip directions, with throws generally less than the thickness of the primary seal.

Considering the dip of the storage aquifer, injected CO₂ is likely to migrate northwards and encounter the first-order Svartalv Fault Zone on its footwall side, which juxtaposes the storage aquifer against shallower sand-rich successions, potentially allowing across-fault migration. However, calculated shale gouge ratio (SGR) values exceeding 0.3 are present at the depth of the storage aquifer, suggesting that a membrane seal is present. Furthermore, second-order E- and NE-dipping faults along the projected up-dip CO₂ migration path juxtapose parts of the storage aquifer against the seal likely baffling and/or redirecting fluid flow. In places, these faults are hard-linked with the Svartalv Fault Zone on its footwall side creating smaller-scale structural traps, which possess a combined gross rock volume (GRV) of $158 \times 10^6 \text{ m}^3$ in the storage aquifer. Overall, we suggest that faults within the Aurora storage site may have a positive impact on CO₂ storage by creating baffles and structural traps thus slowing down plume migration and contributing to the storage capacity.

ER2-07

An assessment of CO₂ and H₂S mineralization efficiency at the Nesjavellir (Iceland) geothermal storage site

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The transition to clean and renewable energy sources such as geothermal is considered as one of the main solutions to limit CO₂ emissions into the atmosphere and avoid climate change crisis. Although lower than for fossil fuels, the geothermal GHG emissions are estimated to 11-78 gCO₂eq/kWh, comparing to hydro and wind offshore that equal to 2-75 and 5-24 gCO₂eq/kWh, respectively (Amponsah et al., 2014). To reduce these emissions and limit the carbon footprint of the geothermal utilization, carbon capture and storage technologies can be implemented. The carbon and sulfur mineralization in the subsurface using CarbFix method has already been applied at the Hellisheiði geothermal power plant. In this technology the CO₂ and H₂S from the gas emission stream are captured through their dissolution into condensed steam from the power plant, mixed with the separated water and injected into the reservoir. Mineralization of the gasses happens as a result of water-rock interaction.

This study describes the likely fate of water dissolved CO₂ and H₂S to be injected into basalts within the Nesjavellir geothermal system (SW Iceland) in 2022. The results show that the injection of CO₂ and H₂S charged waters at the outskirts of the Nesjavellir geothermal system favors CO₂ and H₂S mineralization due to 1) relatively low reservoir temperature at this location, 2) the distance, and 3) low subsurface fluid flow rates between the injection and the production wells. At the planned CO₂-H₂S charged water injection rates, the mineralization efficiency along the flow path between injection and production wells is expected to be about 70% for CO₂ and up to 100% for H₂S. The CO₂ mineralization efficiency, however, can be increased somewhat by increasing the mass of host basalt dissolved into each kg of injected fluid potentially by increasing fluid residence time or degree of matrix versus fracture flow in the subsurface. Although the composition of the Nesjavellir production reservoir is expected to remain similar to its current composition during the pilot injection, the injection of all CO₂ emissions from the Nesjavellir power plant might, however, result in the increased CO₂ flux into the reservoir fluid over time if mineralization is not complete. In such a case, higher CO₂ surface emissions over time can be expected and therefore efforts need to be made to maximize injected gas mineralization prior to recovery of the gas-charged injection fluids in the production reservoir.

Amponsah, N. Y., et al., 2014. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations." *Renewable and Sustainable Energy Reviews* 39: 461-475

ER2-08

Initial conditions at the new injection site at Nesjavellir: Intergrating multiple geoscience models to predict flow paths, mineralization and mass replenishment

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After a successful implementation at the Hellisheiði geothermal field, the Carbfix method will be tested at the nearby Nesjavellir

high temperature geothermal field in SW Iceland. The CO_2 and H_2S will be captured from the gas emission stream of the Nesjavellir power plant and after mixing with separated water and condensed steam it will be injected into a 2138 m deep well, NJ-18, which is located in the northern part of the field. This pilot injection is to begin in 2022. Although the Hellisheiði and Nesjavellir are a part of one volcanic system, their subsurface characteristics is different. The aim of this study was to obtain a solid knowledge of the stratigraphy, mineral alteration and geological structures of the field that will help to predict the flow channels and pathways for the CO_2 , H_2S charged injected fluid. Together with the pre-injection temperature and pressure distribution in the reservoir, it will be used to model the physical processes such as replacement and mixing of the reservoir fluid with the injection water and the chemical reactions that will take place when the dissolved CO_2 and H_2S is injected into the reservoir.

As a part of the GECO H2020 project [1], the vicinity of the Nesjavellir injection well NJ-18 was thoroughly modelled with respect to the geology, the reservoir physical properties and the chemical reactions taking place before and after injection of the gas mixture. A volcanic fissure has been identified as a major barrier to the flow from the injection well to the production aquifer. A simple geological model depicting different formations with respect to porosity and permeability was constructed in Leapfrog and used as a basis for constructing a TOUGH2 reservoir model and the TOUGHREACT reactive transport model. The results of the modelling show a rather slow flow from the injection well towards the centre of the production field that allows the gas mixture to mineralize before reaching the production wells. They also confirm that the mineralisation efficiency depends on the reservoir temperature, composition of the injected and reservoir fluids, and the rock composition in the target injection aquifer. This preliminary modelling was an important first step for the prediction of the CO_2 and H_2S mineralization potential and optimization of the injection conditions in NJ-18. Further hydrological and geochemical data is being gathered to update and improve the models. Apart from basaltic geothermal fields, a similar pre-injection workflow to investigate the CO_2 mineralization potential and storage can be applied for CO_2 injections into ultra-mafic and mafic rock formations.

[1] Sigfússon, Bergur, et al. „GECO—Geothermal Emission Control.” Proceedings World Geothermal Congress. 2020.

ER3-01

Pre-Holocene groundwater within the Icelandic crust

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Pre-Holocene groundwater within the Icelandic crust

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Water stable isotope measurements have been conducted in Iceland since 1963, on groundwater, including geothermal water, surface water, and precipitation. Three generations of IRMS have been used for the measurements. During the last ten years laser-based instruments have also been run for both water samples and for continuous sampling of water vapor, in order to study the atmospheric water vapor cycle.

During the last decade the water stable isotope measurements have revealed that old groundwater, originating from precipitation during the last glacial period, some 12.000 years ago, is

more common in the Icelandic bedrock than originally thought. Some of this groundwater can be characterized by its very low oxygen- and hydrogen isotope ratios due to the cold climate conditions at the time of precipitation. In other instances however, stable water isotopes alone cannot confirm this origin, because the groundwater is often mixed with younger and isotopically more enriched precipitation, making the groundwater not distinguishable from mean annual isotope values of present day precipitation in Iceland. In that case the origin of the groundwater must be based on interpretation of stable water isotopes and water chemistry in connection with the hydrogeology of the area.

ER3-02

Isotope hydrology (2H and 18O) of water from the arctic Ikka Fjord, SW Greenland

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The small Ikka Fjord in arctic SW Greenland is home of more than a thousand submarine tufa columns. A long series of expeditions have visited the fjord from 1995 to 2021 with focus on geology, topography, biology, and hydrology of the columns. As part of the program more than 350 water samples have been collected from streams, springs, and lakes in the catchment areas of the fjord and from the fjord itself and analysed for ^{18}O - and partly for ^2H -concentrations. This work presents the results from isotope studies of fjord water, streams, and submarine springs and illustrates the usefulness of stable isotope studies in arctic hydrological programs. The following conclusions have been made: 1) Seasonal effects exist in isotopic composition between stream samples from early field campaigns (June and early July, depleted) and late campaigns (late July and August, enriched) field campaigns of approx. 13‰ $\delta^2\text{H}$ and 2‰ $\delta^{18}\text{O}$. These differences probably reflect melting of snow and make it necessary to standardize data from different seasons before evaluation. 2) Also clear is a negative altitudinal effect in stream water of 12‰ $\delta^2\text{H}$ and 1.5‰ $\delta^{18}\text{O}$ over 900 meters of elevation reflecting the precipitation at the source areas. 3) The composition of submarine spring water sampled from the Ikka columns is strongly influenced by sampling method and reflects the degree of contamination from fjord water. The least contaminated samples (drawn by syringes embedded in the columns) have isotopic compositions ($\delta^2\text{H}$ between -88‰ and -95‰; $\delta^{18}\text{O}$ between -12.5‰ and -13.4‰) close to that of the most depleted surface spring waters and support the hypothesis that columns are fed from precipitation falling at elevated altitudes. Cation data support this conclusion. 4) The freshwater samples define a local meteoric water line (LMWL: $\delta^2\text{H} = 6.4 \cdot \delta^{18}\text{O} - 11.6$, $R^2 = 0.97$) which is different from the general Global Meteoric Water Line ($\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10$). No significant secular changes in the isotopic compositions of the different freshwater systems have been noticed over the 26 years of sampling. 5) Samples from the fjord system exhibit a well-defined linear mixing between sea water from the Davis Strait ($\delta^2\text{H} \approx -9$ ‰, $\delta^{18}\text{O} \approx -1$ ‰) and stream water ($\delta^2\text{H}$ between -100‰ and -115‰; $\delta^{18}\text{O}$ between -12‰ and -16‰) flowing into the fjord from the surrounding highlands.

Isotopic composition and origin of molecular hydrogen in bedrock groundwater

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The presence of H₂ in bedrock groundwater plays an important role in the safety assessment of radioactive waste disposal as well as underground mining. Naturally occurring H₂ may also form economically important energy reserves. Within the bedrock, molecular hydrogen (H₂) forms in reactions between water and minerals and microbially. Abiotic formation mechanisms span from serpentinization and other iron related hydration reactions to radiolysis of water, and mechanochemical pathways. Assessment of the H₂ production potential intrinsically depends on the understanding of these processes.

In this study, we compiled and analysed isotopic compositions of H₂ and related groundwaters, 12 samples in total, within the Fennoscandian Shield in Finland down to 2.4 km depth. In addition to classical continental serpentinite systems also sandstone, siltstone, metavolcanic and mica schist dominated bedrock environments were included.

Isotopic composition of H₂ in bedrock groundwaters in Finland ranges from -619 to -848 ‰ VSMOW and is among the most deuterium depleted reported from a natural setting. Isotope fractionation between groundwater and H₂ indicate equilibrium temperatures below 106°C, consistent with formation or re-equilibration within the upper 4.5 km of the crust and within temperature limit of the habitable zone. One third of the samples show unrealistically low equilibration temperatures down to -37°C, which could be due to non-equilibrium processes or migration of H₂ from a source where isotopic composition of water differs from that used in the model.

Comparison of different host lithologies reveal similarities of serpentinite, mica schist and metavolcanic environments to other continental serpentinization sites, while H₂ in the basal parts of the sandstone and siltstone units is more deuterium depleted. Process specific fractionation, as implied from previous experimental and field studies, is consistent with serpentinization, mechanochemical and microbial pathways, but differs from radiolytic formation. Abundant occurrence of He and other radiogenic noble gases with H₂ suggest radiolysis play a role, and equilibration can be related to long residence times and reprocessing and cycling of H₂ in the subsurface.

Early diagenesis as a precursor for aquifers in carbonate rocks

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Carbonate rocks are of high interest regarding sustainable energies (geothermal, water resources) and climate change mitigation (greenhouse gas sequestration, waste storage). Past ambitious data collection and observations suggested that the development of good aquifer properties in carbonate formations could be created through early diagenetic processes (Budd, 1994; Budd et al., 1995; Volery et al., 2010; Deville de

Periere et al., 2011; Brigaud et al., 2014; Regnet et al., 2015a; Andrieu et al., 2017; Regnet et al., 2019; Bailly et al., 2019). One of the key process could be the early cementation of calcium carbonate through freshwater-related diagenesis, where the sediment framework is chemically stabilized and rigidified by early cements (EC) at grain interfaces, preventing mechanical compaction, and favoring the preservation of the primary porosity. These early cements might also be partial inhibitors of microstylolitisation and even stylolitisation during burial conditions (Heydari, 2003; Brigaud et al., 2010). This paradigm could work well in coarse granular limestone successions (e.g. oolitic sands) because of their high diagenetic potential, but it fails to explain observations made in mud-rich limestones. In that specific case, porosity enhancement and redistribution could be created during early diagenesis by mineralogical stabilization of metastable mineral species (a process called *Ostwald Ripening, OR*), as summarized by Lucia (2017). This could result in a well-developed porous network thanks to the dissolution of less stable phases (aragonite, high magnesium calcite...) in the rock fabric. Diagenetic processes in these rocks are ubiquitous, from deposition to present day. In nature, we usually observe the finished product of diagenesis with very low constrain on the link existing between the processes and their accountability on rock properties. For the first time, we intend to study these processes under a controlled environment to isolate them, and discern their respective role on the structure and properties evolution of carbonate rocks. The **PREFAB** project will develop an acute understanding of early diagenesis and its precursor role on aquifer creation and preservation in carbonate rocks. The project will provide a thorough understanding on the crucial and deterministic factors conditioning the creation of well-developed porous and permeable units in carbonate rocks by answering two central questions: (Objective 1) what are the roles of the initial sediment mineralogy and fluid chemistry on early diagenetic transformations? And (Objective 2) what are the areas in current carbonate environments that are prone to become potential aquifers? This project is founded on (i) a new apparatus designed to simulate fluid-rock interactions in the laboratory under temperature and stressfield in oedometric conditions while measuring sediment properties evolution (deformation, permeability, ultrasonic velocities), and (ii) on a meticulous field characterization of a modern-day carbonate sediment to understand the spatial partitioning of early diagenetic processes. By subjecting a wide range of carbonate sediments to fluids of various chemical compositions in the laboratory (O1), and combining this approach with observations at a greater scale (O2); it will be possible to perceive early diagenesis with a physical and geological perspective.

Understanding the flow path of reagents in groundwater remediation actions, by means of cross-borehole electrical monitoring

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Soil and groundwater contamination has become a world-wide challenge. In 2017, a total of 1.3 million and 2.8 million contaminated sites were estimated in the US and Europe, respectively. Remediation by excavation is expensive and can lead to a significant carbon footprint. The development of cost-effective in-situ remediation technologies, where contaminant sources and plumes are directly treated in the groundwater, is a high priority.

With in-situ remediation, adequate delivery of remediation agents in the whole target volume is challenging, whether it is directly the source area or a treatment zone intersecting the contaminant plume. Monitoring the spatial distribution of injected reagents is important for engineers and decision-makers, in order to determine the need of more careful injection in some areas. We use cross-borehole electrical resistivity tomography (XB-ERT) to visualize the progressive spreading of chemical reagents that are aimed at degrading chlorinated solvents in groundwater. Two sites are presented.

Kærgård Plantation is one of the largest polluted sites in Denmark, with over 300.000 tons of pharmaceutical waste dumped in sand dunes in the 1960s. The geology consists of sand and gravel layers of high permeability and the remediation targets the contamination hot spots themselves. Farum parking lot is an experimental site in the suburb of Copenhagen, where waste and spills from a packaging factory led to several groundwater contamination hotspots. The in-situ remediation there aims at creating a treatment zone intersecting the contaminant plume coming from the different hot spots. The injection takes place in a fine-grained sandy aquifer of intermediate permeability.

Resistivity imaging by XB-ERT allows visualizing the remediation cloud, composed of sulfate ions at Kærgård site and a complex mixture of solid iron and aqueous species at Farum site. Overall successful spreading is observed in Kærgård, whereas the treatment zone installation is much more problematic in Farum. Two injection rounds were attempted with different strategies in Farum. Both led to heterogeneous spreading, as well as significant upstream leakage and surface spills.

Based on time-lapse resistivity results, chemical monitoring, as well as solid iron analyses in core sediments, we suggest the creation of preferential pathways during injection at Farum, possibly related to the unintentional creation of fractures.

Overall, we find that the XB-ERT technology is suitable for monitoring reagent distribution at the two sites and has a clear impact on follow-up action steps.

ER4-01

Sustainable management of deep-sea minerals within national jurisdiction: the case of Norway

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The global energy system is facing a major transition to green energy. Several countries and companies are working with clean energy technologies which relies on critical elements such as copper, lithium, nickel, cobalt, and rare earth elements. New industries have increased the demand of these raw materials and require reliable and sustainable sources for supply of resources to support the energy transition.

In 2019, the Norwegian Parliament passed the Seabed Minerals Act. The law states that an Opening Process must be carried

out before an area can be opened for Exploration for Marine Minerals. In 2020 the government of Norway initiated a process for opening parts of the Norwegian continental shelf for Marine Minerals activity. The Opening Process consists of an Impact Assessment and a Resource Assessment.

The Ministry of Petroleum and Energy is responsible for the Opening Process and the NPD assists the ministry and co-ordinates the Impact Assessment process.

The Impact Assessment shall consider the environmental, industrial, economic, and social impacts of mineral activity in the area. The program for the Impact Assessment was published by the Ministry of Petroleum and Energy 12.01.2021.

The process involves public hearing of the program for Impact Assessment and of the final document. The program consists of two main parts, baseline studies and studies of the social and economic impact from the activity. Finally, the Impact Assessment will be put forward to the Norwegian Parliament for decision. The process shall conclude on whether the area shall be opened for mineral activity and, in that case, on which terms. In case of mineral activity, the law states that project specific impact assessments shall be carried out on different milestones after licensing.

Resource Assessment is an important part of the Opening Process. The NPD shall map the area and, on this basis, carry out a resource assessment of the mineral resources. Since 2001 we have gathered data in cooperation with Universities in Norway, and since 2018 conducted our own dedicated NPD cruises. We have used different mapping techniques and the talk will demonstrate examples from the mapping and data acquisition made by the NPD.

ER4-02

New technology and mission concept to discover marine critical minerals

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Impossible Sensing, St. Louis, United States

Our mission concept brings robotic laboratories to the ocean's depths to locate, size, and characterize mineral resources and biological communities.

STINGRAI, Seafloor Telepresence INvestigation of Geobiochemistry with Realtime Autonomous Intelligence, is a new way of exploring the seafloor and subseafloor: it acquires and interprets comprehensive data and information needed to understand seafloor characteristics such as depth, topography, type, composition and distribution, and underlying geologic structure.

To achieve this, STINGRAI uses low-mobilization and low-risk AUV (autonomous underwater vehicle) and autonomous USV (uncrewed surface vehicle) platforms and a combination of high-performance stand-off and close-up sensing technologies: multi-beam echo sounder, laser spectroscopy suite, and acoustic sub-bottom profiler. With STINGRAI we are bringing robotic laboratories to the seafloor, as opposed to bringing seafloor samples to the lab. This innovation will lower cost and time to explore the seafloor.

STINGRAI leverages our space exploration capabilities, initially created for NASA, to thoroughly map and discover marine minerals in a sustainable and timely manner, as required by rapid decarbonization. At the conference, we will describe our mission concept and the technology our team is developing.

Geological models for some SMS deposits in the Mohn Ridge in the Norwegian Sea.

Harald Brekke

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Seafloor massive sulphide (SMS) deposits that are found along today's active ocean floor spreading ridges have their analogues in the volcanic massive sulphide (VMS) deposits in ophiolite complexes on land. In 2018, 2019 and 2020, the Norwegian Petroleum Directorate (NPD) conducted data acquisition cruises to the newly discovered SMS deposits, the Mohn's Treasure, Gnitahai and Faavne, in the northern part of the ocean spreading ridge in the Norwegian Sea, the Mohn Ridge. During these cruises, the NPD acquired high-resolution multibeam data, geophysical and electromagnetic data, together with drill cores, and samples by ROV. The current work aims to demonstrate how the data and samples from these deposits may fit into known geological models for the formation of such deposits to develop site specific geological models. This work, which will be presented, includes comparisons with both offshore and onshore examples. Major questions concern the geometry and configuration of the fault systems of the axial valley flanks and how these relate to the SMS deposits. In many places of the world, SMS deposits seem to be connected to large, dominating faults with an even, striated fault plane, so called oceanic core complexes. There is no evidence of such core complexes related to the Mohn Ridge deposits. On the contrary, the bathymetric data show that the overall, large flank escarpments are themselves subdivided by numerous, lesser fault scarps. Models will thus have to take into account how these faults may continue at depth and how they shape and modify the deposit at and near the surface. It is possible that the faults connect to a large, underlying master fault or that they assemble as one large fault or fault zone at greater depth. In any case, it seems that geometric solutions will have to accommodate structures that allow vertical flow of hydrothermal fluids at the location of the SMS deposits. Possible models of the tectonic framework, combined with the surface data, may give some constraints to the vertical extent, and thereby the volumes, of the individual deposits. Furthermore, models of the fault geometry and tectonic framework must fit with the process by which the fault scarps and volcanic complexes of the active axial spreading eventually become inactive, broken off, elevated, and frozen into the main, inactive ocean crust of the ocean spreading process. This inactive ocean crust forms the vast areas of deep-sea floor and is made up of the fragments of paleo axial valleys. From the multibeam bathymetry it is possible to distinguish these fragments that are remnants of previous stages of the axial valley. This allows mapping out the number of previous stages of axial valley activity in an area and thereby set some constraints on the number of possible SMS deposits formed in that area. The model constraints of both the size of individual deposits and their number in a given area will be used as supportive information in the overall evaluation of mineral resources.

Evolution of the metal-bearing fluids at the Fåvne hydrothermal vent field, the Arctic Mid-Ocean Ridges

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The Fåvne hydrothermal vent field (72°45'N, 3°50'E) is located in the central part of the Mohns Ridge, the Arctic Mid-Ocean Ridges, at the depth of ~3,000 m. The vent field is hosted by basalt lava covered with ~50 cm thick layer of deep-marine sediments. The hydrothermal activity seems to be controlled by a normal NE-SW trending fault that underlies the western portion of the field. The vent field hosts nine individual mound structures with associated chimney complexes. Five of the mounds in the central and northern parts of the field currently discharge high-temperature black smoker fluids whereas the southern part of the field is characterized by low-temperature venting and Fe-oxyhydroxide-rich precipitation.

The Fåvne mineral assemblages can be subdivided into two main types: 1) Cu-rich mineral assemblages and 2) Zn-rich mineral assemblages. The Cu-rich assemblages are predominantly composed of anhedral to subhedral pyrrhotite crystals intergrown with anhedral isocubanite crystals. Chalcopyrite occurs as ~1 µm wide lamellae within isocubanite. Rare pyrite grains were observed locally as individual crystals that overgrow pyrrhotite and isocubanite. Minor amounts of sphalerite have been recorded locally. Secondary chalcocite and covellite occur along fractures and grain boundaries of isocubanite. Abundant anhydrite occurs in forms of clusters within the sulphide matrix and as thin crustiform layers along fluid conduits. The Zn-rich assemblages are dominated by sphalerite and do not contain Cu sulphides. Sphalerite occurs as anhedral to subhedral crystals and fine-grain masses that locally exhibit colloform textures. Anhydrite is abundant and mostly occurs in forms of clusters. Variable amounts of pyrrhotite, pyrite and marcasite have been found as well.

The Cu-rich mineralization shows a strong enrichment in Co. The trace element maps indicate that Co is bounded in crystal lattices of pyrrhotite and isocubanite. This type of mineralization also shows an enrichment in As, In, Au and Bi. In contrast, the Zn-rich mineralization is depleted in Co but enriched in Ga, Ge, Mo, Ag, Cd, Sn, Sb, Hg, Tl, and Pb.

The fluid inclusions study has revealed that the Cu-rich mineralization was deposited from NaCl-CaCl₂ aqueous fluids with salinity >8 wt.% NaCl equ. and temperature >330°C. A combination of cooling and dilution due to mixing with seawater resulted with destabilization of Cu-chloride and Co-chloride complexes and precipitation of the Cu-Co sulphide mineral assemblages. Zinc was also transported in form of its chloride complexes but, comparing to Cu- and Co-chloride complexes, Zn-chloride complexes show a greater stability at lower temperatures and lower Cl activities. Therefore, the deposition of the Zn-rich mineralization requires a greater degree of mixing with seawater resulting in the spatial separation of Cu- and Zn-rich assemblages.

Mineral Criticality – why critical minerals are different and why they are not.

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Metals, minerals and materials and their sustainable supply are important for society in general, and for the transition to a green economy in particular. They are key for achieving the goals set out in COP21 and for several of the United Nations Sustainable Development Goals. Some of the important metals to underpin the energy transition are viewed as *critical*.

Criticality of minerals is generally assessed in terms of two dimensions, the likelihood of supply disruption, often termed supply risk, and the economic vulnerability of the consumer to potential supply disruption, the importance. Critical minerals (CRMs) are high on the agenda globally and several initiatives are underway to understand and mitigate criticality, on an international level (e.g., UNECE's resource classification framework (UNFC), and EU assessments and funding initiatives) and on the national level and the level of certain sectors.

Also the UK is committed to developing a CR strategy and establishing long term understanding of implications and possible mitigations of criticality. The British Geological Survey recently conducted the first UK criticality assessment, in which 26 minerals were assessed for their potential criticality to the UK economy in terms of their global *supply risk* and the UK *economic vulnerability* to such a disruption. Three indicators were used to estimate supply risk: production concentration, companion metal fraction and recycling rate. Economic vulnerability was calculated from six indicators: production evolution, price volatility, substitutability, global trade concentration, UK import reliance and UK gross value added contribution. Eighteen of the 26 minerals have a 'high' potential criticality rating and constitute the UK Critical Minerals List 2021 (Lusty et al., 2022).

The history of gold exploration in Iceland by Malmis and associates

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A renewed effort of gold exploration in Iceland started some 32 years ago when a close connection was realized between processes in the active high temperature systems and the precipitation of gold. From that time exploration phases have been undertaken in line with positive results, funding and the state of the international exploration market. Gold exploration is presently ongoing. The exploration has been mainly centered on eroded fossil high temperature systems. Several anomalies have been located with elevated gold values above 1 g/t, the highest concentrations found in the Thormodsdalur prospect east of Reykjavík where a core sample containing up to 415 g/t was found.

Sulphur isotope systematics in sulphide occurrences in the Lovisa region, SE Finland

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A number of polymetallic, In-bearing sulphide mineralizations have recently been recognized in the Lovisa region, SE Finland (Cook et al. 2011; Valkama et al., 2016; Broman et al. 2018). They are hosted by the 1650-1625 Ma Wiborg rapakivi batholith, which, together with the 1665-1645 Ma Häme dolerites, constitutes an expression of a failed intracontinental rift of Baltica and lacks any association to marine sedimentary basins. The rocks surrounding the batholith are dominated by Svecofennian (1.9-1.8 Ga) granitoids and amphibolites. No organic-bearing sedimentary rocks exist closer than 150 km from the batholith. The Wiborg batholith is dominated by coarse-grained granites with plagioclase-rimmed orthoclase phenocrysts. Nevertheless, all sulphide occurrences in the Lovisa region are either closely associated with medium-grained km-sized late-magmatic, highly evolved granitic phases (Sarvlaxviken), or to a caldera-related raft, hosting the Zn-Pb-Ag-In-rich Jungfruberg vein and massive magnetite-sphalerite ores at Getmossmalmen in ongonitic ignimbrites.

The S isotope compositions have been determined for sixteen sulphide concentrates from ten sulphide occurrences in the Lovisa region, yielding a $d^{34}S$ range from -1.5 to +3.7 ‰, with a rough average close to zero. When speculating on the reasons for this fractionation pattern, it is important to remember that the geological setting excludes any influence from sea water sulphate or S-reducing bacteria. Alternative explanations should instead consider that the Marviken Mo-rich system formed at a rather low (km-scale) crustal level, the Korsvik-Högberget Cu-As-In-system at a more shallow level (< km-scale) while the caldera-related Jungfruberg and Getmossmalmen deposits formed at the highest crustal level, partly in ongonitic ignimbrites.

One sample of the Marviken molybdenite vein has $d^{34}S = -0.4$ ‰, i.e. close to unfractionated mantle S compositions. A $d^{34}S$ ratio of +0.9 ‰ was obtained for sphalerite in the adjacent Lillträsket vein. Five measurements on chalcopyrite-arsenopyrite pairs in the Korsvik-Högberget system yielded constant $d^{34}S$ values close to -1.3 ‰ (cpy) and -0.9 ‰ (aspy). Sphalerite from the Getmossmalmen magnetite-sphalerite ore has a $d^{34}S$ value of +1.1 ‰, while the chalcopyrite-galena-sphalerite paragenesis in the Jungfruberg vein have $d^{34}S$ ratios of -0.8, +0.6 and +3.7 ‰ respectively, enabling T-calculations of the gn-sph pair to 217 °C by applying the isotope fractionation equation of Ohmoto and Rye (1979).

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ER5-04

Role of Cu remobilization during the formation of the epigenetic Pahtohavare Cu ± Au deposits, Kiruna mining district, Sweden

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The Kiruna mining district, Sweden, hosts the type locality for Kiruna-type iron oxide-apatite (IOA) deposits and additionally hosts a variety of Cu-bearing deposit-styles. Three distinct time-separated periods of Cu mineralization occurred in the district between ca. 2.1 Ga and 1.8 Ga, with the first occurring during a Rhyacian rifting event (ca. 2.1 Ga; Martinsson 1997) followed by two phases during the Svecokarelian orogeny (ca. 1.89-1.86 Ga and ca. 1.82-1.78 Ga; Smith et al., 2009; Logan, 2022). Multiple overprinting tectonic and metasomatic events invoke the question of the role and extent of remobilization of earlier Cu-mineralization in the formation of the younger Cu-bearing deposits. In the Pahtohavare area, approximately 5 km southwest of the giant Kiirunavaara IOA deposit, three Cu ± Au epigenetic ore bodies are situated within a <900 m radius of a syngenetic Cu-(Fe-Zn) ore body (Martinsson, 1997). Structural analysis separates the relative timing of the formation of the epigenetic Cu ± Au deposits from the syngenetic Cu-(Fe-Zn) deposit by a period of over 100 million years based on the regional tectonic framework. Microstructures from thin sections show that sulfides (chalcopyrite-pyrrhotite ± pyrite) were remobilized from the earlier-formed deposit during the epigenetic ore formation. *In situ* $\delta^{34}\text{S}$ isotope signatures and trace element data were collected on structurally constrained early, remobilized, and/or late sulfide generations to assess signatures associated to the overprinting mineralization event and to determine the role of metal redistribution. Results indicate that the early sulfides have $\delta^{34}\text{S}$ signatures from ca. -26 to -8 ‰, whereas the late sulfide generation is characterized by heavier signatures between ca. -6 to 6 ‰. Additionally, the remobilized sulfides (pyrrhotite-chalcopyrite) show a weak trend towards heavier sulfur isotope signatures and suggest that mixing with a heavier external sulfur source is recorded in the grains. Trace element data indicate Co/Ni ratios are generally <1 for the early syngenetic Pahtohavare deposit but span towards Co/Ni ratios >10 and some even >100 for the late epigenetic deposits. Hydrothermal pulses recorded from a zoned pyrite grain hosted in a quartz-carbonate vein indicate that a Co-enriched hydrothermal fluid played a role in the late mineralization event that was absent during the earlier event. In conclusion, combined textural, S-isotope, and trace element data support that metals were remobilized from the early Cu-mineralization which is subsequently recorded by trends towards heavier $\delta^{34}\text{S}$ signatures and higher Co/Ni ratios, indicating mixing with a distinct metal-introducing fluid during the late Cu mineralization event.

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ER5-05

Volatile transport in the Virginia Formation black shale contact aureole with implications for the formation of the Cu-Ni(-PGE) sulfide deposits of the Duluth Complex, Minnesota

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Fluids mediate volatile transport within contact aureoles and can facilitate formation of ore deposits. The world-class Cu-Ni(-PGE) sulfide deposits of the Duluth Complex, Minnesota, formed as the magmas assimilated sulfur (S) –bearing devolatilization fluids from the adjacent Virginia Formation black shale. To study the devolatilization reactions and redistribution of volatiles during contact metamorphism of the Virginia formation, we characterized the structure of the organic material (OM) with Raman spectroscopy, mineral composition, and volatile contents (C, S, H₂O) outside and inside the Virginia Formation contact aureole.

Outside the contact aureole, the OM is disordered graphitic material. Thermometry based on the structural state of the OM constrains maximum temperature of the regional metamorphism to less than 340 °C. Inside the contact aureole, OM is highly ordered graphite, which indicates that contact metamorphism induced structural ordering and compaction of the precursor OM. The maximum temperature exceeded 640 °C. During contact metamorphism, the precursor quartz + chlorite + muscovite + albite + OM + pyrite assemblage (< 340 °C) changed to quartz + cordierite + plagioclase + K-feldspar + biotite + graphite + pyrrhotite (> 640 °C). This reaction mobilized and redistributed C, S, and H₂O within the contact aureole. At the proximity of the intrusions, the prograde metamorphic minerals are locally replaced by massive sulfide lenses rimmed with retrograde biotite and muscovite. Rocks with these retrograde phases are enriched in volatiles compared to the surrounding contact aureole.

We suggest that the massive sulfides and associated hydrous silicates formed when fluids infiltrated to the contact aureole in the retrograde stage. This process locked back and concentrated the volatiles released in the prograde devolatilization reactions. Our observations indicate that the volatile concentration event near the Duluth Complex intrusions extended to the post-magmatic stage.

Mining of raw material for low emission basalt fiber production in Iceland

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Continuous Basalt Fiber (CBF) is an extremely fine fiber produced by melting basaltic rock of specific

composition. The melt is extruded through small nozzles to form continuous filaments of basalt fibers. Although the concept to use a molten rock to form fibers dates back to the start of last century the initial comprehensive research dates back to the 1970's in the former Soviet Union. The largest mines presently mined are in Ukraine, Russia and Georgia. Surface terrain of basaltic rocks are found from Greenland in the west to Scotland in the east with Iceland in the central, the latter being the largest basaltic domain in the Nordic countries. An extensive search was done in Iceland to locate a suitable source for the fibre production (Jóhannesson et al., 2016), and further research which followed has led to a location of a promising source rock for mining.

The production of basalt fiber is a power intensive industry. The production so far in eastern Europe relies mostly on using natural gas. The planned production in Iceland will rely on green hydro/geothermal energy, with additional reduction of CO₂ emission by lower transport cost.

It is expected that with the location of an appropriate basalt source will lead to a high-quality basalt fibre production. The product can be used to producing industrial parts in various categories such as in space, automotive, marine and construction industries, due to their weight savings, reliable mechanical properties and cost-effectiveness. A reduction in CO₂ emission of at least 30% can be reached by using Icelandic basalt fibers instead of more conventional materials.

Geology, chemostratigraphy and hydrothermal alteration at the Metsämonttu Zn-Pb-Cu-Au-Ag deposit, Aijala-Orijärvi area, southern Finland: Implications for VMS exploration

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Modern data acquisition methods together with the mineral systems approach provide new insights to mature "brown-fields" camps. These accelerate effective target delineation and increase discovery rates of deposits needed to secure raw material resources for the society. We studied the Paleoproterozoic Metsämonttu Zn-Pb-Cu-Ag-Au deposit (1.5 Mt at 3.5 wt. % Zn, 0.8 wt. % Pb, 0.3 wt. % Cu, 13.2 wt. % S, 25 g/t Ag and 1.4 g/t Au, production 1952–1974) (Latvalahti, 1979; Puustinen, 2003) located in the Aijala-Orijärvi area within the Uusimaa belt in southern Finland. The study aims at improving the understanding of the depositional environment and vectors to ore. The Metsämonttu deposit has been significantly modified by deformation and metamorphism. Integration of volcanic facies analy-

sis, lithochemical analysis, and sulfide texture interpretation is necessary to reconstruct the host succession and understand the ore formation. More specifically, we (1) re-logged fourteen drill cores and studied petrography to reinterpret the volcanic facies and mineralization styles of the deposit and their implications for the ore formation process; (2) assayed 157 outcrop and drill core lithochemical samples to identify alteration assemblages and reconstruct the chemical stratigraphy of the host succession.

The study confirms the previous interpretations by Latvalahti (1979) and Mäkelä (1989): Metsämonttu is a synvolcanic, stratabound, carbonate-skarn hosted polymetallic sulfide deposit. Moreover, based on our results, the Metsämonttu succession is dominated by two types of volcanoclastic facies, polymictic fiamme-lithic volcanic breccia and polymictic plagioclase-phyric volcanic breccia, and to a lesser extent sedimentary carbonates and argillaceous metasediments. The ore formation took place during and/or after emplacement of felsic fiamme-lithic volcanic breccia and intercalated limestones but before the garnet-mica rich siltstone and plagioclase-phyric volcanic breccia. The fiamme-lithic breccias were emplaced rapidly and acted as permeable host unit for metal-bearing hydrothermal fluids in the sub-seafloor, relatively shallow water setting. The main alteration assemblages at Metsämonttu are: 1. cordierite-anthophyllite-mica-pyrite, 2. muscovite-quartz-pyrite, 3. tremolite-diopside-chlorite skarn, and 4. quartz-muscovite-pyrite. They represent metamorphic equivalents of a primary, syn-volcanic, metal-bearing hydrothermal solution precipitated within pre-existing volcanic or sedimentary deposits. Our study documents multiple geochemical vector elements (e.g., Tl, Ba, Hg, Sb, Zn, Pb, Cu, S) and chemical alteration indices that form a halo around the deposit, and which can be used in mineral exploration within the Aijala-Orijärvi region.

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Tracing alteration mineralogy using portable X-ray diffraction (pXRD) and hyperspectral (SWIR) analysis for systematic drill core mapping: An example from the Aijala Cu-S and Metsämonttu Zn-Pb-Cu-Ag-Au deposits, Aijala-Orijärvi area, southern Finland

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An understanding of mineralogical and chemical zonation of hydrothermally altered rocks associated with volcanogenic massive sulphide (VMS) mineral systems is necessary to both

ore genesis studies and exploration target evaluation. Globally, polymetallic VMS deposits are regarded as economically important source of base metals and critical raw materials. In this study we traced the alteration mineralogy using portable instruments from historical drill cores of Aijala (Cu-S) and Metsämonttu (Zn-Pb-Cu-Au-Ag) deposits. Deposits are Paleoproterozoic, stratabound, limestone-skarn-associated sulphide deposits hosted within bimodal volcanic-sedimentary succession in the Orijärvi formation part of Uusimaa belt in southern Finland. The deposits were mined between 1948 and 1974 with a total production of 2.7 Mt of ore containing 50459 t Zn, 7050 t Pb, 14897 t Cu and 1717 t Au (Latvalahti, 1979). The present mineralogical composition is a result of primary volcanoclastic lithologies affected by hydrothermal alteration and subsequent deformation and metamorphism. The metamorphic hydrothermal alteration assemblages obliterate primary rock textures in the vicinity of ore deposits. Portable analysis techniques enable a robust method to collect mineralogical data as part of litho-geochemical data analysis.

Portable instruments pXRD and near-infrared (NIR) spectroscopy were used to identify proximal alteration mineralogy. Mineral assemblages were compared to geochemical data results collected with portable X-ray fluorescence (pXRF) and validated against the litho-geochemical assay data. The NIR (0.35-2.5µm) point measurements were gathered with ASD TerraSpec 4 Portable NIR Spectrometer and reference data with TerraSpec Halo. The pXRD data were measured with Olympus Portable On site XRD Terra-542 instrument. Total of 2623 hyperspectral and 268 pXRD assays were analysed from 2700 m of core at intervals between one meter and 10 meters, respectively.

The main mineral phases were identified with pXRD. SWIR data, more specifically Fe-OH, Al-OH and Mg-OH bands and their position, was used to observe chemical variation in micas, chlorites and carbonate bearing minerals. Changes in mineral chemistry were compared with alteration indexes such as Ishikawa Alteration Index AI (Ishikawa et al., 1976) and chlorite-carbonate-pyrite CCPI (Large et al., 2001a) from litho-geochemical reference samples and their relationship to alteration logged lithologies and primary rock composition defined by trace element compositions.

Results suggest that pXRD is a useful method of recognizing mineral phases that might cause overlapping in absorption feature bands (Fe-OH, Al-OH) observed in SWIR data. Some key minerals related to metamorphic mineral assemblages such as cordierite and garnet are identified only with XRD -method, also ore minerals are recognized with XRD only. Fe-OH absorption band shifts toward a shorter wavelength probably caused by chlorite composition changes to Mg- richer by Mg-Fe-S alteration in the vicinity of mineralization. The white mica composition shows only a weak variation in Al-OH absorption feature shifting toward a shorter wavelength near mineralization. Changes in mineral chemistry observed in SWIR data follows the alteration intensity estimated using the CCPI and AI. Combining pXRD and hyperspectral data can be used to identify both mineralogy and alteration intensities as part of exploration target evaluation.

ER5-09

Greenland mineral exploration – comparison with petroleum history

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Greenland has a long and interesting mining and mineral exploration history. Compared to the petroleum exploration history with some remarkable ups and downs (see Christiansen 2021), there is still optimism in the mineral business. Successful examples are, however, surprisingly few in the new Millennium. Based on systematically compiled information on all previous and present exploration licenses (>500), this talk gives an overview of the past and present activities, the companies and partners involved (>200), their main targets, and their continued need for and search of investors and strong partners.

An analysis of the key drivers on different levels is presented: analogues to World class deposits in terms of geology, size and ore grade, strategic projects on specific resources, fluctuations in commodity prices, available maps, data, and research results, and not least co-financing, strategies, and regulations by authorities in first Denmark, now Greenland. Changes in political agenda in Greenland, Denmark and internationally have had a strong influence on the level of exploration activities in Greenland compared to many other mining countries, in some periods creating good incentives for investors, in other cases being showstoppers for future exploration and mining.

Although of similar economic scale, there are many differences – but also some interesting similarities – between the petroleum and mineral exploration in Greenland. For the first time ever, the talk presents a summary of the total costs of mineral and petroleum exploration in Greenland and the total revenue for the governments in Greenland and Denmark. This is compared with the public investments in relevant research, data acquisition, direct investments in national companies, and more recently through venture capital.

Although the number of licenses is at a record high with many new companies entering the Greenland exploration scene, investments in field and drilling activities on new targets have been worryingly low in recent years. There is a strong need for revised strategies in Greenland to attract an industry that can bring both new and some of the very old projects forward.

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Exposure and transport histories of ore-bearing glacial erratics in complex glacial environments using Terrestrial Cosmogenic Nuclide dating.

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The Central Lapland Greenstone Belt has much active mineral exploration particularly due to its orogenic gold potential. The belt has been glaciated on multiple occasions during the Pleistocene and is mostly masked by till. The till poses challenges and opportunities for exploration; it can be a good sampling medium for certain deposit types, but due to weak recent glacial erosion, some locations can be effectively geochemically masked by multiple beds of till. The aim of this study is to introduce Terrestrial Cosmogenic Nuclide (TCN) -dating into glacial indicator tracing of deposits that are difficult to trace geochemically. TCN-dating is used in the study to date the surficial exposure history of mineralized quartz erratics to find out if it can yield new information on their glacial transportation history.

The TCN-dating method is based on the accumulation of nuclides that form in minerals when they are exposed to high energy secondary cosmogenic radiation. The energy flux attenuates with depth and is close to null within approximately three meters of the Earth's surface and therefore cosmogenic nuclides are abundant only at the surface. Two mineralized erratics and two outcrops at a gold exploration target in Kaarestanturi, Sodankylä, Finland were dated with TCN-dating to evaluate the time of initial exposure and glacial erosion history in the area. The erratics yielded apparent ¹⁰Be exposure ages of 39.2 ± 1.3 ka and 30.6 ± 1.0 ka, indicating exposure prior to the latest glacial event. The exposure ages of the outcrops are 98.0 ± 2.8 ka and 53.0 ± 1.8 ka documenting weak glacial erosion. The apparent TCN ages are correlated to the local glacial history by means of stratigraphic studies from five machine-cut trenches.

Modelling the apparent TCN ages of the mineralized erratics against the local glacial history model suggests that the erratics were first exposed in the Middle-Weichselian or earlier. The oldest bedrock sample was likely first exposed prior to the Eemian interglacial, which is in line with previous reports for rock surfaces on tors at Vuotso, Sodankylä. We conclude that multi staged glacial transportation cannot be overlooked for the erratics in this area of low glacial erosion. The study demonstrates that TCN dating is a useful new tool to support conventional mineral exploration methods while it likely benefits most when accompanied by local and regional stratigraphic studies. In optimal circumstances the method can aid in a unique way in construction of provenance probability sectors for mineral prospects.

Geochemical and isotopic fingerprinting of Cu metal using Laser ablation mass spectrometry

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Copper, the first metal utilized by mankind and long considered a crucial raw material for modern societies, may be generated by both natural and metallurgical processes. Manufactured Cu products will undergo a wide range of physical and chemical modifications along the value chain while natural native copper has been affected by geological processes. The capability of precise and accurate measurement of trace elements and Cu isotopes of Cu metals is instrumental in elucidating and understanding these Cu-forming and Cu-modifying processes.

This work is designed for the Michigan International Copper Analogue (MICA) project, which strives to improve the state-of-art understanding of long-term stability of Cu-based canisters for nuclear waste disposal by studying native copper samples from the Keweenaw site, Michigan. We report novel results of 3-D morphology of the laser-ablation pits and various quality-check parameters of trace elemental and isotopic measurements on a series of Cu-based metal standards ranging in compositions from pure Cu to bronze and brass. With analyses of bronze and brass standards underway, completed analyses of pure Cu metal standard (ERM EB075b electrolytic copper) suggest that in-situ ablation of copper with a nanosecond (ns) laser system is viable with optimal laser fluence and repetition rate. Within the experimented conditions (2.2 J/cm² to 5.8 J/cm²; 5 Hz to 15 Hz), the best ablation pits, highest ablation yield (cps/ppm), lowest limit of detection, and best accuracy were produced by the combination of highest fluence and repetition rate. However, similar performance improvement was not observed for lower fluences and repetition rates, which seems to be isotope/element dependent. Cu isotope ratios (⁶⁵Cu/⁶³Cu) measured with a multi-collector ICP-MS vary with differing laser fluence and repetition rate. Higher fluence and repetition rate favors ⁶⁵Cu over ⁶³Cu, indicating larger mass fractionations necessitating larger corrections. The magnitude of the correction factor awaits determination of the actual isotopic composition by solution work, which will also be presented.

The current results on pure Cu metal along with the forthcoming results on bronze and brass carry some preliminary yet potentially significant insights for optimizing ns laser ablation ICP-MS for measuring trace element and Cu isotopes precisely and accurately. It has far-reaching implications for fingerprinting Cu metal sources, understanding the stability of native copper in natural environments, and elucidating underlying processes.

ER6-01

Time constraints on hydrocarbon migration and uplift as recorded by isotopic characteristics of calcite cements in Carboniferous-Permian evaporites from the Barents Sea

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Drill cores from the Carboniferous-Permian Ørn Formation of the Finnmark Platform (Barents Sea, Norway) contain nodules of anhydrite, calcite, and native sulphur within hydrocarbon-stained dolostone-anhydrite host rock, a mineral assemblage consistent with classic evaporite-carbonate rock sequences. These sequences are crucial for the creation of economically viable petroleum reservoirs in the Gulf of Mexico and elsewhere, containing both reservoir and cap rocks, and sometimes also excellent hydrocarbon source rocks. However, many aspects of their formation remain poorly understood, particularly the time interval over which they form. To address key aspects of evaporite-carbonate reservoir and cap rock formation, we present a targeted suite of geochemical data from calcite cements associated with native sulfur to understand the geochronology, clumped isotope paleothermometry, and traditional stable isotope geochemistry of these sequences. In-situ U-Pb dating of the calcite cements indicates that they formed over a surprisingly large interval, from ca. 50 – 15 Ma, some 250 to 285 Myr after deposition of the host rock. Clumped isotope paleothermometry of calcite cements indicates formation across a range of temperatures from ca. 25 to 70°C. The $\delta^{13}\text{C}$ values of the calcite cement are largely between -20 to -10‰, in contrast to 0 to +5‰ of the host rock, reflecting a carbon source for the calcite cement being strongly influenced by oxidation of hydrocarbons and dissolution of the host rock (or seawater). Cumulatively, these data indicate that the carbonate alteration of evaporite sequences in the Finnmark Platform occurred over a long interval (ca. 35 Myr) and at low temperatures (ca. 25 – 70°C), likely during hydrocarbon migration associated with Cenozoic burial and uplift in the Finnmark Platform. This demonstrates the tremendous utility of these geochemical tools for understanding these sequences and providing crucial insights on their formation, as well as directly measuring the timing of hydrocarbon migration.

ER6-02

Provenance of the Middle Triassic Kobbe Formation in the SW Barents Sea

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Intra-cratonic basins are often characterized by large, basin-filling systems of mud-rich sediments that have been transported over long distances, as well as coarser and more mature sediments along the basin margin. These different systems have distinctly different reservoir properties. By understanding how and where these systems interact, it is possible to make a first-order approximation on the distribution of reservoirs with

favorable properties. The Greater Barents Sea Basin represents such basin, and after decades of hydrocarbon exploration, the abundance of well-, core- and seismic data have made this basin to one of the best understood basins in the world. This makes it ideal for studying the controls on provenance, sediment distribution and mixing processes in intra-cratonic basins.

Detrital zircon data have been published for most of the Triassic stratigraphy of the Barents Sea, but as the data are not from time-equivalent units, it is difficult to attribute the variations to either temporal or spatial effects. Here, we apply detrital zircon U/Pb dating of time-equivalent samples from the uppermost part of the Anisian Kobbe Formation to document the spatial variations in the sediment influx to the Barents Sea Basin in the Middle Triassic.

By combining c. 2700 new U/Pb analyses with previously published data from the same sequence, two main sources have been identified. The northernmost samples (north of 72°N) show an age distribution typical for the Urals and West Siberia. These samples are dominated by Triassic to Neoproterozoic zircons, with minor amounts of Mesoproterozoic to Archean grains. The southern samples are mostly characterized by Proterozoic and Archean ages, but samples from the Hammerfest Basin additionally include a late Neoproterozoic – early Paleozoic age component, interpreted to represent erosion of a Timanian foreland basin located in northern Norway. The presence of Permian – Carboniferous zircons on the Bjarmeland Platform indicate that this area represented the mixing zone between the easterly- and southerly-derived sediments during the Middle Triassic. The detrital zircon age distributions from time-equivalent units thus document the regional variations in provenance and pin-points the mixing zone of sediments from the different sources.

ER6-03

The role of organic matter production, preservation and dilution on Triassic black shale formation on the Norwegian Barents Shelf

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During the Triassic, the Norwegian Barents Shelf (including Svalbard) was a site of widespread marine organic matter accumulation, bottom water anoxia and black shale formation. Previous studies have suggested a multitude of factors promoting these conditions, including upwelling of nutritious water and high primary productivity, climatic deterioration and sluggish water circulation, as well as physical restriction of the basin. This study investigates a Lower to Upper Triassic black shale succession in eastern Svalbard and documents the relationship between organic matter production, preservation, and dilution, and how these parameters governed and promoted accumulation of black shales across the Norwegian Barents Shelf. Our organic and inorganic geochemical data indicate that the previously suggested climate-induced transition from warmer to cooler oceans at the Early to Middle Triassic transition represents an important control on black shale accumulation at these northerly latitudes.

Lower Triassic black shales appear to have been formed in a low production–high preservation setting. During the Middle Triassic, increased rates of primary production resulted in the development of an oxygen minimum zone and associated bottom water anoxia. These favourable conditions were eventually terminated in the Late Triassic with the arrival of an Uralian-sourced delta system. We show that organic facies and biomarkers derived from Lower Triassic black shale extracts in Svalbard correlates well with Lower Triassic-sourced petroleum in the region, indicating that organic facies-equivalent black shales formed synchronously across the shelf during the Early Triassic. This challenges the idea that Lower Triassic black shales on the southern Norwegian Barents Shelf are lateral facies equivalents to the renowned Middle Triassic black shales in Svalbard. These findings have important implications for conceptualizing Lower–Upper Triassic black shale deposition on the Barents Shelf.

ER6-04

Geomorphology of continental rift landscapes - analyses inspired by North Sea observations

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Geomorphology of continental rifts appears in fault-bound sedimentary basins and degrading mountain ranges. Fault offset, coupled with climate forcing, lithological erosional durability, and sediment transport energy budgets, in sum control landscapes and their denudation. Herein, focus is on co-seismic elastic rebound of fault-footwall ranges with spatially variable rates of uplift, linking uplands to catchment patterns and inter-related hanging wall sedimentary fans. Catchments signified by water and wind gaps in footwall ranges feed large across-fault fans in hangingwalls, whereas fault-scarp degradation supplies down-fault fans. From statistical analyses, patterns suggest physical equilibrium in the source to sink system is better expressed for across-fault fans than for down-fault fans.

Fault-controlled topography can be quantified by fault-length (L) and maximum throw (T_{max}) along the fault, the latter linked to maximum height of footwall rebound ranges (h) and their width (W) above a reference level. Scaling trends converge for megafaults ($L > c. 50$ km), signaling steady-state faulting as broad isostatic adjustments drive fault rotation leading to abandonment and establishment of new faults. Empirical data on fault L/D ratios versus specifics on co-seismic rebound offer relationships of footwall rebound vs hanging-wall subsidence. Extensional fault throw in both arid and tropical rifts has a systematic relationship, the latter offering smaller rebounds ascribed to faster denudation. Noticeably, width to height (W/h) of footwall rebounds offers a robust linear statistical trend that is applicable in reconstructions of former rift systems in the North Sea and elsewhere.

ER6-05

Late Jurassic rift physiography of the Froan Basin and Frøya High: insights into the extent and longshore distribution of the shallow marine Rogn Formation

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The Froan Basin, located on the Mid-Norwegian Continental Shelf, contains petroleum-bearing, Upper Jurassic syn-rift deposits. These shallow marine deposits (i.e., Rogn Formation) exhibit excellent reservoir properties and have also been identified locally on the Frøya High. These two major structural elements are located on a platform east of the Halten Terrace separated by major, west-dipping normal fault zones. Despite being located updip of a very prolific petroleum province (i.e., Halten Terrace), the Froan Basin and Frøya High remains poorly understood in terms of its Late Jurassic tectono-stratigraphic evolution. Improving our understanding of how fault activity and rift-shoulder uplift influenced rift physiography and the presence of shallow marine reservoirs, is crucial when assessing hydrocarbon prospectivity in this region. In this study, we present a model for the Late Jurassic rift development of the Froan Basin based on seismic reflection and well data, and reverse subsidence modelling. We show that during the Late Jurassic to Early Cretaceous, major footwall uplift meant that the Frøya High and the western margin of the central Froan Basin was subaerially exposed and formed an intra-rift footwall island. Shallow marine areas to the east, immediately adjacent to the footwall island, accumulated shoreface sediments supplied from the uplifted and eroded footwall. We therefore suggest that the extent of the shallow marine system was controlled by the magnitude of footwall uplift along the western margin of the basin and that the longshore sediment distribution was influenced by the paleogeomorphology of the back-tilted dip slope.

ER6-06

Mobilized sand and injectites in the North Sea. Importance for fluid communication in the basin and a proposed triggering mechanism.

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Mobilized sand bodies penetrate the Cenozoic stratigraphy in the Norwegian North Sea from the Paleocene to the Upper Miocene, a section of approximately 1000 m. The area is 350 km long and 60-80 km wide, and within it most Cenozoic sands below the Upper Miocene are mobilized. In the Cenozoic, the North Sea basin was deep marine, and thick shaley and biogenic ooze deposits are intercalated with turbiditic sands deposited from the margins. Mother sands are recognized as the Ty, Heimdal, Hermod, Frigg, Grid and Skade Formations. The sands are high porosity turbidites with a source area to the west at the Shetland Platform. North of Sognefjorden, mobilized turbiditic Eocene to Miocene sands with a Scandinavian source occur.

On a regional scale, the mother sands cut across the shaley formations at low angles. Sill structures shoot from the thicker mother sands and form saucer-and cone-shaped features, typically 1–2 km in diameter. Thinner injectites usually have steep to vertical dips and are not easily visible in seismic data. The style and intensity of deformation is analogous to what is published by Hurst and others from the Panoche Hills, California. Oil and gas fields accumulated in mobilized sands often have the same depth of hydrocarbon-water contacts. Contacts and pressures suggest that fluids communicate through the injectite network in a geological time scale.

Our hypothesis for the formation of injection sands relies on observations in the field and on seismic data. In the field, it is seen that the sand at the time of injection was acting as a fluid with apparent low viscosity. The seismic and well data show that mobilization took place in different phases which can be correlated to the deposition of thick sand packages. The Skade sand deposition took place simultaneously with growth of mud diapirs caused by injectite intrusions. The Frigg sand has an underlying strongly deformed section. The deposition of Grid sand and possibly internal sands in the Paleocene can also be correlated with deformation events.

The hypothesis is that interbedded turbidites and shales responded on heavy and rapid loading caused by huge slides. The capping shales built up overpressure below the additional load caused by the turbidite deposition at the surface. Parts of the sandy beds became liquified due to the load and shaking induced by the slides. As soon as patches of sand are liquified, they lose completely their strength and are exposed to the lithostatic stress of the overburden. Most likely this enhances movement and more liquifaction.

Reference: Andrew Hurst, Antonio Grippa, Simone Y. Silcock, Mads Huuse, Mike Bowman and Sarah L. Cobain. Geological Society, London, Special Publications, 493, 12 May 2021.

ER6-07

Eocene erosion and deposition from the Kolga High, Mid-Norwegian margin: Results from 3D seismic interpretation and stratigraphic well ties

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The Kolga High is a structural high located close to the continent-ocean boundary in the northwest Møre Basin, c. 300 km offshore mid-Norway. It is conjugate to the Jan Mayen micro-continent. Until recently, the nature of the Kolga High was poorly constrained by only a few regional 2D seismic profiles and potential field data. In order to better understand the structure and development of the Kolga High we have undertaken detailed seismic mapping and attribute analyses of Paleogene reflections, including the Top and Base Basalt horizons. This

new analysis relies on new high-quality industry 3D data, the AMN17 survey acquired by TGS in 2017, and high-resolution 2D profiles from the 2020, CAGE20-04 survey. Shallow borehole data on the Kolga High are published from one stratigraphic well drilled by the NPD on the eastern flank of the structure in 2014 (6403/1-U-1) and IODP boreholes from the recent 2021 IODP campaign (U1565A/B and U1566A), cored on the western flank of the structure.

By mapping Top and Base Basalt we find that the basalts are thickest along the flanks of the Kolga High. Along the eastern side of the high, a well-defined prograding lava delta and associated escarpment are mapped on the 3D seismic data. At the crest of the high the basalts are thinnest and in two places there are windows where no basalt is present. Here, the seismic geomorphology indicates that the basalt was peneplained by wave-base erosion, suggesting a subaerial paleoenvironment of the distal margin. The seismic interpretation is corroborated by the borehole ties, as hyaloclastites were recovered from the top of the lava delta, and weathered granite was cored below the Quaternary sediments in the basalt windows.

In the Møre Basin, early Eocene sediments onlap the escarpment and therefore post-date the lava delta formation. In these sediments we observe another prograding sequence above the Top Basalt horizon. The base of this sequence is seismically tied to a base hydrothermal vent reflection mapped further west in the basin, having a Paleocene-Eocene transition age (c. 56 Ma). The top of the sequence is seismically tied to the mid-Ypresian Top Tare Formation. The top of the prograding sequence is interpreted to have formed close to the paleo-seabed. Additionally, lobate features which have high amplitude hard reflections at their tops and soft bases occur close to the Paleocene-Eocene horizon. We interpret these lobes to have formed in deeper water. The high amplitude lobate bodies are in places very narrow compared to extrusive lava flows which are also recognized along the margin. We interpret the prograding sequence as well as the lobate features as evidence of deposition of eroded material derived directly from the Kolga High during the Eocene. This model indicates that the depositional features observed east of the escarpment could include a component of granite-derived sands as well as eroded basaltic material.

ER6-08

Contourites and sediment progradation along the Norwegian continental margin (65–70°N) during the Neogene–Quaternary

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We have analyzed 2D and 3D seismic data together with exploration wells to reconstruct the Neogene–Quaternary evolution of parts of the Norwegian continental margin (65–70°N). The continental margin, which began to evolve with Paleogene rifting and seafloor spreading in the Norwegian–Greenland Sea, continued to develop at this time, allowing for the accumulation of the Kai-, Molo- and Naust formations.

In the mid-Miocene, NE-SW elongated sediment accumulations of the Kai Formation started to build-up in the Vøring Basin and on the slope west off the wide, gently dipping northern Mid-Norwegian shelf (65–67°30N). These accumulations are represented by internal divergent reflections with a progressively upslope onlap, overlying a relief that includes domes, highs,

and ridges: characteristics typical of contourite drifts, deposited from alongslope flowing ocean currents. The contouritic sediments are interbedded with parallel-layered reflections, interpreted to be hemipelagic sediments from suspension fall-out. In the late Miocene, the coastal Molo Formation started to prograde seawards, creating steep clinoforms (up to 13°), interpreted to be a result of coastal outbuilding from fluvial systems. The Molo Formation is not present on the inner part of the steeper and canyonized Lofoten–Vesterålen margin ($67^\circ30'–70^\circ\text{N}$). Instead, chaotic reflections of the Kai Formation dominate, and these are interpreted to be mass transport deposits from gravity-induced processes such as debris flows. Parts of the Kai Formation on the Lofoten–Vesterålen margin also consist of alongslope-oriented contourite deposits.

From the onset of the Quaternary, the sediment supply to the northern Mid-Norwegian margin increased due to the build-up of onshore ice sheets and establishment of ice streams during their expansion onto the shelf. Some of the sediments remobilized into debris flows and turbidity currents on the slope, and together with contourites and hemipelagic sediments they accumulated in a large prograding wedge forming the Naust Formation. In contrast, the glacial sediment supply from land was low on the Lofoten–Vesterålen margin. The onshore alpine relief partly blocked the sediment drainage to this part of the margin, resulting in locally sourced ice streams that delivered subglacial sediments directly into canyons, before being remobilized into mass transport flows on the slope. Large drifts build up on the slope at this time, showing that contour currents prevailed over the mass transport processes.

Our results demonstrate widespread contourite build-ups along the entire studied margin during the Neogene–Quaternary. This indicates that they form part of one large drift system related to the NE-flowing Atlantic Water, with a persistent current direction along the Norwegian margin. Therefore, the main source area for the contouritic sediments is likely south of the study area but it is also possible that the contour currents redeposited sediments from the east. Coastal outbuilding from fluvial and later glacial sources has varied along the margin, and the topography of the source area in the east has played an important role in the sediment input to the margin.

ER6-09

Geometric controls on clinoforms, the building blocks of sedimentary basins – from ripple to shelf-edge

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Clinoforms are the building blocks of sedimentary geology. Their quintessential s-shaped geometry can be observed even in the smallest ripple or can span thousands of meters across continental shelf-edges. Clinoforms are at the heart of almost all prograding units, they form the conveyor belt across which sediment is delivered into basins – small units over small time-scales merging with ever larger seemingly identical yet larger scaled units over millennia and beyond.

This work is based on several studies worldwide attempting to bridge the gap between detailed smaller-scale onshore systems, to seismic-scale clinoforms with point-source well-data. The study focuses on quantifying clinoforms, identifying types and extracting slope curvatures, and studying depositional envi-

ronments and sedimentary processes in order to understand the processes controlling the shapes of clinoforms and thereby predicting sediment properties and partitioning. The analysis could provide predictive tools on type and quality of sand, sand distribution and lateral extent of seals, leading to novel models of paleogeography. Ultimately the study aims to contribute towards reservoir characterization and detailing the implications for CO₂ storability, migration, and trapping mechanisms in heterogeneous prograding reservoirs.

From New Zealand a primary study allowed the distinction of different types of clinoforms-defined by their slope curvature, sediment distribution and internal seismic characteristics. Of particular weight from this study is the observation of asymmetric sediment distribution and associated shallow slopes for bottom-heavy and steep slopes for top-heavy clinoforms. Similar asymmetric distribution was observed in the Ainsa Basin in Spain, where it was associated with a distinctly different slope curvature (linear) compared to symmetric distribution in the sigmoidal (Gaussian) shapes. The Ainsa Basin study strongly supported steeper slopes forming in deeper waters, although coarser sediment composition may contribute to steepening slopes comparatively. This study also supported the findings from SW Australia, which is that accommodation controls the location of the rollover, and sediment rate dictates foreset thickness beyond this point. Onshore-offshore analysis of the prograding Triassic system on the Barents Shelf highlights the flattening of foreset angles occurring in shallow water, both over platforms and near structural highs, and also the difficulty in observing low-angle seismic scale clinoforms in outcrop.

ER6-10

Deciphering the setting of volcanoclastic and effusive Devonian magmatism in the Orcadian basin, Orkney Islands, Scotland

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The Orcadian basin off the Scottish coast is a Devonian pull-apart structure formed during sinistral reactivation of Caledonian transcurrent faults, such as the Great Glen Fault of central Scotland. The Hoy volcanics of the Orkney Islands, NE Scotland, erupted in the evolving Orcadian basin. Based on new field, age, and geochemical data, we interpret the Hoy volcanics as an alkali basaltic monogenetic volcanic field. The volcanic activity was accompanied by extensional faulting, creating a local topography that accommodated volcanoclastic sediments. Multiple explosive eruptions, some phreatomagmatic, contributed to tuffs and volcanic debris that formed aprons around eruption sites. We propose that these volcanoclastics were then mobilised during rainfalls, subsequent eruptions and earthquakes, and formed lahars that streamed out onto an alluvial valley floor. During (seasonal?) flooding events, quartz-rich sand originating from highlands to the SW mixed with the volcanic ash and were deposited in the valley. The volcanism ended with a large effusive fissure eruption of high-Al basaltic trachyandesite, dated by zircon ID-TIMS to 378.32 ± 0.19 Ma. Syn-volcanic extension created space for the up to 100m thick lava along a NNW trending half-graben, potentially stretching more than 20 km. It is likely that several extension-related volcanic fields were active in the area at this time, and volcanism of similar age may also be widespread in the offshore parts of the Orcadian basin.

Depositional environments and sequence stratigraphy in a perennially isolated epicontinental basin: a case study from the Upper Ordovician Williston Basin, North America

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The Williston Basin is the second largest of the four Paleozoic epicratonic basins of North America that evolved in the interior of the western distal Canadian Shield. During the Late Ordovician Katian, the basin occupied southern tropics and was characterized by deposition in dominantly shallow-marine environments that were perennially isolated from the Cordilleran shelf and the surrounding basins. This study focuses on the uppermost Katian Stony Mountain Fm., with a goal of improving the understanding of the climatic and sea-level fluctuations prior to the end-Ordovician Hirnantian glaciation. Ten cores were logged in detail and >100 thin sections were analyzed to document facies stacking. Gamma-ray and combined neutron-porosity and bulk density logs were used to trace gross lithology across the basin and construct isopach maps. Eleven facies grouped into four facies associations were identified; the facies are stacked into five high-frequency sequences that make up a single long-term sequence. The sequence is bounded by lowstand, subaqueous anhydrites in the basin center, and correlative thin subaerial exposure breccias in the updip parts of the basin. The anhydrites formed during relatively short periods of basin restriction under an arid climate. Subsequent transgression resulted in the re-establishment of normal-marine conditions and an increasingly more humid climate with deposition of mud-supported carbonates with siliciclastic components sourced from the Transcontinental Arch. Highstand deposits lack terrigenous particles and indicate the return to drier and increasingly more arid conditions that favored the progradation of peritidal microbialites across the basin. The study provides insight into the evaluation of humid vs. arid episodes in similar tropical settings during the major climatic shifts.

ER6-12

Periplatform ooze in a mixed siliciclastic-carbonate system, Vaca Muerta Formation, Argentina

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Thick carbonate mud successions and marl/limestone alternations are often found in periplatform environments. The sources of these fine-grained sediments and the processes that govern their accumulation and distribution in the basin are frequently a matter of debate. This case study from a Tithonian-early Valanginian mixed siliciclastic-carbonate succession in the Neuquén Basin, Argentina, aims at explaining the origin of several carbonate-rich intervals within the basinal shales of the Vaca Muerta Formation. We characterized four carbonate-rich intervals of different ages with respect to lithofacies, carbonate content, $\delta^{13}C_{carb}$ values and TOC, and placed them into a sequence and bio-stratigraphic framework. The thickest of these intervals is the mid-late Tithonian Los Catutos Member in Sierra

de la Vaca Muerta, which is a wedge-shaped package of micritic limestones and intercalated marls that thins basinwards. Proximal-distal variations and cyclic partitioning in its facies and geochemical proxies suggest highstand shedding and a periplatform origin. The proposed source is a coeval 20m-thick pure carbonate interval located 50km south of the Sierra de la Vaca Muerta within the mixed siliciclastic-carbonate shelf facies of the Picún Leufú Formation. Younger carbonate-rich intervals in the center of the basin (Puerta Curaco area) show similar characteristics to the distal portion of the Los Catutos Member and are also interpreted as periplatform deposits but sourced from carbonate shelves farther east. The high sedimentation rates of the Los Catutos Member require an efficient mechanism to deliver significant amounts of fine-grained carbonate sediment to the basin. This mechanism is envisioned to be sediment-charged hyperpycnal flows cascading from the platform to the basin, analogous to what is observed in modern carbonate systems. The occurrence of periplatform ooze in different stratigraphic levels of the siliciclastic-dominated Vaca Muerta Formation demonstrates that off-shelf transport and distribution of carbonate mud in the basin were also common processes in ancient mixed clastic-carbonate environments.

ER6-13

Rift segment boundaries as key controls on deep-water, syn-rift stratigraphy; the Corinth Rift, Greece

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Stratigraphic variability recorded within deep-water rift basins is broadly attributed to tectonic and climatic interactions that control sediment delivery at <10⁴-10⁵ yrs timescales. In semi-enclosed, marine-lacustrine rift basins, the presence of one or more structural highs at the end of rift segments has the potential to modulate the influx of marine waters from the global ocean, with implications for the syn-rift stratigraphic development. We focus on the Gulf of Corinth, a semi-closed active rift basin which alternated between marine and isolated/semi-isolated (lacustrine) conditions as sea level fluctuated with respect to basin sills during Quaternary glacial/interglacial cycles. We perform a bed-scale stratigraphic analysis on two cores obtained from the IODP Expedition 381 to investigate key controls on rift stratigraphy during the Late Quaternary. Initial results from the Expedition's Science Party indicated cyclic variations in sedimentation rates and basin paleoenvironment on tens to hundreds of thousands of years timescales. Our high-resolution analysis of the bed-scale sedimentology reveal a range of homogeneous to laminated mud beds and sharp-based event beds. The bed-types are organized into three types of stratigraphic packages (bioturbated, bedded and laminated) that are closely linked to eustatically controlled connections to the global ocean. Bioturbated packages record interglacial marine conditions, bedded packages reflect deposition in a non-marine, lacustrine setting during glacial phases and laminated packages demonstrate seasonal variability in a dysoxic non-marine or transitional setting. The timing of stratigraphic alterations between these three packages constrained by our new age-depth model suggests changes in sill height bounding the gulf to the east and to the west controlled by eustatic variations and/or evolution of the normal fault system. Our results show significant differences in average sedimentation rates than previously estimated considering constant sill heights,

with periods of interglacial marine conditions being shorter by up to 50%. This study highlights the importance of structural highs at the ends of rift segments as a first-order control on syn-rift stratigraphic evolution at the rift scale.

ER6-14

Variability of fault-controlled deltas in rifts: Examples from southeastern Corinth Rift, Greece

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Deltas are a common feature in tectonically active basins, such as rifts. Their location, geometry and stratigraphic evolution is strongly controlled by the interaction between sediment supply, tectonics and base-level change. This study focuses on two fault-controlled deltas, Asprokamos and Nemea deltas, that developed during the early rift phase of the Corinth Rift (Greece). These Pliocene to Early Pleistocene deltas were deposited in the hanging wall of north-dipping normal border faults located along the southern margin of the rift and exhibit markedly different stacking patterns.

The Asprokamos delta is developed in the hanging wall of the Platana fault and is strongly progradational, extending over 8 km northwards into the fault's hanging wall with a topset radius of ~1,5 km. The Nemea delta is deposited in the hanging wall of the Nemea fault and has a topset radius of <1 km but is highly aggradational. The two deltas have a classic tripartite clinoform geometry with distinctive topsets, foresets and bottomsets, and show similar sedimentology. Topsets and foresets are composed of metre-thick beds of clast-supported, mainly ungraded conglomerates with erosive base, with occasionally normally graded beds in the foresets. Topset packages are up to 200 to 300 m thick in the deltas, and foreset heights range between 50 and ~200 m. Bottomsets are composed predominantly of mudstones interbedded with erosionally based sandstone and conglomerate beds that are typically a few tens of centimetres in thickness.

Significant stratigraphic variability exists between the Nemea and Asprokamos deltas. The Nemea delta has highly rotated topsets (>20°), that decrease in dip up stratigraphy. Foresets are rotated to sub-horizontal. The youngest set of clinoforms downlap on older delta topsets, suggesting a second phase of deposition with relative higher base level. In contrast, the Asprokamos delta is characterised by strongly oblique, NNE prograding clinoforms with top-truncated foresets. Topsets are slightly rotated (<20°) to the SE. The clinoforms are cut by a series of syn-sedimentary NNE-dipping normal faults, that progressively downstep the delta towards the north. The orientation of the topset and foresets of the deltas suggests the source catchment area to the south, in the footwall of the rift border fault. The highly rotated topsets of the Nemea delta together with the strongly aggradational stacking pattern suggest a strong fault control on deposition. In contrast, the strongly prograding Asprokamos delta suggests lower accommodation/sediment supply ratio compared to the Nemea delta.

ER6-15

Fault-influence on provenance, depocenter development, drainage patterns, and facies assemblage: an example from the alluvial Upper Cretaceous Qahlah Formation in the Fanja Basin (northeastern Oman)

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The Fanja Basin offers a prime example of alluvial half-graben fill with a high level of exposure in a compact, easily accessible outcrop area (7x1,5 km). High exposure allows identification of geometries and architecture, both in axial and cross-sectional sections. The basin is bounded by the exposed north-vergent range-front extensional fault. Basin architecture, fill geometries and facies variations demonstrate how faulting exerted significant control on sedimentary fill, with local depocentres changing position in response to transverse syncline and anticline development driven by evolving fault-displacement gradients. A shift in provenance is recorded both from drainage pattern analysis and from analysis of mineralogical compositions upward through the succession.

The Qahlah Formation (Late Cretaceous) is sandwiched between the exhumed surface of the Semail Ophiolite and a hiatus capped by marine sandstones to limestones of the Jafnayn Formation (Late Paleocene). Qahlah Formation strata are subdivided into three informal units; (i) Green Qahlah at the base contains laterite and green pebbly sandstones, representing an axially draining braided stream system deposited along topographic lows in the half-graben. Green Qahlah grades over 2-5 m into the overlying Red Qahlah that hosts red conglomerates formed in alluvial fans and surrounding floodplain, with drainage overall developing from fault-transverse to parallel with increasing distance to the main fault. Red Qahlah divides into (ii) a lower unit (Wadi al Theepa member) found in a depocentre in the western basin, likely sourced proximal to the basin as suggested by higher immaturity of the sediments and a higher sand:mud ratio. (iii) The upper Red Qahlah (Al Batah member), located in the eastern basin, shows eastward expansion fanning out from an orthogonal monocline, in a depocenter with better sorting, a higher mud:sand ratio, and more prominent graded sub-units compared to (ii). This unit can be ascribed to accommodation developed from localized faulting in a former relay ramp of the master fault.

The depositional changes and shift in colour are also reflected in the mineralogical composition. The Green Qahlah is composed of quartz and lithic mafic rock fragments, whereas the Red Qahlah is composed of mainly (radiolarian) chert and kaolinite. This pronounced mineralogical change reflects a significant shift in dominant provenance area. The Green Qahlah is considered sourced predominantly from the ophiolite and from schists of the metamorphic sole. The Red Qahlah was sourced from the cherts and limestones of the Hawasina Nappe succession south of the basin, in the footwall of the master fault. These changes were partly inflicted by the unroofing of domal structures ascribed to extensional collapse of the Semail Ophiolite.

GA1-01

Recent advances in rockslide mapping in Greenland – some cases and identified knowledge gaps

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On June 17th, 2017 a large rock avalanche occurred in Karrat Fjord, central west Greenland, causing a tsunami that inundated a nearby village, destroyed 11 houses and took four lives. The disaster highlighted a lack of knowledge about this type of geohazard in Greenland and initiated the on-going project on tsunamigenic landslides lead by the Geological Survey of Denmark and Greenland (GEUS).

The project started from scratch in end 2017 as only very limited previous work existed on landslides in Greenland. Initially, a preliminary landslide inventory was produced based on remote sensing data to understand where giant landslides had occurred in the past. 18 potentially unstable areas were identified in this process. Furthermore, recent (<80 years) rock avalanches and tsunamis were examined in detail using historic accounts and remote sensing data to understand the circumstances behind these. Following this initial stage, fieldwork was conducted to examine the identified potentially unstable areas and sites of recent rock avalanches. Additionally, several other tasks were carried out: Marine data were collected in selected fjords to obtain bathymetry for tsunami modelling and to constrain the submarine expression of tsunamigenic rock avalanches. Tsunami modelling was undertaken to quantify the potential consequences of landslide-triggered tsunamis. A network of seismic stations was installed to examine seismic signals from landslides. Near coastal lakes were cored to examine the record of paleotsunamis in selected sites. Additionally, sites for scientific monitoring of mountain permafrost in landslide prone slopes were established.

Examining recent rock avalanches proved particularly fruitful for the understanding of landslide dynamics in Greenland. Several large (>2*10⁶ m³) hitherto unknown rock avalanches were identified thus expanding the record of these from three to eight. Previously unknown mechanisms for conditioning rock avalanches in Greenland was identified, such as unfavourable structural setting and permafrost degradation. Although the sample is small, the record of rock avalanches hints towards an acceleration of these types of events and indicates climate change could play a deteriorating role.

Research into landslides in Greenland is still in its infancy and the recent work have identified a number of knowledge gaps, namely: Several giant Holocene rock avalanches (>km³ -scale) have been mapped. What is the chronology of these events and under what climatic conditions did they develop? Could these conditions develop again? What is the permafrost state of the slopes where recent rock avalanches have developed and what are the potential critical thresholds? And finally: How will permafrozen slopes of unfavourable structural conditions react to projected climate change in Greenland?

GA1-02

10 years of national hazard mapping in Norway - experiences and lessons learned

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In 2010 the Norwegian Water resources and Energy directorate (NVE) was given the national responsibility for the prevention of landslide and avalanche damage. One of the tasks given was to hazard assess built up areas with the aim of identifying buildings in need of mitigation. In 2011 the plan for hazard mapping was made, prioritising municipalities based on the number of buildings suspected to be exposed to avalanches and landslides. Separate plans were made for large unstable slopes prone to rock avalanches and for quick clay hazard mapping. The first hazard maps were published and presented to Årdal and Odda municipalities in 2013. Since then, ca. 80 municipalities have received hazard maps identifying their most hazard prone buildings and pointing out areas safe for future development.

In the 10 years of there have been many lessons learned about for example scale and detail of mapping and weighing competence and price in tender competition. The rise of many new consultant companies producing hazard maps, through increases competition, has led to a higher quality top level hazard assessment, but also to a large group of consultants producing assessments of poor and dangerous quality. This led to a need of an industry standard for hazard assessment that was published in 2020. As the quality of the hazard assessments still is rather variable, further steps are planned to further address this issue.

GA1-03

Extensive paraglacial slope adjustments around Svínafellsjökull, SE Iceland. A warning for other outlet glacier valleys?

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Icelandic glaciers have lost a large amount of ice since the end of the Little Ice Age at the end of the 19th century. Numerous paraglacial slope failures have been documented in the country during this period. In particular, the steep mountainsides by the outlet glaciers of the Öræfajökull ice cap in SE-Iceland are becoming increasingly affected by gravitational mass movements. The Svínafellsjökull outlet glacier has thinned by up to 100 m since 1945, and in the last decade, three major slope instabilities have been observed in the valley. In February 2013 after an intense rainstorm, 5.3 x 10⁶ m³ of unconsolidated

moraine and talus material were released and formed a debris flow which covered a significant part of the glacier surface. On Mt. Svinafell, above the debris flow deposits, a deep-seated slope deformation with an estimated rock volume of at least $100 \times 10^6 \text{ m}^3$, has been under investigation since 2016. Drone surveys and field mapping reveal that the mountain slope is mostly made of sequences of subaerially- and subglacially erupted materials, high stacks of tillites, ubiquitous dikes, and sheet intrusions, and is crosscut by at least three erosive glacial sequences. The main fracture system cuts the northern slope of Mt. Svinafell from east to west for more than 2 km and lies likely along a gravitationally reactivated tectonic fault. Fractures and sinkholes are visible throughout the hillside below the main fracture, indicating that the entire slope experiencing strain. No signs of slope deformation were visible in aerial imagery in 2003, and monitoring equipment installed in 2018 shows displacements on the mm scale, suggesting that most of the deformation occurred between 2003 and 2018. On the other side of the valley, below Mt. Hrótfjallstindar, a recently discovered unstable slope shows clear signs of movement along a planar failure surface where about $1 \times 10^6 \text{ m}^3$ of rock have been sliding downwards following the glacial retreat. These developments show that the whole valley is affected by extensive slope adjustments in response to glacial recession. Comparable mass wasting events, and slope deformations may be expected at many other outlet glaciers in Iceland, especially in volcanic areas with steep adjacent mountainsides and inherited structural weaknesses.

GA1-04

Has climate changes affect slope stability during the last decades in Iceland?

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Changes in weather patterns around the world over the last decades has in many areas affected slope stability, both due to increase in temperature and changes in precipitation. These changes have also been observed in Iceland. Measurements show that from 1980 to 2015 the average temperature has increase $0,47^\circ\text{C}$ per decade. The increased temperature changes have resulted in more frequent thawing periods and rainfall events during winter months, especially in the lowlands. Data indicates that precipitation has increased slightly during the same time interval.

During the last decades, several unusual mass movements events have occurred on the island. These events have been unusual both regarding their size, increased frequency, their triggering factors and not at least the timing within the year they have occurred.

One of the most visible consequences of temperature rise in Iceland is the fast retreat and thinning of outlet glaciers and formation of proglacial lakes. The frequency of mass movements on outlet glaciers have increased, from the turn of the century compared to the last 4 decades of the 20th century. New discoveries of unstable slopes above outlet glaciers have also increased since 2000.

Several mass movements, which can be connected to thawing of mountain permafrost, have occurred in central N and NW parts of the island during the last decade.

Climate change certainly is affecting slope stability in Iceland and is an increasing risk. Especially slopes close to retreating glaciers and those affected by thawing of mountain permafrost.

Changes in temperature and precipitation patterns in late fall and during winter months are causing slope failures that were not as common in the past.

GA1-05

Mitigation alternatives for natural hazards along Nordic infrastructure networks – early results from the NordicLink project

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Weather- and climate-induced natural hazards, including landslides, debris flows, rockfalls, flooding, erosion, and treefalls, present significant challenges in the Nordic region. Transnational linear infrastructure networks – including roads, rails, and power lines – traverse technically challenging terrain and are frequently impacted by hazards. The exposure of these networks and their users to natural hazards is expected to increase in the future as (i) climate change will likely result in increased frequency and magnitude of various extreme weather events, and (ii) societal changes are necessitating network upgrading and increased use and dependency of infrastructure. To secure infrastructure networks against climate-induced hazards, NordicLink collaborates with road, rail, and power infrastructure stakeholders in Norway, Sweden, and Finland to develop hazard and risk-based approaches to selecting mitigation options – including Nature-Based Solutions (NBS) and Early-Warning Systems (EWS).

NBS are risk mitigation and adaptation measures inspired and supported by nature, such as sustainable management of land, water, and resources such as vegetation. EWS are tools that allow to timely depict when and where a hazard event will take place, empowering individuals and communities threatened by a hazard to act in advance. Therefore, NBS reduce the risk by reducing the probability of occurrence of hazard events, and EWS reduce the risk by reducing the exposure of population. NBS and EWS can be jointly applied to reduce the risk due to natural hazards along linear infrastructure. However, guidelines illustrating the conditions for which each type of mitigation measure is most appropriate have not been developed yet.

The objectives of this contribution are to present: (i) a regional overview and ranking of natural hazards most critical to transnational infrastructure in present and future conditions – based on user surveys and an analysis of mainly publicly available hazard and impact inventories in the three Nordic countries and (ii) a review of examples of mitigation with NBS and EWS, from the Nordic Region. Our results have provided interesting insights to model the effect of innovative NBS and develop the components of EWS that can be implemented along Nordic linear infrastructures to reduce the risk of natural hazard events. For selected risks and their related risk management solutions also societal cost and efficiency effects are investigated.

Snow-avalanche hazard in Nunavik, Canada: from snow-avalanche inventory to path identification

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With a growing population within coastal villages and ongoing climate change, Nunavik, in northern Quebec, Canada, faces many disturbances regarding nival regime. The recent years show that snow avalanches occur yearly, both during the winter and spring periods, in Tasiapik valley, close to the village of Umiujaq (56°32'35"N, 76°27'43"W). This valley is equipped since 2017 with several automatic time-lapse cameras operating year-round. The set of cameras enables monitoring target sections of the slope. The recorded snow avalanches correspond to slab and loose snow avalanches; many are triggered by the collapse of the ridgeline snow-cornices. The most active snow-avalanche season corresponds to late spring (June), when wet snow avalanches occurred after rain-on-snow events and rapid temperature rise, being then in contact with the regolith, therefore responsible of debris transfer downslope. However, the longest runout distance snow avalanches occur during the winter time, in April, after sudden temperatures changes or heavy snowfall. Winter snow avalanches reach the road crossing the valley. From the observation of snow-avalanche outlines over the last four years, it was possible to identify snow-avalanche paths, with a specific focus on those with the longest runout.

Protection measures for settlements in Iceland endangered by snow avalanches and landslides

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A programme for the construction of protection measures for settlements endangered by snow avalanches and landslides was initiated in Iceland after catastrophic avalanches hit the towns of Súðavík and Flateyri in the Vestfjords in 1995, claiming 34 lives. The Icelandic Government reorganised natural hazards management and increased public funding to local municipalities for dealing with the threat from snow- and landslides. The Icelandic Meteorological Office was designated as the expert advisory body regarding snow- and landslides hazard and the Government established a Snow- and Landslide Fund to provide funding for local municipalities to implement the necessary measures. Eight deflecting dams and fifteen catching dams, with height in the range 10–22 m, have been built until now and supporting structures have been installed in six starting zones. Several of the dams have already been hit by snow avalanches, some of them up to ten times. Snow avalanches have overrun two deflecting dams and a catching dam. The outlines and other observations of the avalanches provide interesting insight into the dynamics of snow avalanches that hit obstructions and they confirm the great hazard in the respective settlements before the construction of the dams. The avalanches on the deflecting dams have in some cases been observed to form a narrow stream along the damside that is interpreted as an indication of the formation of an oblique shock in the

interaction with the dam as predicted theoretically by depth-averaged granular material dynamics. A dry-snow avalanche that flowed against a 20-m high catching dam partly overran the dam without leaving much of a snow deposit above the dam. The low-density fluidized part of two avalanches that hit deflecting dams at Flateyri in January 2020 overran the dams by several hundred metres and caused some damage to the settlement with one person narrowly escaping serious injury. The avalanche dams that have been constructed in Iceland in the period 1997–2021 have greatly improved the safety of several settlements threatened by snow avalanches, but the experience with the dams shows that they do not provide perfect safety. The engineering principles on which the dam design is based are primitive and the improvement in safety provided by the dams can, therefore, not be quantitatively assessed. It is clear that the dams have stopped or deflected several avalanches that would otherwise have come very close to or even entered the respective settlements. The performance of the dams, in particular the catching dams, for much greater avalanches is nevertheless not certain. Improved models to simulate avalanche flow against dams are, thus, urgently needed. Observations of real avalanches that have hit dams will be essential for the development of such models.

Long-term hazard assessment of explosive volcanic eruptions at Jan Mayen Island (Norway) and their implications for air traffic in the North Atlantic

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The volcanic island of Jan Mayen (Norway), located in the North Atlantic under trans-continental air traffic routes, is considered the northernmost active volcanic area in the world with at least five eruptive periods recorded during the last 200 years. Explosive activity of the volcano may seriously affect the nearby important air traffic routes. However, quantitative hazard assessments on the possible consequences for the air traffic of a future ash-forming eruption at Jan Mayen are nonexistent. This study presents the first comprehensive long-term volcanic hazard assessment for Jan Mayen in terms of ash dispersal and concentration at different flight levels. In order to delve into the characterization and modeling of that potential impact, a probabilistic approach based on merging a large number of numerical simulations is adopted, varying the volcano's Eruption Source Parameters (ESPs) and meteorological scenario. Since current operational forecast products do not always meet the requirements of the aviation sector and related stakeholders (using coarse time and space scales, with outputs on a 40 km horizontal resolution grid and 6 hour time averages), we propose hourly high resolution hazard maps over a 3D-grid covering a 2 km-resolution spatial domain 2000 km x 2000 km wide. Considering a continuum of possible combinations of ESPs to assess and quantify the uncertainty and the natural variability associated with wind fields over 20 years of data, we run thou-

sands of simulations of the ash dispersal model FALL3D. The simulated scenarios are combined to produce probability maps of airborne ash concentration, arrival time, and persistence of unfavorable conditions at different flight levels. The resulting maps can serve as an aid during the development of civil protection strategies, to decision-makers and aviation stakeholders, in assessing and preventing the potential impact of a future ash-rich eruption at Jan Mayen.

GA1-09

Assessment of jökulhlaup hazard and risk for Sólheimajökull outlet glacier, southern Iceland

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The Icelandic Meteorological Office has recently made a hazard and a risk assessment for the proglacial area in front of Sólheimajökull, an outlet glacier from Mýrdalsjökull ice cap. The proglacial area is affected by jökulhlaups that are released from the glacier in connection with volcanic and geothermal activity. Two large catastrophic floods with a maximum discharge on the order of $1 \cdot 10^5 \text{ m}^3/\text{s}$, caused by volcanic eruptions of the Katla volcano, are known in the area during historical times. Medium sized floods with a maximum discharge of few thousand m^3/s are also known, the last one taking place in 1999. The flood in 1999 caused damage to powerlines and other infrastructure but did not damage the bridge across Jökulsá á Sólheimasandi river, which is a part of the main road around Iceland. Smaller floods with a maximum discharge in the order of tens of m^3/s , originating from subglacial geothermal areas, have occurred every few years in recent decades.

Different sized jökulhlaups are simulated using the two-dimensional version of the hydraulic model HEC-RAS. Flood extent, depth, velocity, and arrival times are extracted and used for the hazard assessment. Three scenarios with a maximum discharge of $1 \cdot 10^5$, $3 \cdot 10^4$ and $5 \cdot 10^3 \text{ m}^3/\text{s}$ are simulated on a structured grid with $10 \times 10 \text{ m}$ to $20 \times 20 \text{ m}$ grid resolution. The simulations are sensitive to selection of the Manning's coefficient, which is used to describe bed friction to the flow. Selection of the Manning's coefficient is uncertain due to complicated effects of sediments, boulders and icebergs brought with the floods. Each jökulhlaup scenario is, therefore, simulated using two different fields of the coefficient, i) where one represents a high friction possibility causing large water depth and extent, ii) while the other one represents a low friction possibility with high velocity and shorter arrival times.

Results from the hazard assessment show that jökulhlaups have a substantial damage potential and can threaten people in the area in front of Sólheimajökull and on Sólheimasandur. Information on exposure and number of people in nine selected locations in the area are used for a risk assessment. A methodology, by the British Department for the Environment, Food and Rural Affairs (DEFRA), for assessing and managing flood risk is used for the risk assessment. The main results of the risk assessment show that risk is high (annual risk of death between $3 \cdot 10^{-6}$ and $2 \cdot 10^{-4}$) for groups with high exposure such as guides and staff in the area, if there has not been a successful evacuation in the area before a flood. Good monitoring of flood hazard and evacuation in case of an impending jökulhlaup is therefore important.

GA1-10

The Geomorphological Legacy of the Steinsholtshlaup Rockslide and Outburst Flood in 1967

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High-magnitude floods are extreme geologic agents, transforming landscapes through erosion and deposition within a matter of minutes. On January 15th, 1967, a rockslide fell onto the Steinsholtshlaup outlet glacier and into its proglacial lake on the northern flank of the Eyjafjallajökull ice cap in South Iceland. The rockslide and *Steinsholtshlaup* caused a catastrophic glacial-lake outburst flood (GLOF) down the Steinsholtsdalur valley, producing a unique geomorphological imprint along the flood path. The primary goal of this study was analyzing the post-flood geomorphology with drone surveys, Digital Elevation Models (DEMs) of pre- (1960) and post-flood (1967) surfaces, volumetric calculations, and field mapping. Palaeohydraulic calculations, rockslide volumes, and hummock morphology were used to assess landform formation and the redistribution of debris and the flow hydrology of the flood.

Our results show that the initial rockslide displaced about 20 M m^3 of material which was deposited and reworked throughout the Steinsholtsdalur valley, forming three distinct sets of large sediment hummocks, boulder erratics, boulder bars, and kettle holes. The morphology of these features was analyzed with regards to their deposition post-*Steinsholtshlaup* to further our understanding of the flood hydrology. This study extends our understanding of the variety and complexity of outburst floods from rockslides into proglacial lakes, which may occur more frequently in the future due to impacts of climate change in high-mountain regions.

GA1-11

What is the potential for earthquake-induced landslides in Norway?

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It is well established that the most important triggers of landslides in most places are precipitation and earthquake ground shaking. In Norway, which is a stable continental region of low to moderate seismicity, precipitation has traditionally been considered as the sole triggering mechanism, whereas the potential for earthquake-induced landslides has received more attention in recent years. However, there are still no systematic studies evaluating this potential based on Norwegian data. Written reports on Norwegian earthquakes of $M > 4.5$ during the last two centuries are systematically analysed and compared to meteorological data to reveal at least six landslide-triggering earthquakes in the magnitude range 4.6-5.9. Triggered events include rockfalls, rockslides, clay slides and a debris slide. The events are distributed throughout the country, and triggering occurs up to $\sim 200 \text{ km}$ distance from the epicenter for the largest events. This indicates a fairly large potential for earthquake-induced landslides in Norway, which may have severe consequences, especially in cases where a landslide runs into a body of water to trigger a tsunami.

Mitigation of induced seismic risk associated with geothermal energy in urban environments in Finland

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Deep geothermal energy has a huge potential as environmentally friendly CO₂-free district heat source in urban centers. Currently, there are several geothermal (pilot) projects ongoing and in planning in Finland. A drawback is that geothermal systems can induce small-magnitude earthquakes that pose a risk to critical sensitive infrastructure (such as hospitals, data centers and underground construction). They are associated with inconvenient noise and small-scale ground shaking in urban centers. For example, in 2018 and 2020 during a stimulation of an enhanced geothermal system operated by St1 in Otaniemi, Espoo, several hundreds of small-magnitude earthquakes were induced and recorded by seismic stations around the site. The largest were felt, heard and reported by the citizens to the Institute of Seismology, University of Helsinki. In addition, in 2020 medium deep open geothermal system operated by QHeat induced two small-magnitude earthquakes at Koskelo, Espoo.

SEISMIC RISK – Mitigation of induced seismic risk in urban environments – project is studying, how to evaluate, mitigate, communicate and govern induced seismic risk associated with deep geothermal energy in Finland. The SEISMIC RISK research consortium consists of the University of Helsinki, VTT Technical Research Center of Finland and Geological Survey of Finland. The project is funded by the Academy of Finland from a special call focusing on crisis preparedness and security of supply.

One of the purposes of the SEISMIC RISK –project is to facilitate the development of uniform permitting and regulation for the geothermal energy sector that currently does not exist in Finland. As part of the project, interviews were conducted in 2021, inquiring about the current state of seismic risk management. The views of different actors on who should be involved in risk management and what kind of information different parties feel they need for risk management were analyzed. The key finding is that both perceptions of the nature of the risk and hazard, as well as, the respective roles of different actors and the need for regulation, vary. In 2022, the Ministry of Economic Affairs and Employment in Finland launched an investigation on the legislative needs and potential of geothermal energy in Finland. Large cities in Finland have set up a discussion forum to exchange information between cities on the progress of geothermal projects and to increase related urban planning, permitting and technical know-how in the field.

Climate change and permafrost degradation in northeastern Canada

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In northeastern Canada, climate change has had a major impact on geosystems and ecosystems in Arctic and Sub-Arctic

environments. For example, permafrost degradation, through active layer deepening leads to more frequent landslides, to an increase in groundwater and river turbidity, and to increasing shrub growth (shrubification), coastal erosion, and ground subsidence which affects infrastructure including roads, airstrips and houses. All of these rapid changes have had a direct and significant impact on the Inuit communities that inhabit these sensitive environments.

In this oral presentation, we will show examples of permafrost degradation along a latitude transect that crosses the discontinuous and continuous permafrost zones and we describe the impact of permafrost degradation on the environment. Methodological approaches for monitoring these changes as well as some adaptation techniques and strategies that allow the northern communities to deal with warming permafrost will also be presented.

Improving the resilience of linear infrastructure against climate induced natural hazards; Projects and case studies.

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Critical linear infrastructure comprises roads, railroads and powerlines, all essential for maintaining an operative society. In Norway, roads and railroads are frequently closed due to flooding, landslides and snow avalanches, or because of high hazard for such events. Closure of an important road or railroad for days has high socio-economic costs, and challenges the access to e.g. emergency services. With the projected climate change, in particular the increase in both the frequency and intensity of extreme precipitation, the problems are expected to increase in the coming decades. Here we present three research projects which address the need to improve the climate resilience of such infrastructure systems.

The EU H2020 project SAFEWAY, with 13 European partners, aims to increase the resilience of inland transport infrastructure, while minimizing long-term costs associated with maintenance and rehabilitation. NGI has established a framework for risk assessment of terrestrial transportation systems exposed to extreme events and applied it for flood risk assessment of roads and railways in Europe.

The NordForsk funded project, NordiLink', in which three research partners, NGI, Chalmers University of Technology, the Finnish Meteorological Institute collaborate with important stakeholders, deals with resilience of linear infrastructure in Norway, Sweden and Finland. NordiLink focuses on risk reduction through both early warning and physical mitigation, with case study sites in all the three countries. In Finland, an entire region is studied with regards to power grid failure. In Sweden, instable, sensitive clays along the Göta Älv is the focus, whereas risk from flooding and instability in steep terrain is the focus at a case site in the northern Gudbrandsdalen valley, Norway.

The RCN funded Centre for Research Based Innovation (SFI) 'Klima 2050', includes activities at case study sites focusing on monitoring and early warning for roads and railroads. A slope in Eidsvoll, along the railway line north from Oslo has a marginal stability. Instruments are installed in the ground to monitor changes in pore water pressure, water content and suction. These data are combined with climate variables (precipitation

and temperature) and provide input to models trained to predict near real-time values of the safety factor, for the railway operator to act in case of dangerous situations.

The scenic Trollstigen road on the west coast of Norway is susceptible to flash floods, debris flows, and rockfall, and is closed when threatening weather situations are expected. Although effective, this approach results in more (and longer) closures than is probably necessary. To improve the existing early warning system, local monitoring instrumentation is installed, comprising a weather station, a mobile weather radar and water level / flux measurements in the local streams. Combining data from these instruments with the existing regional data, will enable more reliable warnings, which will lead to a safer road, but also to less unnecessary closures.

In this presentation we will present the activities at the case sites in Norway, their goals as well as some preliminary results. Long-term monitoring at the case sites is planned in close cooperation with the stakeholders.

GA1-15

Permafrost and large slope instabilities – observations, models and implications

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Large unstable rock slopes (LURS) are common in formerly and present glaciated mountain environments. Many of these instabilities started moving or failed shortly after deglaciation due to debulking. However, many LURS failed long after deglaciation or showed varying creep velocities during Holocene. This has been partly attributed to warming and thawing of permafrost, which might influence rock slope stability. This presentation reviews recent studies on the relation of permafrost distribution and rock slope stability in Norwegian mountains, summarizing new observations, models and interpretations, in cooperation with the Norwegian Geological Survey (NGU), The Norwegian Water and Energy Directorate (NVE), University College of Western Norway, Technical University in Munich (Germany), University of Tromsø and EDYIM (France).

GA1-16

H2020 – PHUSICOS, Nature Based Solutions at rural mountain sites in Europe, implementation of measures and barriers experienced.

Anders Solheim, Amy Oen, Bjørn Kalsnes, Vittoria Capobianco, Farrokh Nadim, James Strout

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PHUSICOS is a five-year (2018-2023) H2020 Innovation Action, comprising 15 partners from 7 countries and includes several activities (WPs) to support the main objective of implementing nature-based solutions (NBS); stakeholder involvement, monitoring and assessment, governance, as well as collecting all information in an evidence data platform. The project has three large-scale demonstrator case sites in the Gudbrandsdalen Valley, Norway, in the French and Spanish Pyrenees and in Tuscany, Italy.

A total of 14 NBS interventions to be implemented at the demonstrator case sites comprise measures against flooding, debris flows, shallow instabilities, rock fall, snow fall, erosion, and run-off from farmland. In the Pyrenees, afforestation is performed to prevent release of snow avalanches which threaten a village of Barège, France. Terracing, combined with revegetation and drainage is the preferred stabilizing measure at St. Elena, Spain, where a road-cut through a moraine ridge is defined as a high-risk spot, due to precipitation induced instability. In a steep slope at Artouste, France, wooden structures are mounted near release of rockfall source areas to stop blocks before they gain energy and threaten a main road. A final site in the Pyrenees is the village of Erill-La-Vall, Catalonia, which is affected by frequent debris flows from an area with thick glacial tills and heavy erosion. The NBS here will be a combination of re-vegetation and wooden structures to reduce energy in streams and creeks, and to minimize the feeding of debris from small tributary channels into the main, central debris flow path. In Gudbrandsdalen valley, Norway, the measures are related to flood mitigation at two sites. At a site in Øyer, the preferred NBS is a combination of revegetation, sedimentation basins and constructing a 'blue-green' park area with retention ponds, to reduce flood risk for a new development area for family housing. The other proposed NBS in Norway is to modify an old (1870) dam, in a lake in the catchment of the Skurdalsåa River, a tributary river to the main river Gudbrandsdalslågen. By lowering the threshold gate and adding 0,5m to the old dam, flooding may be delayed by 2 days, enough to reduce damages downstream. This measure has a large upscaling potential, as there are hundreds of similar dams in this part of Norway. In Italy, the NBS are all related to problems of erosion run-off from farmland and flooding in areas around Lake Massaciucoli, and include combinations of vegetated buffer strips, sedimentation basins and optimizing canal shapes. Baseline surveys are conducted at all sites and monitoring of a number of indicators will take place in the years to come to assess the NBS effectiveness.

The measures are under various stages of implementation, and several barriers have been encountered through the course of the project. These include cost issues, stakeholder skepticism, lack of political will, local bureaucracy, national laws and regulations and have caused implementation delays at all sites. The barriers are, however, important as lessons learned regarding new NBS projects.

GA1-17

Rock slope failures along the Isfjorden and Billefjorden coastline, Svalbard: characteristics and implications for controlling factors

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Climate warming and the related permafrost degradation increasingly influence slope stability, landscape evolution, and the natural hazard potential in polar- and high mountain regions. In this context, we investigate the coastal ranges of Forkastningsfjellet and Garmaksla along the Isfjorden and Billefjorden coastline of Svalbard. Both coastal ranges are affected by rock slope deformations of different magnitudes and age. Based on conducted multidisciplinary investigations, we discuss the causes, kinematics and timing of rock slide activity.

The distinct stair-stepped morphostructural relief of the Forkastningsfjellet ridge is the result of a giant postglacial deep-seated rock slide, which involved a minimum rock mass volume of 0.10 km³ and was probably related to the deglaciation of Isfjorden, approx. 11 ka ago.

In August 2016 a rock slide of 175,000 m³ affected the cliff of a coastal tilt block, indicating a transition of the postglacial Forkastningsfjellet rock slide from a dormant to an active state. Field evidence and a back analysis of the rock slide suggest fault reactivation and structural control on the type and mechanism of slope failure but a significant impact of climate-related factors like permafrost degradation and increasing availability of water has to be considered.

At Garmaksla, a flat topped mountain situated at the western margin of Billefjorden, strong rock slope deformations have affected the east facing coastal slope. Extensional movements started at least 6 ka years before present and created different landforms like horst and graben structures and induced different types of gravitational mass movements like rotational rock slides and rock avalanches. Although Garmaksla has a different geological setting than Forkastningsfjellet, analogous structural control on the rock slope deformation is evident. Accordingly, the deglaciation of the Billfjorden and climatically induced factors are considered to drive Garmaksla's past and recent slope failures.

GA1-18

The landslides cycle in the village Seyðisfjörður, east Iceland, 14.-18. December 2020

Sveinn Brynjólfsson

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The settlement in Seyðisfjörður is partly endangered by landslides that have caused accidents and extensive material damage through the centuries since the settlement of Iceland 1100 years ago. After several days of intense precipitation, the largest landslide that has hit a town in Iceland descended on the southern part of Seyðisfjörður in the Eastfjords on 18th of December 2020, destroying 13 buildings and causing enormous destruction. Several other smaller landslides hit the same part of the town in this landslide cycle. Alert phase for Seyðisfjörður had been declared on December 15 and many houses were evacuated in the town that day and in the following days. However, a part of the area where the largest landslide occurred had not been evacuated and some people barely escaped the landslide.

The landslide cycle in Seyðisfjörður 14-18th of december 2020

Heavy precipitation in the Eastfjords during the fall is known to cause severe cycles of landslides and sometimes they are also related to snow melt. An extensive pattern of cracks and spots of soaking wet ground has several times been observed related to such extreme rain events.

The period of extreme rain during December 14th–18th 2020 had the largest precipitation amounts ever observed in the fjord Seyðisfjörður. The accumulated precipitation over these five days was measured over 570 mm. Such a high value has never been observed in Iceland before over a five-day period. For comparison, the mean annual precipitation in Reykjavik is 860 mm and around 1600 mm in Seyðisfjörður.

The largest landslide and almost the last one in the cycle was around 73.000 m³ and rushed at high speed into the ocean. Several smaller slides were released at similar elevation just below the Botnabrún terrace (100–140 m a.s.l.). During the landslide cycle the snowline was mostly just above that elevation and, therefore, landslides were not expected from the upper part of the mountains around the village.

An extensive pattern of longitudinal fractures was found in the sediment at the top of the Botnahlið (the hill below the Botnabrún terrace) and in the surroundings above. The fractures were up to 600 m long with a vertical displacement up to 1 m. Some of the fractures were strongly related to or leading to the scars of the landslides that were released in the cycle. This indicates that a substantial mass could have been released in additional landslides if the precipitation had lasted a little longer.

GA1-19

Past and present landslide investigations in the town of Seyðisfjörður

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At least eight severe landslide cycles have occurred in the past 139 years in Seyðisfjörður that have caused extensive damage to the southern part of town. These cycles are all triggered by periods of heavy precipitation and some of the cycles can also be related to snow melt. The four most destructive cycles in the past were all triggered by heavy precipitation and occurred in August 1950, September 1958, August 1989 and December 2020.

Several landslide investigations have been performed in Seyðisfjörður for the past 20 year, due to the landslide history of the area. That includes geomorphological, geological and geotechnical investigations. Valuable information from these investigations have lead to re-evaluating the risk zones in the area at least two times since 2002. These investigations have led to the discovery of a potentially unstable slope at high elevation where melting of permafrost is a potential candidate for triggering debris flows. Subsurface investigation within the town lead to the discovery of big pre-historical landslides that sits under a part of the current settlement and mapping of the source areas after the destructive andslide cycle in 2020 have given us valuable information about the hydrological and geological conditions that lead to the failures in 2020.

GA1-20

Landslide monitoring and early warning system in the town of Seyðisfjörður, Eastern Iceland.

Jón Kristinn Helgason, Magni Hreinn Jónsson, Harpa Grímsdóttir, Vincent Drouin, Esther Jensen

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It was evident, that after the destructive landslide cycle in 2020 that the town of Seyðisfjörður needed a state-of-the-art land-

slide early warning system. As a response a rather comprehensive system of monitoring devices were installed in the slopes above the settlement. It's composed of multiple different subsurface, surface and remote sensing instruments. The system includes a Total station along with a dense network of prisms, Ground based Insar (GBRI) and webcams to track changes on the surface. To monitor subsurface conditions an automatic water level sensors was installed in pre-existing boreholes and a Shape Array (SAA) was installed to track subsurface displacements. A rain gauge along with soil temperature and moist sensors were installed near the source areas of the 2020 slides, as all historical landslides in the past have been rain and or snow-melt induced. Further expansion of the network is planned this summer, by drilling more boreholes and adding Shape Arrays, Water level sensors and Time Domain Reflectometry cable (TDR) into these holes. It is also planned to install soil extensometers above known surface tension cracks. The main aim of the system is early detections of instability that may lead to major landslides in the future.

GA1-21

Landslide protection measures for Seyðisfjörður following the landslide cycle in December 2020

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In the wake of the Seyðisfjörður landslides in December 2020, immediate protection measures were constructed for the affected part of the town in parallel with cleaning of avalanche debris from within the settlement. Work on assessment of future landslide protection measures for the community of Seyðisfjörður had started few years in advance and the first parts of monitoring system that had been installed only few months in advance proved valuable through the event and in the following weeks afterward. Assessment of permanent protective measures and design of immediate protective measures were thereby intertwined. The immediate protection measures mainly consist of low catching dams as well as a couple of deflecting dams. Future protection measures include higher catching dams with steep upper faces, several debris retention basins as well as draining measures in the landslide starting areas and water diverting measures above them. Rock fall nets and geotechnical support measures are also included in the concept. The developed protection concept additionally includes hazard monitoring as an essential component as permanent protection measures are not believed to provide fully adequate safety for the settlement as required for the most extreme cases. The landslides are generated by gradual movement of thick sedimentary formation covering a significant area. The monitoring system will therefore be vital to document the effect of stabilizing measures through water diversions and drain measures. The presentation will give an overview of the landslide cycle and development of the immediate protection measures, investigations of geological conditions related to the landslide danger and proposed future protection measures that are being designed and will be presented to the community later this year.

GA1-22

Beyond environmental monitoring : are automatic time-lapse cameras an efficient tool for temperature measurement in remote regions ?

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Automatic time-lapse cameras are frequently used to monitor snow and ice related slope processes on slopes in cold regions because of the many advantages they bring to researchers. In addition to providing important informations about the dynamic of the studied area, most of these cameras are now equipped with thermal sensors able to register temperature data when every photograph is taken. The great instrumentation located within Tasiapik valley, near Umiujaq, in Nunavik (northern Québec), enabled us to assess the potential of automatic time-lapse cameras for temperature measurement by comparing data retrieved on photographs with data from two nearby complete weather stations. Our results indicate that the temperature measurements taken by the time-lapse cameras from August to the onset of February are relatively accurate while the weaker performances occurred in late winter and spring (March - June). Moreover, regardless of the year, the time-lapse cameras were most accurate in the morning (09:00 AM – 11:00 AM), while in the afternoon (12:00 PM – 3:00 PM), they tended to over-estimate temperatures. Based on our observation and data analysis, this over-estimation of air temperature seems to be caused by external factors such as the sky conditions and high values of daily mean downwelling that last from February to June. The environment near the cameras might also influence the performances at temperature measurement.

GT1-01

Volcano deformation related to the emplacement of km-scale magma bodies in the upper crust

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In the deeply eroded Neogene areas of Eastern Iceland, the remnants of kilometre-sized magmatic intrusions represent the results of magma accumulation over months to hundreds of thousands of years. The initiation and growth of these magma bodies triggered unrest and, in some cases, volcanic eruptions at the Earth's surface. Our field observations of the Sandfell laccolith, and the Reyðarártindur and Slaufudalur plutons along with structural, petrological, and fabric analyses, and 3D reconstructions allow us to (1) track the growth of magma chambers during single, fast, or multiple, long-term, magma emplacement events and (2) link the related processes with the host-rock deformation.

We identify different styles of magma emplacement that cause characteristic deformation patterns: At Sandfell, layer-parallel

intrusion and inflation of a rhyolitic sill at 540 m depth was accommodated by pronounced surface uplift and faulting. Moreover, strong deformation of the magma itself caused fracturing and faulting that would have been detectable by seismometers at the surface. At Slaufudalur, the intrusion of 10 km³ of magma was controlled by ring-dyking and subsequent cauldron subsidence, a mechanism that also dominated the emplacement of at least 2.5 km³ of magma at Reyðarártindur. Both plutons formed at 1-2 km depth and filled up by addition of several magma batches, likely without causing significant surface deformation. Instead, fracturing, faulting, and dyke emplacement in the roofs of Slaufudalur and Reyðarártindur may have been detectable through associated minor seismicity. Notably, we observed conduit structures and associated roof subsidence at Reyðarártindur that we interpret as evidence for eruptions triggered by magma recharge.

Together, these case studies of solidified magma bodies in the Neogene rift zone of Iceland help delineate the link between magma emplacement and volcano deformation and seismicity. This link can contribute to an improved interpretation of volcanic unrest signals at active volcanoes.

GT1-02

Interaction between propagating basaltic dykes and pre-existing fractures in hyaloclastite

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A large part of magma transported into and through the shallow crust takes place via dykes. The shape and propagation mechanism of such dykes, which strongly influence surface deformation, depend not only on the magmatic characteristics, but also on host rock properties, crustal heterogeneities and external stressfields e.g. due to the tectonic setting.

This study aims at understanding how dykes propagating through the shallow crust are influenced by pre-existing fractures. We mapped basaltic dykes in a caldera-filling hyaloclastite at the extinct Dyrfjöll volcano, Northeast-Iceland, where erosion allows to look into the shallowest few hundred meters below the paleo-surface. Virtual 3D-models from drone-based photogrammetry were used for measuring orientations of dykes and fractures at three cliffs/mountain sides within the caldera as well as quantifying their interactions.

The majority of fractures and dykes dips within 20° of the vertical and follows one of four strikes. The most dominant one is 010-040 and aligns with the strike of the divergent plate boundary at the time of emplacement. The three other sets strike 050-080, 110-140 and 150-180 and their visibility varies between the different sites. More than half of the identified dykes used fractures either entirely or intermittently. Out of 39 changes in strike directions, which were detected across 14 dykes, 21 occur near, at or into a fracture. In most cases, the strike changed by 10-40° and no changes were larger than 60°. Strongly fractured hostrock seems to lead to more frequent and slightly larger changes in strike. If a dyke meets a barrier, e.g. a pre-existing dyke with a significantly different strike, while propagating in otherwise intact rock, it can form thin offshoots

at its tip. These offshoots are aligned with fractures and dykes observed elsewhere in the caldera, indicating the importance of the external stressfield.

In conclusion, our study shows that basaltic dykes in hyaloclastite tend to follow pre-existing weaknesses in the shallow crust. Improving our understanding of the role of pre-existing fractures for the propagation path of pre-eruptive basaltic dykes is important for volcanic areas, where hyaloclastite is one of the major rocktypes.

GT1-03

Models of pre-eruptive processes of the Fagradalsfjall eruption in 2021

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Shortly after the onset of the cyclic uplift and subsidence with associated seismicity at the Svartsengi high temperature field, 8 km west of Fagradalsfjall in January 2020, a group of scientists from GFZ-Potsdam and ÍSOR started to collect data to explain the ongoing process. We collected high-resolution seismic data using both an existing optical telecommunication cable that crosses the unrest area and a dense network of seismic station operated by several different institutions. Furthermore, we collected gravity data in four consecutive campaigns at pre-existing permanent sites along a profile over the uplift area to estimate the density of possible intrusion material and used SAR Interferometry (InSAR) with Sentinel-1A/B acquisitions to calculate the uplift and subsidence of the surface.

Since the uplift occurred in a high-temperature hydrothermal field it is reasonable to expect hydrological processes to contribute to the observed deformation. Therefore, we applied a poroelastic model that assumes inflow of fluid into a horizontal aquifer located at depth below the source of the uplift. The aquifer inflates during the inflow periods but deflates due to diffusion processes in the aquifer when the inflow stops. The fluid intrusion causes poroelastic response resulting in surface deformation, fluid flow in the aquifer, and the Coulomb stress changes on the fault planes. The model explains the InSAR time series, particularly the rapid subsidence following each cyclic uplift, the free air gravity changes and the seismicity variations in time and space. Our best fit model gives a total injected volume of 0.11 ± 0.05 km³, a density of 850 ± 350 kg/m³ and an aquifer depth of 4 km. The wide range of uncertainties in the model is dominantly due to uncertainties in the Skempton coefficient, which depends on the aquifer porosity and the compressibility of the aquifer fluid.

Based on the results of the poroelastic model we introduce a physical model that explains the three observed inflation phases in Svartsengi and the fourth one in Krýsvík in 2020. Furthermore, we developed a conceptual model of the pre-eruptive process that connects our models with geochemical observations of the erupted lava.

The conceptual model suggests accumulation of magma at 15-20 km depth beneath Fagradalsfjall, where CO₂ exsolves

from the magma and migrates upward through the ductile part of the crust. When it reaches the impermeable brittle crust, the CO₂ becomes trapped. When a certain volume has accumulated, a batch of pressurized CO₂ flows along the up-doming brittle-ductile transition to its shallowest points below the high temperature geothermal fields of Svartsengi and Krýsuvík. This leads to the observed surface deformation.

From our results we calculate that the minimum amount of magma necessary to produce the total volume of the injected CO₂ is in the range of 2 – 9 km³ provided that all the exsolved CO₂ has reached the geothermal fields which indeed is unlikely. Therefore, the amount of accumulated melt at 15-20 km depth below Fagradalsfjall must be considerably higher. Only a fraction of this melt reached the surface during the 6 months eruption in Fagradalsfjall.

GT1-04

Un-stressing of crust prior to eruptions: Precursors to the 2021 eruption at Geldingadalir, Mt. Fagradalsfjall, in the Reykjanes Peninsula Oblique Rift, Iceland

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Detailed observations of seismicity and deformation on volcanoes provide steadily increasing information on eruptions precursors and how volcanoes behave. Escalating rates of precursory activity often occur prior to an eruption, that can be used to give an estimate of eruption onset time with the material failure forecast method. However, some eruptions show very different behaviour, even a reduction in precursory activity immediately prior to eruption. This was the case for an eruption that began on 19 March 2021 in Geldingadalir at Mt. Fagradalsfjall at the Reykjanes Peninsula oblique rift in Iceland, terminating about 800 year long period of no eruptions. High rates of deformation and seismicity occurred from 24 February to mid-March in relation to gradual emplacement of about 9 km long magma-filled dyke and triggered strike-slip earthquakes up to Mw5.64, as tectonic stress accumulated over decades or centuries prior to the eruption was released. Seismicity and ground deformation observations show that this period of tectonic stress release ended with a decline in deformation and seismicity over several days preceding the eruption onset. Precursory activity that we observe resembles e.g. that observed prior to the 1975-1976 fissure eruption the Tolbachick volcano, Kamchatka, when seismic swarms sharply decreased 1-2 days prior to opening of new fissures. Therefore, such precursory behaviour may be relevant for eruptions in volcanic rifts in general, that follow the formation of an evolving dyke intrusion fed from a deep magma body. In such tectonic settings, the un-stressing of the crust should be expected prior to eruptions.

GT1-05

Coeruptive subsidence during the 2021 Fagradalsfjall eruption: geodetic constraints on magma source depths and stress changes

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Geodetic observations during volcanic eruptions are important to constrain from where the eruptive products originate in the sub-surface. Some eruptions are sourced from magma reservoirs shallow in the crust, whereas others may tap magma directly from the mantle. The 2021 Fagradalsfjall eruption took place on the Reykjanes Peninsula, Iceland, during March 19 to September 18, resulting in approximately 0.15 km³ of erupted basaltic lava. A wide-spread crustal subsidence and inward horizontal motion, centered on the eruptive site, was observed during the eruption using GNSS and InSAR. Nearest to the emplaced lava flows, additional localized subsidence is observed due to the loading of the lavas. The regional subsidence rate varied during the course of the eruption: it was low in the beginning and then increased, in broad agreement with changes in the bulk effusive rate. In this study, we use GNSS and InSAR data to model the deformation source(s) during different periods of the eruption, primarily aiming to resolve the central location, depth, and volume change of the magma source. We furthermore calculate crustal stress changes during the eruption and compare to the regional seismicity.

GT1-06

Pressure increase at the magma-hydrothermal interface at the Krafla caldera, North-Iceland, 2018-2020: magmatic processes or hydrothermal changes?

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The Krafla volcanic area in the Northern Volcanic Zone of Iceland was characterized by deflation starting in 1989, suggesting a general pressure decrease and/or volume contraction at depth. In fall 2018, the volcano behaviour shows a change in the deformation pattern as observed both by Global Navigation Satellite System (GNSS) geodesy and Sentinel-1 satellite radar interferometry (InSAR). The difference in surface ground velocity fields 2015-2018 and 2018-2020 reveals uplift (relative to prior subsidence) centred on the area between Leirhnjúkur and IDDP-1 well at a rate of 5-6 mm/yr in 2018-2020. The differential velocity field broadly fits deformation caused by spherical

source of pressure within a uniform elastic half-space, with a volume change of $2.6 - 3.8 \times 10^5 \text{ m}^3/\text{yr}$ and centre depth 2.1-2.5 km. The possibility of inflation due to changes in the geothermal system, natural and/or eventually due to change in net geothermal mass extraction for the Krafla power plant or change in water reinjection, is also evaluated. We use the Finite Element Method to understand if the deformation can possibly relate to about 0.1 MPa/yr pressure increase in the geothermal system, as measurements in monitoring well KG-10 in the area indicate. The numerical modelling shows that inferred volume change can be due to a spherical source with radius = 1.4 km and 0.1 MPa/yr pressure change if the surrounding crust has Young's modulus $E \sim 7 \text{ GPa}$. However, the average regional Young's modulus for the upper crust in Iceland has been estimated to be $E = 30 \text{ GPa}$. Further investigation with the finite element analysis helps us to evaluate how deviations from a uniform elastic half-space may affect deformation. We test the influence on displacement of the presence of a local crustal volume around the source with lower Young's modulus value in near-field and higher value in the far field. Such a model can reproduce significant features of the observed deformation, indicating that both hydrothermal and magmatic processes should be explored as an explanation for the present inflation. Seismic moment release shows only slight variations until middle of 2019, but thereafter it increases. Seismic energy is released in fewer and larger earthquakes. That could indicate strengthening of the crust and/or relate to crustal strain and stress changes in the crust in relation to the overall change in deformation pattern. No noticeable changes have been observed in the chemical composition of fumarole discharge. Gravity stations in the area were remeasured in November 2019 for allowing comparison with earlier observations, and for providing reference for later studies.

GT2-01

Towards the implementation of site effects in a site-specific seismic hazard study for Oslo (Norway)

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Common practice to perform a seismic hazard study at regional scale is to present the results computed at bedrock condition. Site effects are usually not considered because soil information is not always available. Our goal is to carry out a site-specific seismic hazard study for the city of Oslo (Norway), conducting a microzonation study that will include site effects. More specifically, the Vs30 value has been introduced to become the main attribute to characterize the soil type and subsequently account for soil type related seismic amplification. Vs30 values are missing for the Oslo area, therefore we aim to invert Horizontal-to-Vertical (H/V) spectral ratio of ambient seismic noise as a proxy for S-wave velocity (Vs) profiles. A campaign with 61 measurements has been performed between March and June 2021 at specific locations in Oslo. In addition to resulting Vs30 values, this method will also allow us to define depth to bedrock estimates, which will likely be required for an updated Eurocode. The Vs30 values extracted from H/V measurements are compared to the Vs30 estimates from topographic slope attributes extracted from DTM (Digital Terrain Model). This procedure is applied in specific areas in the Oslo urban environment that are susceptible to site effect amplifications.

GT2-02

Pinballing across the faultplane: the 1.5-year-long migration of earthquakes in the Bitdalsvatnet swarm (Telemark, S Norway)

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The Southern Norwegian mountain plateaus belong to the least seismically active areas in Norway, yet a persistent swarm of earthquakes started on a NW-SE striking fault plane 3 km north of the Bitdalsvatnet (Telemark) waterpower reservoir in November 2020. Since then, the Norwegian National Seismic Network has recorded more than 70 earthquakes with magnitudes greater than 1 in the swarm, and with sensitive template matching we detected more than 1000 small earthquakes in addition. Careful analysis of the earthquakes shows that they extend across a patch of the fault plane that is 1.5 km long and 700 m high. The hypocenters follow a clear, but complex migration trend in three phases: (1) from NW to SE and downwards with a velocity of $\sim 40 \text{ m/day}$, (2) from the same initiation point, again from NW to SE but with a slower velocity of $\sim 4 \text{ m/day}$, (3) from SE to NW, against the previous direction, and upwards, at $\sim 12 \text{ m/day}$. The migration occurred mainly during more than 20 bursts of seismicity that each lasted a few days, with individual bursts interrupted by breaks of up to a month. Even though the earthquakes occur at shallow depth of less than 3 km, there is no apparent correlation with any environmental parameters (e.g., anthropogenic activity, precipitation, groundwater level, temperature, snow depth). Earthquake swarms with clear migration trends occur naturally in a range of environments, with the earthquake migration commonly attributed to the migration of fluid in the fault. Considering that there is no clear evidence for a fluid source near the initiation point of the swarm, we investigated a range of parameters derived for the earthquakes (locations, magnitudes, stress drop, space-time distribution, seismic moment, fault patch size). Based on these parameters, we present two models of the process driving the earthquake swarm: (i) Spreading of a pore-pressure wave within the fault plane driven by a fluid of a yet unknown source, or (ii) a purely tectonic cascade of slip on the fault plane driven by stress transfer between failing patches of the fault plane.

GT2-03

Iceland GeoSurvey's seismic monitoring of developed geothermal fields in Iceland

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Geothermal fields in Iceland, specifically the high-temperature fields, are located in tectonically active areas that naturally experience seismicity. Iceland has successfully utilised their bountiful energy resource, both for electrical power production and space heating. Iceland GeoSurvey (ÍSOR) currently monitors six developed geothermal fields with permanent seismic stations for three Icelandic energy companies: Landsvirkjun (LV), Reykjavík Energy (ON) and Norðurorka (NO). Previously, ÍSOR also operated seismic networks for HS Orka and Veitur, and has

in the past run various temporary networks for the Icelandic energy companies. The geothermal fields currently monitored are Krafla (LV), Peistareykir (LV), Námafjall (LV), Hellisheiði (ON), Nesjavellir (ON) and Eyjafjörður (NO). Additionally, ÍSOR takes part in multiple European collaboration projects with the respective energy company and various independent research institutions and universities.

All data from the different seismic networks is streamed in real-time to ÍSOR, and subsequently, automatic locations of earthquakes are available to the respective energy company. The seismic networks are a combination of stations owned by the energy companies, ÍSOR stations operated for the energy companies, stations from the national seismic network of the Icelandic Meteorological Office and research stations. The seismic networks comprise 1s, 5s, 30s and 120s instruments.

For automatic earthquake detection and location and day to day monitoring of the geothermal fields, ÍSOR uses the Seis-ComP software, where the majority of events are manually refined. We observe increased but variable seismic rate in production and injection areas, while it can be challenging to distinguish between natural and induced seismicity. In some cases, the shallow seismicity at <3km depth is linked to either production or injection. Seasonal fluctuations are observed in both seismicity rate and magnitude range in some areas, with varying *b*-values and *V_p/V_s* ratios. The mapping of seismic activity can give valuable information about e.g., fracture permeability and orientation, while a detailed mapping of the brittle-ductile transition below the geothermal fields gives important information on the physical state and properties of the crust, including constraints on temperature. ÍSOR strives towards interdisciplinary interpretation of the seismic data with existing geophysical, geological and geochemical data sets.

GT2-04

Using natural seismicity on the Reykjanes Peninsula for an enhanced understanding of the crustal structure with emphasis on the high-temperature geothermal fields within the NASPMON project.

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The NASPMON project (NATural Seismicity as a Prospecting and MONitoring tool for geothermal energy extraction) benefits from a € 1 370 000 grant from Iceland, Liechtenstein and Norway through the EEA Grants and the Technology Agency of the Czech Republic within the KAPPA Programme. The NASPMON project is a 3.5-year long project which started in April 2021. It is based on the local seismic network REYKJANET, operated on the Reykjanes Peninsula by the Czech Academy of Science and Iceland GeoSurvey (ÍSOR). The network was deployed in 2013 and now consists of 17 stations, all streaming data in real time since early 2021. Since the deployment of the network in 2013, it has been operated continuously and captured the largest seismic swarms on the Reykjanes Peninsula in 2017, 2019, 2020 and 2021. The project was well placed when the seismic unrest started on the Reykjanes Peninsula in December 2019, and with the 2021 Fagradalsfjall eruption in the central part of the REYKJANET network.

Wide collaboration and data sharing agreements have been established within the project, such as with the Icelandic Met Office, University of Cambridge, University of Uppsala, Universi-

ty of Potsdam, University of Iceland, University of Durham, GFZ Potsdam and ON Power. The project objectives are to enhance and update the current crustal model of the Reykjanes Peninsula, where seismic data plays a key role with the emphasis on high-temperature geothermal fields and energy extraction. The current seismic unrest will naturally be a big part of the project. Here we present various results of the project at this point in time, such as, seismic analyses of the 2021 Fagradalsfjall dyke intrusion in the context of previous seismic swarms in the area, deep seismicity below Fagradalsfjall, eruption tremor analysis and attenuation of seismic waves in Krysuvík.

GT5-01

Lateglacial and Holocene sealevel history for the island Værlandet, western Norway

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We here present a new sea-level curve from Værlandet, an island in the sea gap northwest of the mouth of Sognefjorden in western Norway. The results are based on studies of sediment cores retrieved from isolation basins and exposure dating (¹⁰Be) of erratic boulders. Radiocarbon dates may suggest that the island became deglaciated as early as around 15,8 ka while the ¹⁰Be ages suggest that it happened a thousand years later or thereabouts. The marine limit has been found to be 14-15 m a.s.l. and was attained during deglaciation. A rapid fall in sea-level occurred during the Bølling chronozone (14,5-14,0 ka) and after a period of stillstand was followed by a transgression of more than 4 m during the Younger Dryas. During the early Holocene, sea level dropped well below the present level before it again rose up to 6 m a.s.l. during the Tapes transgression. The course of the sealevel changes is reflecting the glacial history through isostatic and gravimetric (geoid) responses but is of course also governed by the eustatic changes.

GT5-02

Glacial Rebound and Crustal Movements affecting Coastal Engineering Projects

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Abstract

The Icelandic Road and Coastal Administration, IRCA, is working on several projects on the south coast of Iceland where glacial isostasy and vertical crustal movements play an important role.

Hornafjarðarós is a tidal inlet on the southeast coast close to Vatnajökull with a glacier rebound of 13 mm/year. Inside the inlet there are two shallow bay areas which will partly be dry with the expected relative changes between sea and land. It has been estimated that the tidal prism will decrease of about 35-66% with a relative land rise of 0.5-1.0 m. The ebb shoal outside the inlet is a limiting factor for navigation through the inlet and to the fishing town of Höfn. It is unknown what the implications of the decrease in tidal prism will be for the depth over the ebb shoal.

IRCA is now looking into the possibility of dredging a navigational channel through the ebb shoal.

Jökulsárlón á Breiðamerkursandi is a glacial lagoon on the southeast coast. The lagoon is separated from the sea by a narrow strip of land which the Icelandic Route 1 passes through with a bridge over the glacial river. The advance of the glacier early last century pushed out material into the sea. After the glacier started retreating this narrow strip of land has been eroding heavily and the road and electrical lines passing have already been moved once.

The question is when the isostatic rebound which has been measured as 20 mm/year will begin to tick in and turn the erosion into accretion or if a major coastal protection scheme will be needed.

Vík í Mýrdal is a coastal town on the south coast. Neither is the sandy beach in front of Vík a stable phenomenon nor has it a long history. Supposedly, it started to develop in jökulhlaup's from Katla in 17th century. At the start of the 20th century, the beach was rather narrow and eroding. After the Katla eruption in 1918, the beach accreted for 50 years at a rate of 10 m/year. Widest was the beach around 1970. Then it started to erode with a similar erosion rate as it had accreted. Coastal engineering studies showed that it would be possible to halt the beach erosion by building groynes perpendicular to the coastline. The first groyne was built in 2011 and the second in 2018.

A new road is planned seaside of the town, but is it possible to stop the erosion with the groynes? In the long term the isostatic rebound, 7 mm/year, is believed to decrease the erosion and help in stabilising the coast.

Grindavík is a fishing town on the south coast of the Reykjanes peninsula, an active volcanic area, with tectonic boundaries and geothermal exploitation, resulting in land subsidence of 9 mm/year. The harbour is protected by breakwaters and the land with rubble mound revetments. All structures are subjected to depth limited waves and with more depth the wave load on the structures will increase. Flood risk will also increase.

GT5-03

Glacially induced stress across the Arctic from the Eemian interglacial to the present - implications for faulting and seafloor methane seepage

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Release of methane, a potent greenhouse gas, is of major concern as the climate changes. Large amounts of this gas leak along continental margins, forming pockmarks on the ocean floor: a process known as seafloor seepage. Faults and fractures are known to play a key role in the transport of the gas towards the seabed and into the ocean. In the Fram Strait and the Barents Sea, for instance, the periodic release of methane has been associated with glacial – interglacial transitions and faulting. Yet, the processes that determine the stress field that controls fracture and crack-related seepage remains poorly quantified. Glacial stresses are constantly evolving, creating stress perturbations in the lithosphere that extend significant distances away from the ice. To quantify the impact of glacial loading and unloading on the regional stress field, we use Glacial Isostatic Adjustment (GIA) modelling and calculate the response of a viscoelastic Earth model to the ice load. We use recent time-dependent ice-thickness models that cover Greenland, North America and Northern Europe from the Eemian interglacial (~

122 kyrs BP) to present time. The magnitude of the vertical GIA-induced stress closely follows the thickness of the ice cover, whilst the horizontal stresses are governed by the subsequent flexure of the lithosphere. This means that the differential stress induced by GIA changes over the course of a glaciation and has an evolving effect on fault stability. Our model predicts that the GIA maximum horizontal stress contribution is compressive in regions covered by ice and tensile off the edge of the ice-sheet. Along the west-Svalbard margin, which is in the forebulge, the maximum horizontal stress induced by GIA remains tensile (~0 to -4 MPa), and East-West oriented, between the last glacial maximum and present time. The Barents Sea shelf lies in the flexural trough region where horizontal stresses are compressive at both the LGM (~20-25 MPa) and present (~5-8 MPa). Our calculations of the Coulomb failure stress in these two regions show that GIA-induced perturbations of the regional stress field could be sufficient to destabilize pre-existing submarine faults and favor gas seepage.

GT5-04

Fault stability in northern Europe through past and future glacial periods

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Fennoscandia, being located well inside a tectonic plate, is a low seismicity region with only a handful of known earthquakes of magnitude 5 or larger in the historic record. However, in northern Fennoscandia several prominent fault scarps exist, the largest with offsets of more than 20 meters and traceable for over 160 km across the terrain (e.g. the Pärvie fault in northernmost Sweden). In the vicinity of these, various land forms and soil disturbances typically associated with strong shaking have been identified. Relative dating of scarps and soft sediment disturbances indicate that the ruptures occurred around the end of the last glaciation or shortly after. The faults are therefore known as Glacially Triggered Faults, GTF's, believed to have been activated by earthquakes with estimated magnitudes in the range 6-8 and reverse faulting motion. During the last decade similar structures have been identified in the Baltic countries, Poland as well as northern Germany, albeit to date it remains to be proven that these have not been generated by other mechanisms. Glacial Isostatic Adjustment, GIA, modelling of the Weichselian glaciation show that the induced stress field in a reverse faulting background stress field favoured fault slip in northern Fennoscandia at the end of glaciation and after, while inhibiting fault slip at earlier times. At present it is unknown if GTF's were activated also during earlier glaciations. Here we present fault stability predictions for the region based on GIA modelling of the significantly larger Saalian ice-sheet as well as different scenarios of future glaciations. Results are presented for a selection of Earth models previously found compatible with Holocene and present day uplift in the region and we discuss the implications for past and future glacially triggered seismicity in Fennoscandia as well as in other formerly or presently glaciated regions of the world.

Investigating a possible onshore-offshore correlation between the Frøya High and Frøya Island, mid-Norwegian margin

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Following hydrocarbon discoveries within fractured and weathered basement on the Utsira High, Norwegian North Sea, basement highs on the Norwegian Continental Shelf have received renewed interest. Among the targets is the Frøya High, located in the Norwegian Sea about ~40 km south-west of the island Frøya, just off the western coast of Norway. In this study, we investigate the possible correlation between the top basement surface and unconformities identified offshore on the Frøya High and the exposed basement surface onshore on Frøya Island.

The formation of the Mid-Norwegian Rifted margin comprised several discrete and successive phases of crustal thinning and displacement along major detachment faults. These phases record the evolution from orogenic extensional collapse of the Caledonides to break-up and ocean spreading. During periods of tectonic quiescence, mature paleo-landscapes had time to develop, controlled by paleoclimate and sea-level fluctuations. The major Devonian Høybakken Detachment Zone resides east of the Frøya Island, while the next major seaward breakaway complex is formed by the western constraint of the Frøya High, the Jurassic-Cretaceous Klakk Fault Complex. The Klakk Fault Complex shows signs of multiple periods of displacement, each corresponding to a distinct crustal response involving significant footwall uplift and back-rotation.

Rock samples of the crystalline basement, obtained from deep drillcores on the Frøya High, shallow stratigraphic cores from the Møre-Trøndelag coast, and outcrops on Frøya Island have displayed physico-chemical alteration, possibly due to circulation of meteoric fluids during subaerial exposure. Alteration of solid crystalline rocks may improve the reservoir potential, and one of the goals of this study is to trace the alteration history of the basement unconformity(ies) from onshore Frøya and offshore towards the Frøya High. Three unconformities are identified across the Frøya High, possibly linked to specific periods of uplift and/or subsidence. Knick-points across the high separate erosional surfaces with different dips. In the case of a corresponding basement landscape, seismic-to-well ties, outcrop and core sample dating may help constrain the formation of these unconformities, and indicate which period of system subsidence and/or displacement along the Klakk Fault Complex these erosional surfaces may be linked to.

We use an integrated approach, compiling results and analyses of seismic reflection data, potential field data and well data offshore, with core analysis within basement and outcrop studies onshore. To reduce the impact of human bias in the interpretation, the morphometrical characteristics and lineament analysis of both top basement surfaces are analyzed and quantified using experimental computer algorithms currently under development at the Geological Survey of Norway.

Rift propagation north of Iceland: A case of asymmetric plume dynamics?

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The Iceland plume system has been able to feed into the North-east Atlantic spreading ridge system since continental breakup at ~55 Ma. This has led to the formation of the anomalously ~30 km thick igneous crust along the Greenland-Iceland Faeroe Ridge (GIFR). However, spreading history and plate kinematics south and north of the GIFR have been very different. South of the GIFR spreading has been relatively simple and symmetric along the Reykjanes Ridge. North of the GIFR, spreading initiated along the Aegir Ridge within the Norwegian Basin. But from ~50 Ma onwards, northward rift propagation from the plume west of, and overlapping with the Aegir Ridge occurred, and spreading along the Aegir Ridge began to retreat northward. The two competing systems effectively formed a coupled propagating and retreating rift system until all plate separation eventually took place along the Kolbeinsey Ridge at ~23 Ma. This working hypothesis is based on detailed seismic mapping of the igneous crust that forms most of the Iceland Plateau. Four phases of accretion, Iceland Plateau Rift I-IV followed by a proto Kolbeinsey Ridge stage just prior to the full formation of the Kolbeinsey Ridge are recognized. IODP Proposal 976 includes 6 drill sites sampling the igneous basement of stages IP I-IV, the proto-Kolbeinsey Ridge stage, and the Kolbeinsey Ridge prior to the formation of the Tjörnes Fracture Zone north of Iceland. A seventh drill site will address the significant faulting, in part transpressive, that affected the continental crustal fragments that were torn off from the East Greenland margin as a consequence of the northward rift propagation. The basement sampling serves two purposes: (1) to determine the precise age of the IP I-IV rift stages and the proto-Kolbeinsey Ridge stage; and (2) to map the temporal evolution of the composition of the mantle that sourced the formation of the Iceland Plateau. The latter is of considerable interest since there are indications that this mantle might be of a much more depleted nature than that originating from Iceland and the northern Reykjanes Ridge, and yet form anomalously thick oceanic crust. Together with

the compositional evolution and modelling of the potential mantle temperature T_p , drilling will allow us to characterize a 'northern' and so far uncharacterized component of the Iceland plume mantle through time. Sediment sampling will focus on the Oligocene record of the transition into the ice-house world and on the Plio-Pleistocene evolution of sea-surface temperature and ice-cover. IODP proposal 976 was accepted by IODP in February 2022 for possible inclusion in the R/V JOIDES Resolution expedition schedule 2023-2024.

GT6-02

The influence of orogenic collision inheritance on rifted margin architecture and segmentation: Insights from comparing numerical experiments to the mid-Norwegian margin

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Most rifts and rifted margins around the world developed on former orogens. This implies that the pre-rift lithospheric configuration is heterogeneous in most cases. Here we investigate how collision inheritance in the form of inherited weak thrusts, long-term thermal weakening, compositional changes, and orogenic collapse, could have played into the spatio-temporal evolution and final architecture of rifted margins. We present interpretations of dynamic numerical experiments, including constraints representative of the North Atlantic Mid Norwegian rift system phases of continental collision, orogenic collapse, and extension, and compare these to interpretations of seismic reflection profiles.

The experiments form rifted margins characterized by basement structures and sedimentary geometries very similar to the Norwegian Møre and Vøring rifted margins - with onshore collapse-related basins, extensively deformed continental crust with detachments, shear zones, core complexes, rotated thrusts and an offshore succession of distinct structural domains (proximal, necking, hyperextension, exhumation, and outer).

Although extensional models developed on homogeneous lithosphere are a good approximation of rifted margin architecture, our results suggest that models that consider pre-rift orogenic inheritance tend to reproduce more accurately the geometries observed in our natural example.

GT6-03

3D evolution of large-magnitude extensional faults and their effect on the architecture of rifts and rifted margins

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The successive incision of continental crust from early to late stages of evolution in rifts and rifted margins is rarely explained in 3D. One reason is likely the lack of a unifying model for how

very large faults grow, and link laterally through the temporal evolution of the margin. As fault shape exerts a fundamental control on syn-rift basin architecture, the 3D evolution of detachment faults is critical to understand sedimentation in associated basins.

In the proximal margin offshore Norway, the differential exploitation of 'extraction' geometries that evolved above the ductile crust controlled temporal and lateral variations in fault style including flips in fault polarity and lateral transitions in the architecture of supradetachment and half-graben style, Late Paleozoic-Triassic basins.

The growth of an extensional fault past a few kilometers of displacement will involve a change in 3D fault geometry caused by the isostatic rollback of parts of the fault plane. As displacement magnitude varies along the fault plane, so will the amount of extensional unloading and associated isostatic compensation. With increasing extension, this will enforce a particular shape on the fault plane, with an extensional culmination developing in the area of maximum displacement, and synclinal recesses evolving on the flanks. With continued extension, the culmination may evolve into a core complex. Necking domains, where faults propagate into the ductile middle crust appear to be prime locations for this type of faulting. As large-magnitude faults combine into domain-bounding breakaway complexes, this results in intermittent occurrences of core complexes along the main breakaways and lateral transitions into steeper megafaults and fault arrays. This predicts that profiles across different parts of a margin or margin segment will show very variable geometries. Parts of the Jurassic-Cretaceous north Møre and south Vøring basins of the Mid-Norwegian margin appears to illustrate this type of evolution. Components of strike-slip may modify this type of pattern, as illustrated by continental core complexes exposed in areas such as Death Valley and western Norway.

GT6-05

How Caledonian structures camouflage as Permo-Carboniferous structures in the Oslo Region, Norway

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The Cambro-Silurian sedimentary successions of the Oslo Region record two major, distinct Palaeozoic tectonic events: SE-directed thrusting during late Silurian/Early Devonian Caledonian compression and E-W-directed extension associated with the creation of the Permo-Carboniferous Oslo Rift. It has been proposed that the Oslo Rift is connected to the Variscan orogenic front through reactivation of the Sorgenfrei-Tornquist Zone and rifting in the offshore Permo-Carboniferous Skagerrak graben.

It is commonly argued that NNW to NNE-striking strike-slip and oblique-slip faults in sedimentary units of the Oslo Region are late Carboniferous to Permian in origin and either represent the transfer zone between the Vestfold and Akershus half grabens or are caused by a transitional strike-slip regime during early rift phases.

However, field mapping and balanced geological cross-sections along several sub-vertical strike-slip faults show that they reflect Caledonian deformation. Detailed fieldwork has revealed two different mechanisms for formation of Caledonian faults with apparent strike-slip fault movement. Firstly, faults and

stratigraphy relations demonstrate the existence of tear faults that accommodate lateral differences in displacement between segments of thrust sheets and account for associated structural and lithological breaks. On a small scale, such tear faults are seen to terminate against overlying and underlying Caledonian thrust faults. On a larger scale, the lateral breaks between adjacent domains of different compressional structures can only be explained by Caledonian tear faults.

Secondly, a number of steep faults with sub-horizontal slickenlines contained within Caledonian thrust sheets reflect rotation of earlier thrust faults into sub-vertical position by a second generation of Caledonian thrust faults. The rotation to sub-horizontal lineation is due to a local atypical Caledonian thrust direction towards the ESE.

Due to their similar strike-directions, sub-vertical faults of Caledonian origin can easily be misinterpreted as Permo-Carboniferous strike-slip faults. Therefore, age determination through detailed mapping of the fault and surrounding geology is important in order to differentiate between the two fault groups.

Numerous sill intrusions of late Carboniferous age have commonly been used to postulate a possible far-field compressional stress regime of that age in the area. A number of thrust faults are thus proposed to be of late Carboniferous age. However, field relations show that these sills are strata-concordant within the dipping and folded Cambro-Silurian succession and thus not indicative of late Variscan far-field stresses. Furthermore, detailed mapping strongly suggests that the thrust faults in question are of Caledonian age, like the rest of the thrust faults in the region.

GT6-06

Geochronology of the norther part of the Karasjok Greenstone Belt records ~500 million years of plume induced magmatism and rifting.

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The Palaeoproterozoic Karasjok Greenstone Belt (KGB) is situated in the north-eastern part of Norway. It continues through Finland and into Russia as the Central Lapland Greenstone Belt (CLGB). The stratigraphy is well preserved and divided into four different formations (from base to top): The *Vuomegielas formation* lies unconformably on top of the Archaean Jergul Gneiss Complex (JGC). The lower part consists of clastic sediments while the upper part consists of tholeiitic metabasalts, komatiites, rhyolitic extrusives and mica-schist. The *Skuvvanvårri formation* lies unconformably on top of the JGC and Vuomegielas. The basal contact is a polymict and matrix supported conglomerate. The formation is dominated by arenitic sandstone and mudstone. The *Gollebåiki formation* is composed of psammitic rocks, tholeiitic metavolcanites, mica-schists and interlayers of dolomite. (Ultra)mafic Layered intrusions are common in this formation. The *Báhkilvårri formation* is dominated by tholeiitic banded amphibolites and is interlayered with several komatiitic units where the lowermost, the c. 300 m thick *Fossestrand Member*, is the largest and best preserved. We have sampled and analyzed all relevant units in northern KGB, including the underlying JGC, to constrain their age and temporal relationships, both internally and to other Paleoproterozoic supracrustal successions. JGC samples yielded U-Pb zircon ages between 3000 ± 12 and 2743 ± 17 Ma, the same age span as found in the Kautokeino Greenstone

Belt (KkGB) and West Troms Basement Complex. A rhyodacite from the upper part of the Vuomegielas formation gave an U-Pb age of 2456 ± 3 Ma. This age slightly pre-dates the age of the Salla group in the CLGB which has been related to the 2.45-2.43 Ga Matachewan plume event which led to a large igneous province producing huge volumes of flood volcanics and initiated rifting of the Kenorland supercontinent. The age and geographical location of northern KGB indicates that it records the early stage of this event. The lowest depositional age of the Gollebåiki formation is defined by the 2145 ± 2 Ma Coalbmejávri layered intrusion. The age is similar to the basalitic volcanites found in KkGB, the Alta-Kvænangen area and the Savukoski group in CLGB. The presence of this magmatism in KGB confirms a major tectonic event that led to rifting and extensive magmatic activity on the Fennoscandian shield. Zircons from a synvolcanic gabbro in the komatiites of the Fossestrand member were dated to 1983 ± 5 Ma. Further up, an intermediate volcanite from Báhkilvårri formation yielded 1962 ± 3 Ma. Similar ages are found from volcanites both on the Karelian and Kola cratons. This plume induced volcanism is the last known major tectono-magmatic event on the Fennoscandian shield before onset of the Lapland-Kola orogeny and concludes almost 500 million years of plume activity, rift processes and crustal thinning recorded in the stratigraphy of KGB.

GT6-07

Extensional tectonic geomorphology along the northeast Atlantic margin? A field-based investigation of three half-graben basins

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This study investigates landscape evolution along passive continental margins on long timescales.

In tectonically active extending regions, the relations between geomorphological features and evolving controlling structures have received much attention. How such landscapes evolve on long timescales is, however, poorly understood.

Recent work from onshore parts of the northeast Atlantic margin suggests that some present-day landforms are inherited from rifting and opening of the North Atlantic Ocean in late Paleozoic, Mesozoic and early Cenozoic times. These relict landscapes are difficult to recognize, as much of the topography is reworked by post-rift Cenozoic uplift and erosion, as well as by repeated glaciations during the Quaternary. For that reason, interpretations of these landscapes vary considerably. However, some of the rift features are demonstrably preserved in the form of half-graben sedimentary basins. We consider these areas to be ideal to analyze basement morphologies and the relationships between rift-related and other landscape elements.

This work uses three half-grabens as study areas to assess possible landscape inheritance from rifting and margin formation. Two of the field sites are located on the Mid-Norwegian mainland. These are the late Jurassic Sortlandsundet half-graben in Vesterålen and the Beitstadjorden half-graben in Trøndelag. Both half-graben basins are submerged in fjords and have no post-rift cover preserved. The third study area is the late Carboniferous Billefjorden Trough on Svalbard, which in contrast has post-rift cover preserved in both the footwall and hanging wall of the basin-controlling fault, and additionally exposes

the entire basin stratigraphy onshore. Thus, the Billefjorden half-graben is an excellent example of how an ancient half-graben basin and its surroundings undergoes erosional disintegration under Arctic climatic conditions.

We use structural and geomorphological field observations, seismic images, and apply remote sensing techniques to digital elevation models to analyze and compare landscape evolution around the three half-graben basins. We classify landscapes in detail, systematically reviewing present-day landscape distributions to distinguish tectonic landforms from other geomorphological features.

Preliminary results show that certain landscape features appear to be directly associated with rift-related faulting and/or post-rift fault reactivation, as all three half-grabens are characterized by marked topographical escarpments that run parallel to the basin-bounding normal faults. The formation of these escarpments was likely assisted by erosion into fault cores and damage zones containing fault-rock assemblages and increased fracture densities. Additionally, all three study areas have very distinct landscape signatures. For example, the Beitstadfjorden landscape appears to be strongly influenced by inherited ductile structures and transposed lithological boundaries. In Sortlandsundet, however, the topography appears similar to that of actively extending regions. This may indicate that Sortlandsundet experienced later reactivation of the basin's controlling structures. We therefore also conclude that present-day landscape components strongly reflect the pre-, syn- and post-rift history of the region. Important factors include erosional exploitation of pre-rift structures, syn-rift displacement and rotation of pre-rift surfaces, possible late-Cretaceous or younger reactivation of basin-bounding normal faults, and variable fluvial and Quaternary glacial incision.

GT6-08

Geomorphic Evolution of a Passive Margin of Korean Peninsula: Initial Uplift, Tectonic Inversion, and Divide Migration

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Although the Passive margin occurs across most of the oceans and the continents of the globe, it has drawn less attention than the Active margin. Tectonically inactive since the middle Miocene, the Korean Peninsula is generally considered a typical passive continental margin with asymmetric relief with only low levels of seismic activity.

The Taebaek Mountain Range (TBR) initially formed via extension of a back-arc basin in the East Sea during the early-Miocene (ca. ~22 Ma) and exemplifies a typical escarpment on a passive continental margin. The TBR acts as a major watershed and divide across which topography changes from gentle western side slopes to steep eastern slopes. Compared to the geologic history of the flanking extensional basin, which is well known from analysis

of its sedimentary fill, the post-extensional geomorphic history of the escarpment and basin margin has been minimally studied because of a lack of terrestrial archives.

To infer the geomorphic evolution of the passive margin, we took a first look at the eastern flank of TBR, which has recent report of uplift as high as 150–350 mm ka⁻¹ from fluvial and

marine terraces. We evaluated the geomorphic status of eastern Korea using denudation rates at geomorphic timescales of 10³–10⁶ years, which are equivalent to the rates previously reported at local points. The CWDR data are ~2–3 times lower than rates of coastal uplift and river incision. The relationship between CWDRs and topographic indices such as elevation, relief, and slope indicates that most of the study area rests in a near steady-state condition. However, in contrast to the smooth concave longitudinal profile expected for a steady-state landscape, topographic analyses reveal the presence of major knickzones. Our 1-D modeling of knickpoint propagation suggests that tectonic disturbance is the factor most likely to produce knickzones in the study area, raising the possibility that erosional signals caused by late-Pleistocene tectonic disturbance affected channel gradients, but that the knickpoints have not yet propagated through the entire catchment area. The eastern part of the Korean Peninsula is approaching, but has not completely reached, a geomorphic steady-state, and that transient conditions may have been induced by reactivation of the rift-flank margin (~5 Ma).

Then, we determined the rate and cause of divide migration of the TBR using a suite of relatively new geomorphic and geochronologic tools. We used geomorphic analyses of relief, slope, river long profiles, swath profiles, and \bar{D} parameters to study this transient topography. CWDR east of the divide from drainages with steep slopes average nearly two times counterparts with gentle slopes west of the divide. Gilbert metrics used to assess divide mobility strongly suggest that catchments in the eastern TBR may have captured counterpart catchments in the west. Both CWDR and Gilbert metric results reveal that retreat of the main TBR divide likely accelerated in the late Quaternary following tectonic inversion (~5 Ma), surface uplift, and tilting or flexure in the eastern TBR. Geomorphic disequilibrium across the current divide of the TBR continues until the present.

GT6-09

New apatite thermochronological data from Western Norway

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By using apatite in thermochronological studies, we can unravel the cooling history, and thus potentially the erosion history of the uppermost continental crust (<120°C). This study fills a regional data gap and focuses on the northern part of Western Norway (Nordfjord region), an area situated onshore of the transition zone between the N-S trending North Sea and NE-SW trending Norwegian Sea. 19 samples were analysed by apatite fission track (AFT) and 17 samples for (U-Th)/He analysis. Five of the AFT samples and 13 of the (U-Th)/He samples were collected close to sea level. These samples show AFT ages from 117 ± 9 Ma to 167 ± 16 Ma and (U-Th)/He ages from 57 ± 7 Ma to 228 Ma ± 23. The remaining 15 AFT and four (U-Th)/He samples were collected along a subvertical profile up the Skåla mountain (from 63 to 1841 masl) with a regular spacing of approximately 100–150 m. The samples represent an intact structural block as no major faults were observed along the sampled profile. The low-T ages show a general increase with the elevation from 146 ± 10 Ma AFT age and 80 ± 9 Ma to 109 ± 13 Ma (U-Th)/He ages in the lowermost sample (63 masl), and an AFT age of 236 ± 20 Ma for the uppermost sample (1841

masl). The highest sample for (U-Th)/He analysis was collected at 1691 masl and shows ages from 229 ± 30 Ma to 277 ± 31 Ma. The dataset will be complemented by 14 AFT data from the same region. The results are used to perform time-temperature modelling and, combined with brittle structural investigations, K-Ar fault gouge and U-Pb calcite dating, will allow us to better comprehend the exhumation history of the northern part of Western Norway.

GT6-10

Fault outcrop analysis in porous siliciclastic rocks

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Faults are complex structures that substantially influence the geometry and properties of their host rocks with important consequences for mechanical behaviour and hydraulic connectivity of rocks. Therefore, studying faults is important for different applications such as CO₂ and waste sequestration, geothermal reservoir management, seismology and geohazard studies. Faults in porous siliciclastic rocks can be localized in the form of clusters of deformation bands, encompassing displacement up to tens of meters. These faults usually form in the damage zone of larger faults with hundreds of meters displacement. In order to document structural and petrophysical heterogeneities along fault strike, we studied fault core and damage zone details of a 120 m well-exposed normal fault in porous siliciclastic rocks of the Rio do Peixe Basin, Brazil. Our approach combines structural, geometric, and in-situ permeability measurements along fault core and across damage zone, as well as drone imaging and sampling in the field. We investigated and constrained the damage zone width by studying the changes in the frequency of deformation structures (fractures, deformation bands) on 18 scanlines. The damage zone width decreases toward the fault tips and is largest around the central fault segment. Further, we investigated the changes in microstructure, porosity, and capillary threshold pressure of the samples both along the fault core and across the damage zone. Our study shows that the thickest part of the fault core has the lowest porosity and permeability and the highest capillary threshold pressure. Our study shows the importance of fault segmentation and heterogeneities on fault rock properties and its fluid flow behavior.

GT6-11

Integration of different methodologies to analyze surface deformation: examples from Iceland and Mt. Etna

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In structural geology and volcanotectonics, data collection and field observations are essential to understand the role played by magmatic intrusions and tectonics in dictating surface deformation. Unfortunately, this analysis relies on a great amount of field data, to be collected in sites that are often characterized by difficult logistic conditions, thus not easily reachable. As a next step, these data should be interpreted and associated with tectonics and/or magma paths below the surface.

Here, we show how the integration of different methodologies can be useful to overcome these difficulties, presenting some examples from active tectonic and volcanic areas around the world, such as in Iceland and Italy.

In Iceland, we mapped the whole fracture zones of the Husavik-Flatey Fault (HFF) and the Theistareykir Fissure Swarm (ThFS), in the Northern Volcanic Zone. Here, thanks to the integration of classical field surveys and Structure-from-Motion (SfM) photogrammetry techniques applied to drone-collected images, we placed special emphasis on studying offsets along the easternmost section of the HFF, and the geometry and kinematics of 649 faults and 1208 tension fractures in the ThFS. These data have been integrated with analogue scaled models, aimed at analyzing the possible conditions that could have led to the formation of the observed fracture pattern at the intersection between the two main fracture zones. Thanks to this data synergy, we were able to confirm a prolongation of the HFF through the ThFS.

In Italy, we performed a multidisciplinary investigation on faults and fissures associated with the 1928 dike event on the flank of Mt. Etna, based on detailed field surveys and numerical modeling using the Final Element Method (FEM): this resulted in possible, different relations between surface deformation and the geometry and physical characteristics of the underlying dike.

Finally, we present here a modern and innovative method aimed at overcoming limitations in data collection, through the use of Immersive Virtual Reality, that allows to navigate within 3D digital outcrop models (DOMs), reconstructed with UAV-based SfM techniques.

IM1-01

The composition of apatite in the Archean Siilinjärvi glimmerite-carbonatite complex

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The Siilinjärvi glimmerite-carbonatite complex, located in Eastern Finland, is one of the oldest carbonatites in the world (~2610 Ma, Rukhlov and Bell 2010). The rock types range from glimmerite (phlogopite rock) to calcite-carbonatite, with glimmerite being the more voluminous endmember (O'Brien et al. 2015). All rock types contain abundant apatite and the deposit has been mined for decades for phosphate fertilizer raw material. Only one study (Decrée et al. 2020) has previously focused on the composition of apatite in different rock types within the Siilinjärvi complex. In this study, we expand the knowledge on the differences in apatite chemistry within the Siilinjärvi complex.

The chemical composition of apatite was studied from rock samples obtained from two active production sites in the Siilinjärvi mine – the Särkijärvi main pit and the Saarinen satellite pit. Six samples (thick sections) were studied *in situ* with back scattered electron (BSE) and cathodoluminescence (CL) microscopy techniques and subsequently analyzed with electron

microprobe (EPMA) and laser ablation inductively coupled mass-spectrometer (LA-ICP-MS).

The concentration of Ca is similar (9.92 ± 0.04 atoms per formula unit) in both pits, showing little substitution of Ca by other cations, e.g., Sr and Na. Fluorine is the primary halogen in all analyses, yet some zones show high concentrations of up to 1.9 wt-% Cl, which is unusual in carbonatitic apatite. There are notable differences in the mineralogy and textures between the samples from the two pits. Saarinen samples are more melanocratic, contain sulfides (pyrite with minor chalcopyrite), show signs of shear, contain apatite with ample inclusions (mainly calcite), and have pigmented carbonates. The differences are also noticeable in apatite mineral chemistry as apatite from Saarinen have lower Sr and F concentrations and consequently higher calculated OH concentrations.

Larger differences are observed in the rare earth element (REE) and Y and in trace element ratios such as Sr/Y and REE ratios that display fractionation between the light and heavy REE typical for carbonatitic apatite, with high Ce/Yb ratios of 150 and 120 in Särkijärvi and Saarinen, respectively. The total REE concentration is on average 4000 ppm in Särkijärvi and 3300 ppm in Saarinen, which is low compared to average apatite from carbonatitic rocks (e.g. Webster and Piccoli 2015). Concentrations of Th, U, and Pb are below 20 ppm and 5 ppm, respectively. The ratios of Sr/Y are very high, when compared to a global database of apatite compositions. Apatite from carbonatites generally have the highest Sr/Y ratios but analyses from Siilinjärvi define a global end-member composition caused by low Y rather than high Sr concentrations combined with low HREE concentrations. We interpret that the geochemical characteristics of the Siilinjärvi apatite were likely derived from the parental magma and have not been strongly affected by alteration processes as opposed to many other carbonatite localities.

IM1-02

Untold Tales From the Deep Dark Crust: Importance of Lower Crustal Magmatism for the Formation of LIPs

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The lower continental crust is one of the most intangible frontiers in geosciences. At the few localities where the deep crust is properly exposed, primary features are obliterated by high-grade metamorphism and deformation. At magma-rich volcanic margins, the lower crust is even more elusive because vast emplacement of high density mafic and ultramafic plutons (a.k.a. mafic underplating) inflict burial rather than uplift. Acoustic velocities of 7.1-7.7 km/c imply c. 80 vol% of mafic/ultramafic bodies also known as Lower Crustal Bodies or LCBs comprise the lower crust.

We propose that the Seiland Igneous Province (SIP) in N. Norway represent an easily accessible epitome of such an LCB. SIP is matching the description of the lower continental crust at magma-rich passive volcanic margins in featuring c. 80% mafic, ultramafic plutons formed from basaltic, picritic, komatiitic and alkaline melts emplaced into gneissic basement rocks at depth of 30-40 km's.

SIP is mostly formed in the Ediacaran at Ma 570-560 Ma and is associated with a LIP known as the Central Iapetus Magmatic province. Our preliminary studies show that the emplacement of dense juvenile melts in SIP is enforced by unexpectedly high volatile contents, which partially is buffered by co-existing hydrous-carbonated alkaline silicate melts. It is comprising >20.000 km³ of mafic and ultramafic intrusions with minor alkaline-carbonatitic complexes and felsic rocks.

Four large peridotite complexes are regarded as the main conduit systems for inter-crustal emplacement of thousands of km³ of basic and ultrabasic melts. Gravimetric studies suggest an average thickness of the layered gabbros of >4 km and show four major ultramafic conduits extending >9 km downwards. These ultramafic conduits are well exposed in a right-way-up position in steep-sided 20-200 km² plugs. From edge to core, they comprise a marginal fusion zone towards the country rock, followed by olivine-clino-pyroxenite cumulates, then wehrlitic and, at the centre, dunitic cumulates. Parental melt modeling implies ultramafic parent melts with 16-22 wt.% MgO, Cr of 1594 ppm and Ni of 611 ppm. They were emplaced at 1400-1500 °C and mostly formed at 1630 °C at 7 GPa by partial melting of carbonated asthenospheric peridotite in the presence of a mantle plume. Abundant hornblendites, carbonatites and lamprophyres throughout SIP confirm the volatile-rich nature of the mantle source region and are further corroborated by high average contents of magmatic sulphides (0.5-1%), as well as carbonated and hydrous phases (1-5%) throughout mafic and ultramafic rocks. Volatile-rich phases are particularly common at PGE-Cu-Ni occurrences where they co-exist with the ore-forming sulphide-rich assemblages and we hypothesize that immiscible volatile-rich alkaline melts aided in both deposition and later disruption of ore-deposits. Volatile phases will also lower melt densities and viscosities and may be important for rapid fluxing from the mantle throughout the deep crust to the more shallow crustal realm of these nominally dense basic-ultrabasic melts.

IM1-03

New insight into the hydrological and thermal conditions of Surtsey and relation to the time-lapse alteration.

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In summer 2017, the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and Innovative Concretes (SUSTAIN) drilling project, drilled three cored boreholes through Surtsey Volcano, a very young oceanic island, nature preserve and UNESCO World Heritage site. The new boreholes (SE-2a, -2b and -3) in addition to the borehole drilled in 1979 (SE-1) provide a unique opportunity to study the subsurface geothermal system on a young volcanic island.

Time series measurements of well SE-01 show that the maximum temperature at a vertical depth of about 100 m has decreased since 1980 from about 140°C to 124°C, although the general topography of the temperature profile remains similar over the time period. The temperature profile of SE-2a shows a similar trend. However, the maximum temperature in SE-2a is about 1.5°C higher. Temperature logs of the vertical wells indicate an inflow of cold water at about 145 m below the surface. The temperature in the diatreme beneath the island is about

60°C, well above the expected ambient temperatures for ocean floor. The maximum temperatures in the angled well SE-3 measured during the annual Surtsey research expeditions 2018 yield a temperature of 138°C, which is 14°C hotter than in the vertical wells with the temperature maximum being about 20 m deeper than in the vertical wells. Time series measurements started shortly after drilling was completed. They indicate that the well SE-3 had reached thermal equilibrium after drilling in 2017. The rise in temperature towards west suggests that the hottest part of the geothermal reservoir within the edifice lies under the main craters of the 1963-1967 eruption. The thermal conditions of Surtsey were analyzed after the drilling in 1979. However, the data from the 2017 drilling campaign requires an update of the hypothesis.

Despite the cooling of tuff deposits of the tuff deposit time-lapse alteration continued over time. This allows us to quantify the time-lapse alteration of basaltic glass and the associated element transport.

IM1-04

Petrology and geochemistry of the Sveinar-Randarhólar fissure (Central East Iceland): Insights into magmatism following post-glacial lithospheric rebound

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The Icelandic extensional, intraplate environment has experienced extensive changes in lithostatic pressures during deglaciation in the past at least ~11 ka¹. The recently established project "FinMag" aims to conduct multifaceted research aimed at improving our understanding of mantle melting regimes and possible modifications of crustal plumbing systems in response to isostatic uplift (i.e. post-glacial lithospheric rebound) and its effects composition of melts produced. This case study focuses on the early-Holocene Sveinar-Randarhólar fissure system (Central East Iceland), which formed contemporaneously and/or in response to recent deglaciation. The Sveinar-Randarhólar fissure system consists of a discontinuous row of relatively small scoria cones (typically <50m in height and <200m in diameter) and the associated Sveinahraun basaltic lava flows, which together extend for more than 75km from the southern side of the Route 1 Highway (~20km east from Mývatn) to Raufarhöfn on the northern coast². This crater row and associated lava flows presents an excellent opportunity to examine the geochemical variability across a long fissure system. Furthermore, the geochemistry and petrogenesis of the Sveinar-Randarhólar fissure is unconstrained and it is undetermined whether this fissure system is related to other larger magmatic systems (e.g., Askja volcano²), or formed from an independent magma source(s).

We present an overview of our results and other in-progress research aimed at: i) characterizing changes in the composition (i.e. major and trace elements, Sr-Nd-Pb-Hf isotopes) of the Sveinar-Randarhólar fissure system from south to north, as well as any mantle source heterogeneity. ii) Constraining the depths and rates of magma ascent using mineral and melt thermobarometry and diffusion timescales. iii) More accurately constrain the melting dynamics and minimum ages using short-lived U-Th-Ra radiogenic isotopes. iv) Developing a geodynamic model to constrain the source of the Sveinar-Randarhólar magmatism, as well as delineate links between mantle melting, magma ascent and postglacial rebound lithospheric rebound.

IM1-05

Structural control on the preservation of mantle heterogeneity during plume-ridge interaction along the southern Kolbeinsey Ridge

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The transition of the plume-related intraplate melting environment of northern Iceland into the Arctic Kolbeinsey Ridge is one of the classic regions of plume-ridge interaction. The geochemically enriched intraplate mantle sources emplace unique tracers into the upwelling, depleted mid-ocean ridge melting regime that allow tracking the interaction of the distinct source and melting regions. Here, we present new major element, trace element and Sr-Nd-Pb isotope data of glasses from the 290 km long southernmost Kolbeinsey Ridge segment and its southern boundary to Iceland, the Tjörnes Fracture Zone, along with published data from the northernmost Iceland volcanoes. The southern Kolbeinsey Ridge is characterized by trace element (e.g., (La/Sm)_N, Nb/Zr, K/Ti) and Sr-Nd-Pb isotope signatures that range from enriched intraplate signatures in northern Iceland to mid-ocean ridge like signatures at the northern segment. On a smaller spatial scale, we can show that the incompatible element and isotope variability along the southernmost 25 km of the Kolbeinsey Ridge is comparable to those observed at the Tjörnes Fracture Zone and Theistareykir volcanoes. The variability of the southernmost Kolbeinsey Ridge segment cannot easily be explained by simple mixing of melts and the enrichment and variability of trace element compositions can also not be explained by simple changes in the degree (e.g., (Ce/Yb)_N) or depth ((Dy/Yb)_N) of partial melting. Estimating the variability of degrees of partial melting using fractionation-corrected major elements (Ca₈, Na₈, Al₈) shows that the degrees of partial melting generally exceed 10-15%, too large to sufficiently fractionate the incompatible element ratios. Here, we propose a model in which the geochemical mantle heterogeneity between the plume and Kolbeinsey MORB asthenosphere is preserved in melts rising along the Tjörnes Fracture Zone and the slower spreading sections of the southernmost Kolbeinsey Ridge segment. We propose that structural crustal pathways can preserve much of the original mantle heterogeneity even in plume-ridge environments in which a relatively strong mantle plume interacts with a slow spreading center (<20 mm/a), whereas melts may more efficiently homogenized along the central parts of the spreading axis.

IM1-06

Environmental impact of Large Igneous Provinces: does the mantle source matter?

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Both lithospheric and sublithospheric mantle sources contribute to the vast volumes of primitive magmas in continental flood basalt provinces. Several large igneous provinces (LIPs) on cratons have been directly associated with rapid climatic and biotic change on a global scale. The outgassed volcanic

CO₂ and SO₂ (and other volatiles) responsible for the observed environmental impact have been suggested to be sourced from either recycled crustal components in deep-seated mantle plumes or from volatile-rich components within ancient continental lithospheric mantle. These scenarios compete with models in which greenhouse and other gases are primarily released from sedimentary rock units intruded by LIPs. Distinguishing between these options has implications for modeling potential links between deep volatile cycles, volcanic activity, and environmental change.

Many basalt and picrite units of the ca. 180 Ma Karoo LIP in Africa–Antarctica show trace element and isotopic features that are best explained by melt contributions from incompatible element enriched components within the lithospheric mantle of former Gondwanaland. This implies that thick continental roots took actively part in magma formation. However, the exact nature of these strongly incompatible element enriched components remains elusive.

We identified a ca. 180 Ma old lamproite magmatic event in south-central Africa, sourced from within the diamond stability field. The ultrapotassic lavas provide first constraints on the origin and evolution of ‘pure’ K-rich components within the mantle source regions of a continental flood basalt province. Non-traditional stable isotope data do not support an origin of the K-rich component by subduction recycling of continental or oceanic crust. Rather, radiogenic isotope systematics suggest that such ultrapotassic components accumulated within a cratonic mantle root during episodic percolation of low-degree alkaline silicate melts since ca. 1 Ga. Such K-rich metasomes have relatively low melting points and, thus, are readily remobilized as the dominant enriched component of continental LIPs, which are sourced mainly from below the lithosphere. The most enriched Karoo picrites may contain up to 10% mass fraction from such K-rich cratonic mantle components. The carbon and sulfur budgets of these metasomes are, however, too small to cause significant environmental impact.

IM1-07

W, Os, and Pb isotopic evidence for an early formed deep mantle source of Karoo flood basalts

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Growing evidence suggests that the sources of many flood basalts and related hotspot tracks come from the Earth’s deep mantle: what has been suggested by the elevated ³He/⁴He in multiple flood basalt provinces has been recently backed up by anomalously low ¹⁸²W/¹⁸⁴W in the Deccan Traps.

We report here W, Os, and Pb isotopic data for low-Ti picrite lavas from the Karoo flood basalt province, southern Africa. The Os and Pb isotopic data and previously reported Sr and Nd isotopic data and chemical compositions are compatible with a primitive mantle-type source, with the least-contaminated lava plotting on the 4.56 Ga Geochron in uraniumogenic Pb isotopic space (initial ²⁰⁶Pb/²⁰⁶Pb 17.390 ± 0.0100, ²⁰⁷Pb/²⁰⁶Pb 15.454 ± 0.0080). The W isotopic compositions range to anomalously low $\mu^{182}\text{W}$ (-7.2 ± 2.2) values, which is compatible with incor-

poration of material from the Earth’s core-mantle boundary into a primitive mantle-type source.

Given that recent studies have favored generation of low-Ti Karoo flood basalts from primitive mantle-type sources, the combined evidence suggests an early formed mantle reservoir at the core-mantle boundary might have been a significant source for Karoo flood basalts. This hypothesis does not exclude other recycled or depleted mantle sources for other magma suites of Karoo flood basalts – the African LLSVP, where the early formed source would lie, hosts a variety of other mantle components at its margin. The Karoo plume likely sampled many of them, as well as components in the upper mantle.

IM1-08

Heterogeneous Karoo mantle plume and its relation to southern Atlantic Ocean hotspots

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The source composition of the Jurassic continental flood basalts of the Karoo province is important for understanding the origin and evolution of mantle plumes in the South Atlantic region. The Karoo basalts are not linked to any of the present hotspots surrounding southern Africa by conspicuous volcanic tracks or geochemical correlations and, due to uncertain plate motions during initial Gondwana break-up, any of the present hotspots could represent the tail of the Karoo plume.

We present chemical and isotopic (Sr, Nd, Pb) data for presumably plume-derived and uncontaminated rocks from the Karoo province. All samples show close to chondritic initial e_{Nd} (i) (+0.05 to + 3.9) and bulk-Earth like ⁸⁷Sr/⁸⁶Sr(i) (0.7040 to 0.7057) coupling with relatively low ²⁰⁶Pb/²⁰⁴Pb (17.21 to 18.50) and high ²⁰⁷Pb/²⁰⁴Pb(i) (15.43 to 15.62) and ²⁰⁸Pb/²⁰⁴Pb(i) (37.55 to 38.85). The samples collected from the main Karoo rift zone (SE rifted margin) show high ²⁰⁸Pb*/²⁰⁶Pb*(i) (1.01 to 1.08) and mantle-normalised incompatible element patterns indicative of enriched mantle 1 (EM1) sources, whereas the samples collected from the main Karoo Basin show low ²⁰⁸Pb*/²⁰⁶Pb*(i) (0.97) and incompatible element patterns compatible with a primitive mantle (PM) -type source.

Overall, the EM1-affinity Karoo (rift zone) flood basalts are remarkably similar to the so-called Gough type lavas of the Gough, Discovery, and Shona hotspot tracks and were plausibly derived from the same source region. In contrast, the PM-affinity Karoo (basin) flood basalts seem to record a plume source that has not been incorporated into the Cretaceous hotspot tracks. Our results suggest that the Karoo flood basalts record the arrival of a heterogeneous plume head from the same source region that has fed the Gough-type tracks. Judging from the correlation of the Gough hotspot with the Etendeka flood basalts and the <40 Ma age of the Discovery track, we consider the Shona hotspot to be the most probable location of the waning Karoo plume. We propose that the EM1- and PM-affinity Karoo flood basalts reveal plume head components from the recently postulated enriched and primitive mantle reservoirs in the plume generation zone underneath the present South Atlantic hotspots.

Long or short silicic magma residence time beneath Hekla volcano, Iceland?

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Timescales of magma transfer and differentiation processes can be estimated when the magma differentiation mechanism is known. When conventional major- and trace-element analyses fail to distinguish between various processes of magma differentiation, isotope compositions can be useful. Lower Th isotope ratios in silicic relative to basaltic magmas at a given volcano, could either result from magma storage over a period of several tens of thousands of years if the differentiation process was fractional crystallisation alone, or from crustal anatexis on a much shorter timescale. Recently mapped bimodal tephra layers from Mt. Hekla, Iceland, confirm lower ($^{230}\text{Th}/^{232}\text{Th}$) and higher Th/U in silicic versus mafic magmas. Higher Th/U has been taken to indicate either apatite fractionation or partial crustal melting. In-situ trace element analysis of apatite and the enveloping glass in basaltic andesite, dacite and rhyolite was undertaken to examine its capacity to fractionate trace elements and their ratios. Both Th and U are compatible in apatite with a partition coefficient ratio $D^{\text{U}}/D^{\text{Th}}$ of 1. Hence, apatite crystallization and separation from the melt has a negligible effect on Th/U in Hekla magmas. Consequently, partial melting of hydrothermally altered crust remains the preferred mechanism for producing silicic melt beneath Hekla. Ten to twenty percent partial melting of metabasaltic crust with 0.4-1.2 wt% H₂O produce dacite magma with 4-6% water. Absence of low $\delta^{18}\text{O}$ values in Hekla magmas compared to silicic magmas of the rift-zones suggests mild hydration of the hydrothermally altered crust. Silicic magma formation, storage, differentiation and eruption at Hekla occurred over a timescale of less than a few centuries.

New insights on shallow intrusions from the early stage of the Oslo Rift

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The Oslo Rift mildly alkaline magmatic province was emplaced in the latest Carboniferous to Permian in a continental rifting context, across multiple phases of intrusive and effusive magmatism. Sill intrusions radiometrically dated to the Late Carboniferous (308–305 Ma; [1-2]) are considered the first magmas emplaced during the prolonged (40-60 Myr) activity of the Oslo Rift [3]. Although the sills have been investigated from the 19th century, they are poorly studied with modern techniques. Due to recent infrastructure developments, several spectacular new sections have become available. We sampled sills emplaced in Cambrian and Ordovician black shales from new road sections (Jevnaker, Kistefoss), one borehole core (Brevik; [4]), and classic localities (Gran, Slemmestad, downtown Oslo) all along the Oslo Rift, with the aim of geochemical characterization of the sills, and their potential interaction with the host rocks. The sills vary in thickness from dm-scale to over 10 meters, and in some sections they cumulatively make up over 90% the stratigraphic

thickness. The sampled sills are mildly alkaline, with some subalkaline exceptions, and range in composition all across the TAS diagram, from a basaltic, lamprophyric end-member (camptonite [5]), to trachytes (locally named mænaites) and rhyolites. The mafic sills are strongly porphyritic with large phenocrysts of hornblende and clinopyroxene, and plagioclase, hornblende, oxides and apatite occupying the mesostasis. The original mineralogy of the evolved sills is almost completely substituted by secondary phases, as also shown by high LOI (up to 12 wt%). The relatively fresh samples show absence of mafic minerals, large crystals of feldspars either as pristine phenocrysts or as pseudomorph phantoms, and abundant secondary sulfides. We observe strong local chemical variability in the investigated rocks, both within one same locality and among different sampling sites. Due to significant alteration, variations in relatively immobile elements such as Ti or REE are regarded as more informative. Tightly defined major and trace element correlations reflect a strong role of fractional crystallization coupled with some crustal assimilation. For example, sills from outcrops sampled downtown Oslo show exclusively evolved compositions, along with evidence of strong crustal assimilation. Possibly, local tapping of specific mantle sources is needed to explain some of the observed variation. Future work will focus on unraveling the connection between camptonites and mænaites [6], and the interaction of the sills with the organic- and sulfide-rich host shales. We aim at distinguishing between contemporaneous vs. diachronous emplacement of these sills, with implications for the magmatic evolution of the Oslo Rift.

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Asymmetric distribution of enriched components in the Iceland mantle

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Volcanoes in Iceland are supplied by excess mantle melting caused by interaction between the mid-Atlantic ridge and a deep-rooted mantle plume. Geochemically, this plume-ridge interaction is expressed in erupted basalt as a wide range of radiogenic isotope and trace element signatures reflecting variable mixtures between the upper mantle source of mid-ocean basalts (DMM; $^3\text{He}/^4\text{He}$ of $8 \pm 1 R_0$), a high- $^3\text{He}/^4\text{He}$ (up to 34 R_0) plume component, as well as at least three "enriched mantle" components (EM) that can be distinguished by their isotopic (e.g., He-Sr-Nd-Pb) and trace element (e.g., La/Yb, Nb/Zr, Ba/La) fingerprints. However, the spatial distribution of EM components in the mantle beneath Iceland is poorly constrained. This is in part due to imperfect geographical sample coverage, but

also because decreasing degree and increasing depth of mantle melting away from the rift axes may create a sampling bias toward the more fusible EM components by off-rift volcanoes. To provide better geochemical constraints on the origin and spatial distribution of EM components in the Iceland mantle, we present new major, volatile and trace element compositional as well as He-O-Pb isotope data from subglacially erupted basalts of the Kverkfjöll volcanic system, located in central-east Iceland in between the main rift axis (Northern Rift Zone = NRZ), and an off-rift volcanic belt (Öræfajökull Volcanic Belt = ÖVB).

Kverkfjöll basalts have distinctly enriched K_2O/TiO_2 , Cl/K, Nb/Zr values and clearly elevated $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ signature (i.e., positive $\delta^{208}Pb$), but lower $^3He/^4He$ values (8–9 R_A with a single 11 R_A outlier) relative to the NRZ volcanoes (9–34 R_A). Instead, the geochemical signature of Kverkfjöll points toward a mantle component resembling the global EM2 endmember, which in Icelandic neovolcanic zones has previously only been identified in the ÖVB. Indeed, all geochemical tracers of both mantle enrichment (e.g., positive $\delta^{208}Pb$) and depth and degree of melting (e.g., La/Yb, Sm/Yb) have intermediate values between the NRZ (more depleted, higher degree shallower melting) and ÖVB (more enriched, lower degree deeper melting), exactly mirroring Kverkfjöll's intermediate geographical location. The highly systematic correlation between geographical position and geochemical mantle source and melt-degree indicators suggests that (1) an eastward-thickening "lithospheric lid" away from the rift axis truncates the melting column at increasingly deeper levels, accentuating sampling of enriched mantle lithologies, and that (2) an EM2-type component is exclusively present in the mantle beneath east Iceland, and completely absent to the west of the NRZ. Further, the notable scarcity of high $^3He/^4He$ signatures east of the NRZ implies that the high- $^3He/^4He$ plume component is mostly constrained to the west side of the NRZ. Thus, the new Kverkfjöll dataset provides an important missing piece to the complex Icelandic mantle puzzle, highlighting the strongly asymmetric East-West distribution of enriched components in the Iceland mantle.

IM1-12

Li and Pb isotopic constrains on LCT pegmatites petrogenesis in Kaustinen area, Finland

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The Kaustinen Li province in the Pohjanmaa schist belt is part of the Paleoproterozoic Svecofennian accretionary arc complex in central and western Finland (Kähkönen, 2005). Dozens of Lithium-Cesium-Tantalum (LCT) pegmatites as well as numerous associated boulders have been described in the area. Pegmatite petrogenesis and their relationship with the local country rocks is a matter of debate between the advocate of the granitic and the sedimentary-controlled anatectic model. Radiogenic isotopes fractionation of Pb isotopes are powerful tools to identify petrogenetic links between pristine and most differentiated melts, while the stable isotopes of lithium provide more information on the physico-chemical processes.

The Li-rich mineral phase of spodumene and whole rock pegmatites have been analyzed for their Pb isotopic composition. The isotopic compositions of Pb are aligned along the so-called "Phanerozoic ore lead trend" coined by Johansson and Rickard (1984) and observed in the Swedish segment of the Fennoscandian shield as well as in base metal mineralization at the

bottom of the nearby Bothnian bay (Hanski et al., 2019). This trend is commonly associated with late fluid infiltration during the Caledonian orogeny and therefore overprint the original Pb isotopic signature associated with an emplacement age of the Li-pegmatites defined by U-Pb dating of columbite (1.79 Ga; Alviola et al., 2001). Pb isotopes will also be performed in more Pb-rich phases such as feldspar from the pegmatites and the Kaustinen granite, which is the most probable source of the LCT pegmatites according to a granitic model (Martikainen, 2012).

The Li isotopic composition of spodumene and pegmatites from the different deposits show a bimodal and regional distribution, with eastern samples having significantly heavier Li isotope ($\delta^7Li = +7.1 \pm 0.9$) when compared to the western samples ($\delta^7Li = 1.1 \pm 2.0$). This bimodal distribution has been confirmed from the boulder samples. The origin of this temperature sensitive stable isotope gradient is compatible with the North-South metamorphic isograd (Hölttä and Heilimo, 2017) and support an anatectic model.

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IM1-13

Non-dissolved mantle zircons record hyper rapid translithospheric ascent of lamprophyres

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Lamprophyres represent deep, mantle-derived magmas of ultramafic to mafic, and in some cases intermediate, compositions. They are generally alkaline and enriched in incompatible elements and volatiles reflecting low degree of partial melting, often of enriched mantle domains. The ultramafic to mafic lamprophyre groups have high alkalinity and zircon should dissolve rapidly in such magmas. We report data from upper crustal camptonitic and monchiquitic lamprophyre dikes from the Orkneys, Scotland, which contain zircon with relatively uniform grain sizes between 100 and 200 μm . These zircons have 'typical' mantle zircon textures and trace element chemistries, as well as showing very high crystallisation temperatures (Ti-in-zircon thermometer). Melt temperature calculations and zircon saturation modelling indicates that the zircons, which probably were picked up by the lamprophyre melts during melt-formation, could have remained in the melts from <40 hrs to >500 hrs without dissolving completely, depending on the melt composition. Given estimates of melt formations for these lamprophyres of > 80 km depth (Wallis 1989), the non-dissolved zircons record minimum average ascent speeds from the

base of the lithosphere to the upper crust (<3 km depth) at the time of emplacement of as rapid as 0.6 m/s.

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IM1-14

Rapid source shifting of a deep magmatic system revealed by the Fagradalsfjall eruption, Iceland

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Recent Icelandic rifting events have illuminated the roles of centralized crustal magma reservoirs and lateral magma transport, important characteristics of mid-ocean ridge magmatism. A consequence of such shallow crustal processing of magmas is the overprinting of signatures that trace the origin, evolution and transport of melts in the uppermost mantle and lowermost crust. We present unique insights into processes occurring in this zone from integrated petrologic and geochemical studies of the 2021 Fagradalsfjall eruption on the Reykjanes Peninsula in Iceland. Geochemical analyses of basalts erupted during the first 50 days of the eruption combined with associated gas emissions, reveal direct sourcing from a near-Moho magma storage zone. Geochemical proxies which signify different mantle compositions and melting conditions (K_2O/TiO_2 , La/Yb and radiogenic isotopes) changed at a rate unparalleled for individual basaltic eruptions globally. Initially, the erupted lava was dominated by melts sourced from the shallowest mantle but over the following three weeks become increasingly dominated by magmas generated at a greater depth. This shift in lava chemistry is greater in magnitude than the entire five-century output during the last eruptive episode on the Peninsula (circa 700 to circa 1240 AD). This exceptionally rapid trend in erupted compositions provides an unprecedented temporal record of magma mixing that filters the mantle signal, consistent with processing in near-Moho melt lenses containing 10^7 – 10^8 m³ of basaltic magma. Exposing previously inaccessible parts of this key magma processing zone to near-real time investigations, provides new insights into the timescales and operational mode of basaltic magma systems.

IM1-15

Phenocrysts through time: what can we learn at a high-speed glance

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Geological processes and our understanding thereof occur from planetary scales down to the atomic level. Accordingly, the ability to investigate such phenomena is wide and varied, often encompassing a multi-disciplinary and multi-technical approach. One key area in geological sciences is the ability to transition from the field to the laboratory, and this is where analytical techniques such as micro-XRF can be extremely useful, not only in its own right, but as a powerful component in a productive and timeous workflow. Specifically, micro-XRF has many analytical features, such as a focused beam and trace level elemental capabilities, that yield fast results over large samples with minimal sample preparation.

In this case study, samples from different modern day volcanic regions, such as Chile, Japan and Hawaii (U.S.A), as well as historic volcanic events such as komatiites from South Africa, are compared. Specifically, an overview of the samples phenocrysts is readily provided from a single scan over a large area of a cut surface. This includes elemental distribution and composition, as well as modal mineralogy, grain size distribution, and mineral associations. Such information is important in understanding the processes of the eruption that lead to the formation of samples, particularly if applied over various volcanic flows through time in a localized region to understand how it is evolving. Furthermore, with such petrographic data, it is possible to select ideal samples for further analysis using analytical techniques with higher resolution or detection limits, which are often limited in analytical area, and thus maintain control as samples and information is upscaled or downscaled.

IM1-16

Metal transport in volcanic gases from Vulcano, Italy

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Metals and magmatic systems are closely associated. Many of the exploited ore deposits formed within magmatic-hydrothermal systems, while metal-rich toxic plumes are emitted at degassing volcanoes. Understanding the volatile transport of these elements is, therefore, important. Our study focuses on trace element transport at Vulcano (Italy) in the high temperature fumaroles of the 1990s (Wahrenberger, 1997) and lower emission temperatures during 2008-2012. Major gas composition of the fumaroles sampled shows the previously described contribution of the hydrothermal system (Chiodini et al., 1993), varying in space and time, and its effect on the SO_2/H_2S ratio of fumarolic gas. A sample with typical magmatic composition was chosen for thermochemical calculations, using trace element data from fumarolic condensate. We distinguish elements depending on their gaseous transporting ligand and the type of sublimates they form as temperature decreases. Alkali metals and alkaline earth elements are mainly transported by halogens (Cl and F) with a minor role of OH ligand. The former deposit as

chlorides while the latter form silicates and sulfates. Transition metals can be divided into two groups, one with predominant gaseous Cl complexes, and the other with both Cl and OH ligands. The first group shows evolving sublimates, from oxides to sulfides and occasionally sulfates or chlorides as temperature decreases, whereas oxide and chloroxide dominate the other group. Some elements (Au, Ag, Bi and As) show a different behavior, with predominance of gaseous sulfur complexes and/or elemental transport. These elements deposit as chloride, sulfides or pure metal. Finally, some elements (Hg, Tl, B, Se) display a volatile behavior until low temperature, with minimal deposition. Our results show the predominance of chloride as the gaseous transporting species. HCl content in volcanic gases is prevalent compared to metals and is seldom affected by redox and temperature variations. This is not the case for sulfur species SO_2 and H_2S , which may therefore affect metal transport and deposition.

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IM1-17

Small length scale H₂O heterogeneity in the Icelandic mantle

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It is well established that the mantle is chemically heterogeneous on length scales of 10s of kilometres or less; a product of recycling melting residues and subducted lithosphere, followed by stirring and mixing during vigorous convective cycling. We might also expect these mantle components to have distinct H₂O concentrations, determined by their history of hydrous alteration near Earth's surface, devolatilization during subduction, or H₂O extraction during melting. However, the rapid diffusion of H⁺ in mantle minerals will act to dampen or remove this H₂O heterogeneity during residence in and transport from the lower mantle. The persistence of mantle H₂O heterogeneity which remains coupled to the heterogeneity in the lithophile elements can, therefore, place a lower bound on the length scales of mantle heterogeneity.

Since subaerially erupted lavas lose most of their volatile element budget prior to or during eruption, volatile studies are limited to glasses quenched at high pressures, their eruption having occurred on the sea floor or at the base of glaciers. We combine new and existing H₂O, trace element, and radiogenic isotope analyses for glasses erupted on the submarine ridges adjacent to Iceland, subglacial glasses on Iceland, and olivine-hosted melt inclusions from 8 primitive Icelandic eruptions. To estimate pre-eruptive volatile concentrations, we develop methods for filtering melt inclusion datasets for the effects of H₂O degassing and H⁺ diffusion. To link the pre-eruptive H₂O concentrations to mantle H₂O contents we develop numerical models to account for mantle dynamics, near-fractional melt generation, and partial melt aggregation during transport and crustal storage.

Together, the datasets demonstrate pervasive small-scale H₂O heterogeneity is present throughout the mantle beneath Iceland and the surrounding spreading ridges, implying small-scale mantle heterogeneities are large enough that H⁺ diffusion has not eroded their presence. Furthermore, the mantle components associated with recycled crust (and are enriched in lithophile trace elements) are relatively depleted in H₂O compared with the other mantle domains melting beneath Iceland.

IM1-18

Oxygen isotope analyses in melt inclusions as an archive of crustal contamination processes underneath Bárðarbunga volcano

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Oxygen isotope ratios ($\delta^{18}\text{O}$) have been widely used to study the role of the crust in Icelandic basalt petrogenesis, due to the fact that Icelandic crustal rocks differ significantly from mantle values. In multi-level magmatic systems, magmas are stored and processed at variable depths within the crust and therefore multi-level systems are ideal targets to pinpoint crustal contamination processes. With the goal of quantifying the extent of oxygen isotope exchange as melts ascend through the crust, we present new SIMS analyses of trace element concentrations and $\delta^{18}\text{O}$ values in melt inclusions (MIs) and groundmass glasses from a well-characterised eruptive suite from Bárðarbunga volcano, Iceland. $\delta^{18}\text{O}$ values of MIs vary between +3.2‰ and +6.4‰, whereas groundmass glasses have $\delta^{18}\text{O}$ values between +2.6‰ and +5.5‰, which on average are lower than those of MIs. Oxygen isotope ratios correlate with MgO and trace element ratios (e.g. Zr/Nb) and primitive MI compositions record the largest spread in $\delta^{18}\text{O}$ values and trace element ratios. Relationships between Zr/Nb and $\delta^{18}\text{O}$ values are consistent with the supply of a mixture of primary melts that contain depleted (DM) and enriched (EM) mantle signatures and that acquire a low- $\delta^{18}\text{O}$ signature upon progressive contamination with crustal rocks. Using binary mixing equations, we have calculated that the majority of MIs required 10-30 % exchange of oxygen with the Icelandic crust. Finally, by using the Olivine-Plagioclase-Augite-Melt (OPAM) barometer, we show that most of the contamination occurs at 3-7 km depth and that it correlates with the extent of oxygen isotope exchange. We propose the occurrence of a progressively assimilating plumbing system underneath Bárðarbunga volcano in which melts become more contaminated as they migrate towards higher levels.

Mineral-scale evidence for magma-evaporite interaction in basaltic sills from the Siberian Traps (Tunguska basin, Russia)

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The Tunguska volcanic basin in Siberia (Russia) hosts an extensive network of sills that make up the upper portion of the Siberian Traps Large Igneous Province plumbing system. Geochronology linked the initial phase of sills emplacement to the end-Permian biotic crisis [1], whereby a cascade of environmental catastrophes led life on Earth to an almost complete demise [2]. Magma-sediment interaction initiated by the sills emplacement likely produced vast amounts of thermogenic gases that impacted severely the end-Permian atmosphere. Evidence of thermogenic gas generation comes from basin-scale observations and thermal modelling [2], and from whole-rock geochemistry [3-4]. We use a microscale approach to define the details of this interaction in-situ at the mineral scale. We find that evolved late-stage interstitial pockets are widespread in the Tunguska sills. These domains occupy interstitial spaces that form among large plagioclase and clinopyroxene crystals of the main doleritic assemblage. The late-stage interstitial pockets have an evolved, volatile-rich mineralogy, dominated by biotite and quartz, with minor K-feldspar, apatite and occasional baddeleyite and zircon. Elemental maps and electron microprobe spot analyses revealed high Cl concentrations in the biotites, especially at the rims. Chloro-apatite is also found. Plagioclase surrounding the pockets shows highly albitic rims. We interpret these compositions as reflecting crystallization from a late-stage melt enriched in Cl and Na mobilized from the halite-rich evaporitic host-rocks. High-Cl biotite and albitic plagioclase rims are widespread throughout the Tunguska basin, when sills are intrusive in halite-rich evaporites. Most investigated sills are geochemically correlated with intrusions dated coeval with the main extinction horizon [1;4]. Raman microspectroscopy of fluid inclusions in quartz are underway, investigating the potential presence of carbon species as previously done in similar sills intruded in shales and evaporites from the Central Atlantic Magmatic Province [6]. These findings suggest that halogens, potentially along with carbon and sulfur, were mobilized from the evaporitic host-rocks by heating due to extensive magma injection, and that this happened throughout the Tunguska basin. Importantly, these late-stage evolved interstitial pockets are excellent targets for geochronology, as they contain uranium-bearing phases, allowing for high-precision dating of basaltic sills [7-8].

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Chemical evolution of the gem-beryl bearing Luumäki pegmatite in SE Finland

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The Luumäki gem quality beryl-bearing pegmatite in Finland, belonging to the somewhat little studied miarolitic class, is an excellent case study to compare the two competing petrogenetic models for pegmatite formation based on the works of London and Thomas, namely the magmatic driven and the fluid driven model (London 1992; Thomas *et al.* 2012). In-situ fluid inclusion studies by means of state-of-the-art analytical methods, such as laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) have been used to determine the origin of the aqueous fluids involved in pocket mineral formation. The presented major and trace element data from these fluids, especially their halogen ratios, are a novelty approach to show the direct evidence of their primary magmatic origin, thus suggesting they were involved in the beryl formation within some of the pockets (Michallik *et al.* 2020). Other miarolitic pockets within the pegmatite can be better explained by a magmatic-dominated petrogenetic model, as suggested by London, thus showing that both petrogenetic models can be applied to the same pegmatite body. In addition, mineral trace element compositions of the pegmatite and surrounding host rock rapakivi granite, in combination with previous reported studies proved the origin of the pegmatite to be within the host rock itself, which further constrains the pressure conditions of emplacement for the rapakivi granite Wiborg Batholith.

Olivine biosignatures and/or abiotic features?

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Biosignatures, such as microscopic tunnels and galleries, have been found in both terrestrial and martian rocks, indicating potential microbial life utilizing minerals and glass to gain metabolic energy. Collecting Earth analogues of abiotic and biotic weathering of basalts are of great value to understand martian biosignatures potentially found by the Curiosity rover.

In this study we examined alteration zones in olivines sampled from picritic lavas from the Reykjanes peninsula. Samples were collected as part of the Planetary Terrestrial Analogues Library (PTAL) project.

Olivines were mostly unaltered, but some grains were fractured with brownish alteration features. High-quality optical microscopy reveals a range of alteration structures, some most likely abiotic and related to dislocations. Other structures, such as bifurcating and twisting stalks, never before observed in olivine with such details, are difficult to explain by any abiotic mechanism. Scanning Electron Microscopy micrographs shows abundant biofilms/fungi colonizing the most altered parts of the basalt, but the relation of these to the alteration features in the olivine is yet to be known.

Blue copper-rich speleothems in Icelandic lava tubes: strongholds to subsurface life on Mars?

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Aim: Lava caves on Mars are targets for human shelter in future missions, as well as areas of astrobiological interest, with the potential of harboring traces of extant or extinct life. To support the development of future astrobiological mission concepts we investigated Icelandic lava tubes, host to a variety of microbial communities and secondary minerals (speleothems).

The Planetary Analogues and Exobiology Lava tube Expedition (PELE) team was set up to investigate the life that subsists within these environments. Through the analysis of speleothems and their associated microbial mats, we aim to characterize any biosignatures that may be relevant in the search for subterranean life on Mars.

Iceland is host to numerous lava tubes, most only minimally touched by human exploration. Here we report on sampling technique and findings of blue copper phyllosilicates and their associated microbial diversity. While the blue samples reported here are only one of many findings in the caves, these were chosen as a case study to describe our sampling protocols, workflow, and take an in depth look at one population of microbes living in one biotope, namely blue speleothems.

Methods:

The PELE team worked closely with the Iceland Speleological Society (ISS) to access the caves. Biological samples of microbial mats were collected, along with in situ X-ray fluorescence measurements with a portable spectrometer, and geochemical and geological samples of the lava rock underneath the mats. Biological samples were analyzed using 16S rRNA gene sequencing methods, biogeochemical samples with Raman spectroscopy, and geological samples with scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS).

Results:

Blue features were characterized from microbe to mineral in order to define their validity as biosignatures and better understand the biogeochemical fingerprints that may persist therein. Chrysocolla was identified as the main copper phase in the blue speleothems accumulating within the caves. This is significant as chrysocolla and other oxidized copper mineral phases have been detected on the surface of Mars and may well be present in the subsurface. It appears that much of the copper found in the Icelandic lava tubes likely originated from hyaloclastite and ash deposits from nearby volcanic eruptions, filtering into the caves through copper-enriched rain and groundwater.

The microbial community composition was found to be majority Proteobacteria with *Ralstonia*, *Caulobacter*, *Cupriavidus*, and *Corynebacterium* accounting for 97% of the genera detected. These genera are known for their high metal-resistance, which may explain their presence in areas of high copper accumulation. We also detected a carotenoid signal using Raman spectroscopy, which is a promising biosignature candidate, as carotenoids are very resistant to oxidative stress, are found in many of the microbial genera identified, and serve many functional properties that might also be compatible with early Mars organisms.

Conclusion:

Analysis of blue copper-rich speleothems revealed them as a biotope in Icelandic lava caves. If found in Martian lava tubes, blue copper-rich mineral precipitates would be deserving of astrobiological investigation, as they have potential to preserve biosignatures and harbor life.

Molards as an analogue for ejecta-ice interactions on Mars

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Landforms indicating post-impact volatile mobilisation formed when the Hale impact crater penetrated the martian cryosphere 1Ga. We have found landforms similar to "molards" in the ejecta blanket of Hale Crater, which we link to the past presence of volatiles at/near the surface of Mars. Molards on Earth are conical mounds of debris associated with landslide deposits in periglacial environments, resulting from the degradation of blocks of ice-rich material mobilized by a landslide. We investigate the spatial and topographic distribution of mounds at the regional and local scale around Hale Crater, and compare them to those of molards on the deposits of the Mount Meager debris avalanche, Canada. Hale Crater's conical mounds are located at the distal boundary of the thickest part of the ejecta blanket, which is the closest to the main crater. We observe a similar spatial arrangement of molards along the distal parts of the terminal lobe of Mount Meager debris avalanche. We have also found that the conical mounds on Hale Crater are similar in morphology and morphometrics to other terrestrial molards on the Paatuut and Niiortuut rock avalanches in western Greenland, themselves a result of permafrost degradation. The conical mounds in the ejecta blanket of Hale Crater could be the first Martian molards described, and their morphology and morphometrics, comparable to terrestrial molards, indicate that they derive from impact-generated volatile disturbance in Hale.

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3-D geologic modeling of the iron-oxide apatite (IOA) deposits from the Kiruna Mining District

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The Kiruna Mining District is situated in the Northern Norrbotten Ore Province of Sweden and belongs to the north-western part of the Fennoscandian Shield (Bergman, 2001). The study area stretches over a distance of 15 km (NE-SW) by 7,5 km (NW-SE) by 2.5 km (depth). The area has been the focus of several studies during the last century due to its high economic potential and numerous geological, geochemical, and geophysical studies have been carried out which resulted in extensive mapping, prospecting, and drilling campaigns. We aim to build a geological 3D model of the central Kiruna area, in close collaboration with the mining company LKAB.

The economic mineral potential of the region has led to the collection of abundant legacy datasets, which must be compiled, analyzed, and interpreted to maximize their value. In the Kiruna area, the basin architecture was studied and examined by several authors (Andersson et al., 2021 and references therein), which resulted in conceptual geological profiles and models, however, these models do not offer a 3D view of the subsurface structural setting and due to the lack of constraints, they cannot be tested and reconciled. The 3D geospatial environment strengthens interpretation and visualization of the data, which in turn can be used for key economic decisions, such as exploration targeting (De Kemp, 2016) and future drilling. 3D camp-scale models must integrate regions with sparse data availability with regions having abundant data available from local clusters of measurements such as drill holes (De Kemp et al., 2016). To connect these highly heterogeneous spatial data, interpretive support is needed, and therefore the elements of the models will be variably constrained (i.e. different degrees of uncertainty).

This approach is applied in the present study on the Kiruna Mining District, which aims at producing a wider spatial perspective of the structural and stratigraphic geology of the subsurface focusing on the iron-oxide-apatite (IOA) ore bodies and their relationship with the hosting horizons. This will provide new insights on 3D geometries and relationships of the structures from surface to depth, that are not readily apparent on 2D maps and cross-sections of the district.

Defining mappable criteria for mineral systems model elements in mineral prospectivity modeling

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Mineral Systems Model (MSM) concept is a holistic approach which defines the essential geological factors relating to formation of a mineral deposit. These factors include e.g., sources for mineralizing fluids and ligands, sources for metals and other ore-forming constituents, pathways for the fluids, energy

source, structural focusing mechanism at the mineralization site, and physical and/or chemical traps for ore deposition. These critical MSM components can be further divided into separate theoretical criteria. The MSM is used as basis for generating GIS based mineral prospectivity models (MPM). The challenging part of the MPM is to determine which of the theoretical measures can be converted into practical mappable criteria from the available geodata and how to extract the criteria out of the geodata via different preprocessing methods.

In this work we used relatively complex MSM model of iron oxide-copper-gold (IOCG) deposits for a knowledge-driven fuzzy logic prospectivity modelling study for northern Finland. Total of 17 practical mappable criteria were generated from original data sets and derivatives of geophysical, geochemical, drill core, and bedrock observation data as well as geological maps. These were combined into seven MSM component maps representing different elements of the IOCG MSM and into final mineral prospectivity map. Statistical validation was carried out for each of the mappable criteria, MSM component and final prospectivity map. The validation was carried out using ROC method and known deposits as true positive validation sites. True negative validation sites were generated randomly. The resulting prospectivity map outline the most potential IOCG areas including new areas where exploration for the deposit type has been marginal.

Validating country wide cobalt prospectivity models in Finland

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The current policies on green energy transition are likely to remain due to pressure from EV sector. Therefore, it has been predicted that the global demand for raw materials may grow 5 to 10 times to current need within couple of decades. If all the countries would follow the Paris agreement the demand would be even up to 40 times. This gives us straight motivation to find new target areas for cobalt which is one of the commodities used broadly with the automotive industry.

It is challenging to produce a single mineral prospectivity model for cobalt as it can be seen rarely as a main commodity in an ore deposit. Therefore, we developed a unique mineral prospectivity mapping study where we combined together critical parameters derived from five different cobalt bearing mineral systems models within Northern Fennoscandian Shield, Finland: 1) Orthomagmatic Ni-Cu-Co sulphide deposits; 2) Outokumpu-type mantle peridotite associated volcanogenic massive sulphide (VMS) style Cu-Co-Zn-Ni-Ag-Au deposits; 3) Talvivaara black shale hosted Ni-Zn-Cu-Co-type deposits; 4) Kuusamo-type (orogenic gold with atypical metal association) Au-Co-Cu-U-LREE deposits; and 5) Iron-oxide-copper-gold (IOCG) Fe-Cu-Au-Co-U-REE-Ba-F deposits. In addition to these mineral systems-based models, a mineral prospectivity model combining geochemical anomalies derived from regional till survey, bedrock drilling data and mineral indications from boulders and outcrops was created. As data integration method we used fuzzy logic overlay in GIS platform to combine datasets derived from publicly available regional-scale geological, geochemical and geophysical maps of Geological Survey of Finland. While we did not use any known deposit's locations to train the models, we needed to validate the model using the known deposits and mineral exploration drilling sites with cobalt assay values exceeding 500 ppm as true positive sites. To represent true negative sites, we tested both random location and other

deposits sites and compared the results of these two approaches. For the other deposit to represent the true negative sites we selected 101 industrial mineral deposits and exploration prospects from GTK mineral deposit database. Validation techniques used were Receiver Operating Characteristic (ROC) curve and Efficiency Curve methods.

The resulting prospectivity maps define new exploration target areas. Many of these high-prospectivity areas coincide significantly with the existing exploration license areas. Therefore, we can expect that many of those areas will be tested inevitably. The different validation methods used in this study seem to give almost identical results and gives us reasons to study those techniques further in more detail. Comparison of using random locations vs. other deposits sites as true negative sites indicates that the AUC values of latter are slightly smaller and the ROC curves thus somewhat deflated, difference being only negligible. This suggests that using random true negative sites is a valid procedure.

IS2-04

EPOS-Norway Portal

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The European Plate Observing System (EPOS) is a European project about building a pan-European infrastructure for accessing solid Earth science data, governed now by EPOS ERIC (European Research Infrastructure Consortium). The EPOS-Norway project (EPOS-N; RCN-Infrastructure Programme - Project no. 245763) is a Norwegian project funded by National Research Council. The aim of the Norwegian EPOS e-infrastructure is to integrate data from the seismological and geodetic networks, as well as the data from the geological and geophysical data repositories. Among the six EPOS-N project partners, four institutions are providing data – University of Bergen (UIB), - Norwegian Mapping Authority (NMA), Geological Survey of Norway (NGU) and NORSAR.

In this contribution, we present the EPOS-Norway Portal as an online, open access, interactive tool, allowing visual analysis of multidimensional data. It supports maps and 2D plots with linked visualizations. Currently access is provided to more than 300 datasets (18 web services, 288 map layers and 14 static datasets) from four subdomains of Earth science in Norway. New datasets are planned to be integrated in the future. EPOS-N Portal can access remote datasets via web services like FDSN-WS for seismological data and OGC services for geological and geophysical data (e.g. WMS). Standalone datasets are available through preloaded data files. Users can also simply add another WMS server or upload their own dataset for visualization and comparison with other datasets. This portal provides unique way (first of its kind in Norway) for exploration of various geoscientific datasets in one common interface. One of the key aspects is quick simultaneous visual inspection of data from various disciplines and test of scientific or geohazard related hypothesis. One of such examples can be spatio-temporal correlation of earthquakes (1980 until now) with existing critical infrastructures (e.g. pipelines), geological structures, submarine landslides or unstable slopes.

The EPOS-N Portal is implemented by adapting Enlighten-web, a server-client program developed by NORCE. Enlighten-web facilitates interactive visual analysis of large multidimensional data sets, and supports interactive mapping of millions of points. The Enlighten-web client runs inside a web browser. An important element in the Enlighten-web functionality is brushing and linking, which is useful for exploring complex data sets to discover correlations and interesting properties hidden in the data. The views are linked to each other, so that highlighting a subset in one view automatically leads to the corresponding subsets being highlighted in all other linked views.

IS2-05

EPOS ICS Data Portal

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The European Plate Observing System (EPOS) addresses the problem of homogeneous access to heterogeneous digital assets in geoscience of the European tectonic plate. Such access opens new research opportunities. Previous attempts have been limited in scope and required much human intervention. EPOS adopts an advanced Information and Communication Technologies (ICT) architecture driven by a catalog of rich metadata. The architecture of the EPOS system together with challenges and solutions adopted are presented. The EPOS ICS Data Portal is introducing a new way for cross-disciplinary research. The multidisciplinary research is raising new requirements both to students and teachers. The EPOS portal can be used either to explore the available datasets or to facilitate the research itself. It can be very instructive in teaching as well by demonstrating scientific use cases.

EPOS ERIC had been established in 2018 as European Research Infrastructure Consortium for building a pan-European infrastructure and accessing solid Earth science data. Sustainability phase of the EPOS (EPOS-SP – EU Horizon2020 – InfraDev Programme – Project no. 871121; 2020-2022) is focusing on finding solutions for long-term sustainability of EPOS developments. The ambitious plan of geoscientific data integration started already in 2002 with a Conception Phase and continued by an EPOS-PP (Preparatory Phase, 2010-2014) where about 20 partners joined the project. The finished EPOS-IP project (EPOS-IP – EU Horizon2020 – InfraDev Programme – Project no. 676564; 2015-2019) included 47 partners plus 6 associate partners from 25 countries from all over Europe and several international organizations.

The EPOS ICS Data Portal provides access to data and data products from ten different geoscientific areas: Seismology, Near Fault Observatories, GNSS Data and Products, Volcano Observations, Satellite Data, Geomagnetic Observations, Anthropogenic Hazards, Geological Information and Modelling, Multi-scale laboratories and Tsunami Research.

The presentation is showing achievements of the EPOS community with focus on the EPOS ICS Data Portal which is providing information about available datasets from TCS and access to them. We are demonstrating not only features of the graphical user interface but also the underlying architecture of the whole system.

Cartograms in geosciences: Alternative visualisations of our dynamic Earth

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Cartograms have been used in human geography and other social sciences as an alternative approach to visualising quantitative data for quite some time. However, in geo-sciences, this mapping technique has rarely been used, often also due to its (presumed) limited capabilities of showing more complex datasets. This presentation introduces *gridded cartograms* as an alternative map projection. Gridded cartograms provide unique insights into highly detailed datasets from social as well as Earth sciences. They can also be used to depict correlations between several spatial dimensions in a different way than conventional maps do. While the results are unusual depictions, these techniques have the capability to providing unique new perspectives on our environment and reimagine the complex dimensions that shape our planet. This can be relevant in communicating science to the public as much as increase understanding of the data that we are working with as scientists.

Paleomagnetic data and the Deep-time Digital Earth program

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The Deep-time Digital Earth (DDE) program of the International Union of Geological Sciences (IUGS) has been developed to address the unstructured and inherently heterogeneous geoscience data that resides in institutions, universities and on individual geoscientists' computers (e.g., Stephenson et al., 2020). Under the umbrella of the DDE program, a three-year Paleomagnetism working group (<https://wg11dde.wixsite.com/website>) led by Zhang, Evans and Salminen has been established to coordinate with affiliated fields (geochronology, geophysics, paleogeography, petrology and geochemistry, stratigraphy, tectonics) in addressing both data curation and scientific integration. At present, there is still a lack of a comprehensive paleomagnetism data dictionary, knowledge system and knowledge graph that cooperate with DDE platform. The goal for the working group is to start constructing the DDE paleomagnetism knowledge graph. We also aim in establishing standards of paleomagnetic data production and existing paleomagnetic data quality criteria are proposed for evaluating the paleomagnetic data for the purpose of applications (e.g., Meert et al., 2020). In addition, the working group intent to streamline the archiving of paleomagnetic data, since deep-time paleomagnetic data are currently assembled into three global databases paleoMAGIA (Veikkolainen et al., 2014), MagIC (<https://earthref.org/MagIC/>), GPMDB (Pisarevsky, 2005), all of which purport to be comprehensive in scope. Two of these databases originated from the foundations of the work that has been done in the Nordic Paleomagnetic Workshops (NPW) (e.g., Brown et al., 2018). The ultimate aims of the working group, harmonization and sharing of the multidisciplinary global geoscience data and knowledge, is also a mission of DDE program.

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Geoheritage in Iceland, an inventory and assessment

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In 2015 a new Nature Conservation Act (no. 60/2013) in Iceland came into force, completely renewing an older law from 1999. With the new act, geoheritage carries more weighting than previously, within Iceland's nature conservation. The aim is to protect the landscape and geodiversity, as well as systematically conserve a comprehensive picture of geological processes and formations that gives a continuous overview of the geological history of Iceland. In addition, it aims to protect geological formations that are special or unique in an Icelandic or international context. In the act, increased emphasis is put upon specific geoheritage phenomenon that are under special protection and, according to the legislation, are identified as follows: volcanic craters, lava fields, lava caves and rootless vents (pseudocraters) from the Holocene, hot springs and other thermal sources, surficial geothermal deposits (sinter and travertine), lakes and ponds (larger than 1.000 m²) and waterfalls. The new act also emphasizes the development of an organized network of conservation areas that will contribute to the protection of biodiversity, geodiversity, and landscape diversity.

Since 2016 the Icelandic Institute of Natural History has been working on the Nature Conservation Register according to the Nature Conservation Act from 2015. The register is divided into three parts, which are identified as:

Part A contains a register of natural heritage sites and areas that have been protected or designated as nature reserves.

Part B is the strategic plan of the Nature Conservation Register, i.e., a register of natural heritage sites that the Icelandic parliament has decided to prioritize for protection or designation as nature reserves within the next five years.

Part C is a register of natural heritage sites for which there are grounds for preservation or designation as nature reserves.

The Icelandic Institute of Natural History manages documentation of natural heritage sites, it is responsible for the management of Part C of the Nature Conservation Register and recommends sites for inclusion in the strategic plan of the Nature Conservation Register (i.e., Part B). The Institute is now working on Part C, reevaluating the register of natural heritage sites from 1996 and at the same time preparing a new strategic plan of the Nature Conservation Register where the focus will be on geoheritage.

Since 2018 the Icelandic Institute of Natural History has compiled a database for the purpose of systematic inventory and assessment of the geoheritage value. The main emphasis in evaluating the conservation values is on criteria of scientific knowledge, integrity, and rarity (nationally or internationally), but in all there are eleven criteria. There is also assessment on potential threats that could have an impact on the geoheritage values.

As the geoheritage database grows, a better overview of geoheritage in Iceland is achieved and a comparison can be made between similar geosites. At the same time a new approach for a geoheritage conservation network for the country is in development, which could ensure minimum protection of geoheritage for the future.

IS3-02

A claim for the promotion of landslides in the global geoheritage

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Landslides are of high geomorphological significance and carry significant evidence of landscape evolution and environmental changes both at human and geological timescale. Landslides can be considered as part of the global geoheritage, but they have received scarce attention from the international landslide and geoheritage community so far. This work aims at highlighting the importance of landslides in the global geoheritage. We have surveyed the literature to understand to what extent landslides have been considered as part of geoheritage and consequently identified as geosites/geomorphosites. We found that there are few cases of landslides defined as geomorphosites, and that the majority of them are located in Europe. In order to bring the attention of the international landslide and geoheritage community to the importance of landslides in the geoheritage, in addition to the commonly recognised value to define a geosite, we have defined three new aspects that should be considered when identifying a landslide as a geomorphosite, namely (i) present and past climate changes, (ii) anthropic signature, and (iii) risk perception. These three aspects are mutually dependent and extremely topical. We emphasise the importance of such aspects by exploring some cases of famous and spectacular landslides worldwide, among which stands out the case of the diffused landslides of Tröllaskagi peninsula in north-central Iceland.

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IS3-03

Geotourism: A Strategic Opportunity for Public Engagement

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Aim

Provide a new vision for how geotourism can provide benefits and opportunities for our profession.

Method

Typically, when geologists think about the potential for geotourism, it is images of geoparks that come to mind. However, this talk seeks to shine a light on a far more strategic role that geotourism can play in our relationship with the public.

Despite living in a moment in history where we urgently need to improve our relationship with nature, in an increasingly digitalised and urbanised world, one of our greatest challenges the geological profession faces is in creating a more informed appreciation among the public of the Earth and its workings.

Yet wherever you are on the planet, geology has shaped that environment and acts as the cradle of our very history. Equally, the global travel business by its very nature delivers its customers into many locations that could hold great potential for geotourism to be applied.

This opens up a number of avenues that can be turned to our advantage in applying a geological lens to tourist experiences:

Geotourism does not have to be restricted to areas of the most spectacular landscapes

Opening up history/experiences to the even more epic context of "deep time"

All stories start and end with people: Showing how geology is the "cradle of events"

Expanding the public's connection with nature to include that of geodiversity

Geology as "a moveable feast" and international "passport to discovery"

The central message for earth scientists is that this provides us with one of the most powerful tools at our disposal for capturing the imagination and engagement of the public, if we learn to deploy it effectively.

Results

Examples of how this could be achieved in practice:

Embed the deeper geological history of locations into cultural and historic tours, sites and media. This should include urban areas.

Help existing tourism businesses which have environmental aspects as a key part of their attraction enhance their product, e.g. flightseeing, adventure sports, nature trails, vineyards

Work to raise the geological knowledge base and awareness of local guides, especially those already providing touring services around natural landscapes or history

Provide new dimensions to existing attractions that seek to develop a sustainability, nature-related or approach around geographic setting

Offer geo-tours to companies and public bodies as part of their sustainability awareness programmes and community engagement

Conclusions

Reach out to local tourism and regional authorities to offer our help and guidance

Contribute to knowledge bases aimed at the public and tell those geo-stories

Work with historians, archaeologists, tour guides to colour in the geology of their stories

Take opportunities to boost businesses and attractions with geotouristic content

Seek ways to work internationally and get collective impact from this topic

IS3-04

How is geodiversity and geosites presented to visitors of nature reserves? A pilot study of information boards in Skåne, southernmost Sweden.

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Geotourism has a relatively minor role within nature tourism in Sweden. There is however a growing interest among geologists and geological organizations to promote the values of geosites and geodiversity. The Geological Survey of Sweden has e.g. appointed "Swedish Geoparks" in two areas of great geological interest. Here, the tourists are not only offered aesthetic geological values but can also get a detailed knowledge and understanding of the context and processes of the geoattractions. Other areas with a great potential to offer geological experiences and knowledge are the more than 5000 nature reserves of Sweden. In many of these, however, the geological information leaves a great deal to be desired.

The aim of this pilot study is to investigate the information boards at the entrance of nature reserves in Skåne, southernmost Sweden. Skåne is probably the most geodiverse region in Sweden and has more than 300 nature reserves. This study investigates a selection of reserves, where you find some of the main geosites in Skåne considered to be of international and national value. Both quantitative and qualitative results will be presented to answer questions like: How much of the total information of the information boards concerns geology? What kind of information about the geosites and geodiversity are presented? Are the geosites put into a wider regional context?

IS3-05

Historic quarrying of the Virolahti pyterlite – unique cultural heritage landscape in SE Finland

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The exploitation of red pyterlite of Virolahti in southeastern Finland started in the middle of the 1700s for construction of the city of St Petersburg, Russia. As no hard rocks were available

near the newly founded city, the building material was brought from the Wiborg rapakivi granite batholith, situated northwest from the city.

These studies have been carried out as a part of NaStA project that aims to facilitate the operational environment of enterprises by increasing knowledge on natural stones used in historical constructions, their origin and possible substitutes in restoration works. The main objective is to promote the uniqueness of rapakivi granites utilized in the historical constructions and monuments. The European Union, the Russian Federation and the Republic of Finland in ENI CBC Programme 2014–2020 between southeastern Finland and Russia fund the project.

NaStA project has provided new information on extraction of the Virolahti pyterlite and the quarry locations. The historical quarries are located both on the islands and in the coastline of Virolahti Bay. Approximately 120 historical quarry sites have been identified around the bay and on islands if every small quarry is outlined as a separate quarry site. The size of quarries varies from 25 m² to 5.5 hectares.

The old quarrying methods included channelling and splitting. During the 18th century, the quarrying was done mainly by channelling. The channel was made by removing the rock by chiselling, forming a wedge-shaped groove approx. ten cm wide. These grooves could be carved through the detachable block, extending down the horizontal fracture at the bottom. Alternatively, the grooves were more shallow and the detaching was done by wedging. Later, during the 1800s, the channelling was combined with drilling. First, grooves approx. 30 cm deep were carved, after which holes were drilled (approx. 25 cm apart) down to the bottom of the block. The drilling was done by three men, two hitting the drill bit (chisel) with a sledgehammer, the third slowly turning the bit after each beating, occasionally lifting the chisel and removing the cuttings from the hole and pouring in water. The final detachment was done by wedging. If there was no natural horizontal fracture at the bottom of the block, also horizontal drill holes and grooves could be made.

From Virolahti, more than one million cubic metres of granite was extracted in these manners for the construction of St Petersburg during the 1700s and 1800s. The quarries constitute a unique cultural heritage landscape in Finland.

IS4-01

Geoscience Education and Technology – Results from Two Worldwide Surveys

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Many different types of technology are used in the geosciences, both in universities and in companies. There are many different types of technologies, including CT-scanners, computer software (e.g. for seismic interpretation), microscopes and lidar drones. These technologies therefore also are an important part of geoscience education. However, not much is known on how each of these technologies can be taught in an optimal way. It is also not clear how these technologies are actually currently being taught, what the teachers and students think of this etc. A complementary, and perhaps more fundamental, question is whether teaching and (geo)science education can actually be classified. This is more than a purely academic issue as various definitions exist and have been used in making policy and budget decisions. The educational foundation of these classi-

fications however has been disputed. Yet another issue is how the recent covid pandemic has affected this aspect of teaching.

In order to investigate this in more detail we conducted two surveys on the use of technology and geoscience education. These surveys were conducted among university geoscience education teachers worldwide. The first survey was done in 2017 and the second one in 2021. The number of responses were, respectively, 71 and 121. Some of the main results of these surveys are that the use of technology in geoscience education has increased and is expected to continue to increase. At the same time it seems that lectures are still the dominant way of teaching. Active learning methods are used but still seem to be less important than traditional lectures. Moreover, the lockdown both had negative and, unexpected, positive effects. The negative effects were not only cancellation of classes and fieldwork but also a reported overall negative impact of online teaching on learning. A positive side-effect of the lockdown was the emergence of new teaching material and teaching methods. A more detailed analysis of the survey will be presented at the meeting.

IS4-02

Fieldwork culture in Higher Education Geology

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Geological fieldwork and teaching in the field constitutes a significant part of the curriculum in Nordic higher education geology programmes. Learning in the field is perceived fundamental for understanding nature, its processes and in becoming a geologist. In several studies, we have explored what is at stake for university students when they engage in fieldwork practices, as they learn the disciplinary knowledge, negotiate identity and their belonging in the programme (Malm et al., 2020; Malm & Håkansson, 2021). The aim is to explore cultural ideas about fieldwork practices, how students are recognised, what is celebrated in the culture and how this influence students learning and identity processes in higher education geology. The strong culture around fieldwork can be understood as a 'culture of power' (Calabrese Barton & Yang, 2000; Carlone, 2004), where a specific culture around i.e. fieldwork defines exactly what 'good' participation entails. This in turn excludes some students from participating (Brickhouse, 2001) as they find it difficult to either participate or find meaning in participating. In order to explore the fieldwork culture, ethnographic observations were conducted in several fieldwork settings in the Arctic and Europe, with students from the first year bachelor level to last year of master level. Individual interviews with students follow up on the experiences in the field, and further explore the students learning processes and associated identity work. The studies show how learning in the field includes both visible acts and tacit knowing, and these are connected with students understanding of the cultural discourse and how they can be recognised as competent within the discipline. The work demonstrate how analysis of learning situations in the field can unfold students' identity work when establishing their disciplinary knowledge. The intersections between learning, sense of belonging, disciplinary culture, tacit knowledge and students' identity work create a valuable framework to study students' experiences in higher education. The research show how educational fieldwork practices convey narrow ideas about how to be and become a geologist. This is particularly troublesome in

the light of equal participation and educating geologists for the future.

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IS4-03

How can student involvement enhance geoscience higher education?

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This presentation will focus on how student involvement can be used to improve the learning environment in geoscience education on a national scale. Student involvement and engagement in teaching is important to ensure proper, effective and timely feedback for development of the curriculum and improvement of teaching methods. The active members in the iEarth student organization in Bergen has worked towards this through several social and educational activities. This include Georakel services, where students can discuss course related material with teaching assistants and work together. Publecture is another activity that connect students and the institute research groups in informal and social gatherings. The student organization arranges course evaluation in direct dialogue with students to engage and motivate them to give relevant feedback as well as ensuring teaching quality in the chosen course. Career days gives an opportunity for students to get a direct insight in occupational life of a geo scientist and provides an arena for networking. Both the student organization and other iEarth members have been attending and arranged the GeoLearning Forum in Oslo, 2021. Which has also been a networking event nationally.

Through these activities the organization have experienced an increased interest in teaching from the students, which further improves the valuable education-research. Data from these activities are currently being collected from our iEarth students and teachers to be presented.

Troublesome knowledge and signature pedagogies in geosciences – a possibility to re-focus teaching and learning

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This ongoing project, within the Norwegian iEarth initiative, aims to identify troublesome knowledge that needs more attention in geoscience teaching and learning [1, 2]. Geoscience teaching strategies used to overcome such learning hurdles are identified, analysed and shared within the Norwegian geoscience education community (iEarth) and beyond. This is done to help geoscience instructors and students to re-focus efforts towards critical curriculum, i.e., identify and develop key signature pedagogies in the geosciences [3]. Data are gathered through semi-structured group interviews (students and instructors at Geoscience UiT and UNIS Svalbard), and with the use of formative Classroom Assessment Techniques in undergraduate and MSc courses at the two institutions [4, 5]. This involves decisions on which geoscience curriculum need extra attention. It also illuminates pedagogical approaches that are best suited to enhance learning of challenging knowledge in the geosciences. Early preliminary results indicate three kinds of troublesome knowledge: 1) geoscience curriculum that require mastery of other science disciplines (physics, chemistry, math), 2: geoscience curriculum that relies on an abstract understanding of concepts, and 3) curriculum that students consider alien in relation to their geoscience identity.

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Student and staff collaboration for education development - course representatives for the 21st century

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University teachers are subject experts in the courses they teach. As such, they are typically tasked with developing and adapting their courses to achieve the best possible teaching and learning.

Students, on the other hand, are experts on their own prior knowledge and skills, what they find particularly challenging, engaging and interesting, and the personal and professional constraints they must contend with. It is also our experience that students tend to have more up-to-date and diverse experiences with teaching methods than teachers.

To bring together both sets of expertise in course development, we piloted a model of student representatives in each class - course representatives - engaging with the teacher in continuous dialogue during the course in 2021 at the Department of Geosciences, Oslo University. In this presentation, we wish to share some of our experiences, and inspire teachers and students to try out collaborative course development.

The initiative and the preliminary brief for the course representatives came from students involved in course development through the iEarth Centre for Excellence in Education. Five courses tried out course representatives during the year, with positive, sometimes transformative, experiences. However, it also became clear that there was a need for scaffolding for students and staff to maximize the benefits of collaboration: who does what, how, and when?

To answer these questions, the iEarth student chapter is drawing on the experiences of current and previous course representatives to design a model for course representatives that emphasizes a) collaboration between teachers and students, valuing both teacher and student perspectives, b) continuous course development that addresses issues during, not after the course, c) strengthening student motivation through increased student ownership of the courses.

The model is intended to make sure that the role of the course representatives goes beyond gathering and transmitting data for the teacher to develop the next iteration of the course, and leads to genuine discussions between staff and students. Thus, course representatives support both students and teachers.

How important are extracurricular activities for student employability?

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Students in higher education are often encouraged to do volunteer work and engage in extracurricular activities. It is argued that these real-world practical experiences allow students to apply theoretical knowledge and develop personal and professional skills, making them both better students and more attractive for future employers.

But to what extent do extracurricular activities actually contribute to make geoscience students more attractive to Norwegian employers when applying for part-time jobs?

This question was explored through interviews with people in different companies who were advertising for geoscience students for part-time positions. The interviews explored what the employers were looking for when hiring students, and to what degree they emphasise grades, course subjects and extracurricular activities.

Throughout my interviews I found that employers first and foremost look at grades and subject compositions. However, extracurricular activities were also highly emphasised. The interviewees described extracurricular activities being used to distinguish students among peers with similar backgrounds and grades. Furthermore, the extracurricular activities is taken as a signal of good communication and collaborative abilities by the employers; the employers expect these students to do well in social settings and the work environment.

Extracurricular activities and student involvement are, in other words, an important quality that employers in this study seek out. Interestingly, it seems to matter less what type of extracurricular activity students engage in. The interviewees were not only interested in students with geo-related experiences. They viewed all extracurricular activities as positive, since they were all regarded as indicators of good social and communicative skills.

Also, it appears that a student cannot be *too* active (as long as grades do not suffer). Subject skills will always be put first for the employers I have been in contact with. If extracurricular activities come at the expense of good grades, the employer may not consider the student for a position. On the other hand, if a student maintains good grades, there is no such thing as too many extracurricular activities.

This leads me to conclude that it is important to promote extracurricular activities. If it is related to geosciences or simply an interesting hobby, it will be valued by prospective employers.

IS4-07

Education for Earth's future. iEarth is the Centre for Integrated Earth Science Education.

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In iEarth we have a vision to create a student-centred, innovative learning environment for future Earth system scientists and citizens to meet complex societal challenges and opportunities. We aim to realise our vision by using the following strategies: (1) transform national Earth science curricula through a competence-oriented curriculum redesign; (2) create an effective learning environment by engaging students as partners in the educational process; (3) build a collaborative, innovative, research-based culture for teaching and learning among students and staff; (4) enhance student learning in the field by systematically investigating the effectiveness of field-based learning activities; and (5) develop alumni networks and internship practices as natural interfaces between students and future employers. Each of these five topics has its own Focus Area (FA) that will help facilitate transformation in an efficient way.

We aim for all staff and students to be involved in iEarth by working as change agents within our institutions, creating cultures that promote change inside the departments and institutions. In the 35th Nordic Geological Winter Meeting, we present the main targets and activities for the last year under the different focus areas. We will highlight some key activities across focus areas such as internal projects, the course in Leading Education Change - through SoTL, and the GeoLearning forum. These activities have had success in 2020 and 2021 with positive feedback and evaluations.

IS4-08

The European Federation of Geologists: The Voice of Professional Geologists in Europe

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Aim

To present the European Federation of Geologists (EFG), which represents the national associations of professional geologists in Europe and the role that Nordic associations can play in its activities.

Method

We shall see how EFG has for over 40 years pursued the goal of instilling the highest of standard of practice in the region's geologists, whether that be in the responsible extraction of resources, protecting the environment, ensuring public safety, education or safeguarding infrastructure.

This began in 1980 with several of the largest associations co-operating to create a continent-wide professional title. Today, our Federation has expanded to encompass a total of 28 countries and through offices in the heart of Brussels provides a range of services for members that connect and amplify the work of our member associations through outreach, skills development, global partnerships, provision of expertise and promoting our science to EU and other international institutions. In addition, our involvement in EU-funded Horizon Programme projects on a wide range of progressive areas, such as geothermal energy, critical minerals, education and innovative technology puts us at the heart of the latest developments in research and application of geoscience.

As the European point of contact for professional geology, we are both a reference for expressing the views and perspective of working geologists from across the continent and an interface for a range of international organisations and networks, for both geoscience and the wider world.

We continue to manage the European Geologist title, which is central for the practice of our profession in licenced industries such as mining and geotechnics and are currently looking to expand its reach to offer a full-career route.

For this conference, we would like to show how Nordic geologists play a role with EFG and the benefits they draw from membership, as seen through the eyes of the Chair of one of our most active associations, Sweden's Naturvetarna/Geosektionen.

Results

In 2022, by encompassing the national geological associations of 28 countries within Europe, EFG aims to be the voice for a community of c.45,000 professional geologists.

We do this through a range of mechanisms:

Communications & outreach

The EurGeol professional title

Expert Panels and Working Groups

A suite of established member services

A global network of partners and contacts

Participation in EU-funded projects

Conclusions

The European Federation of Geologists (EFG) is the professional organisation representing geoscientists from across Europe and its main aims are to contribute to a safer and more sustainable use of the natural environment, to protect and inform the public and to promote a more responsible exploitation of natural resources.

IS4-09

The International Continental Scientific Drilling Program (ICDP) – a Nordic perspective

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The International Continental Scientific Drilling Program (ICDP – <https://www.icdp-online.org/home/>) has 21 member nations, including Iceland, Norway, Sweden and Finland. UNESCO serves as a Corporate Affiliate. GeoForschungsZentrum (GFZ) in Potsdam is acting as ICDP's Executive Agency and is also hosting an Operational Support Group that assists in planning and provides technical support to the drilling projects.

Future drilling projects supported by ICDP will target issues of great scientific and societal importance, such as environmental changes, geohazards, Earth resources, and the origin and evolution of life through Earth's history. There is also a clear ambition to form closer partnerships and collaborate on drilling projects with other organizations, especially IODP.

Over the years, more than 80 planning workshops and 50 drilling projects have been supported by ICDP. Several projects have been completed or are planned in the Nordic countries, and Nordic scientists are also involved in various drilling projects around the world.

Drilling projects in Iceland have focused on volcanic processes and associated hazards, as well as geothermal potential. A recent initiative – Krafla Magma Testbed – proposes to drill into and sample the rock-magma interface at the Krafla volcano.

The COSC-2 drilling project (Collisional Orogeny in the Scandinavian Caledonides) is a follow-up of the COSC-1, located near the front of the Caledonides near Åre in central Scandinavia. Drilling was successfully completed in 2020, and drill cores are now available through key sections of the Caledonian Nappe stack and the underlying basement of the Fennoscandian Shield.

ICDP has previously approved support for a drilling proposal (DAFNE – Drilling Active Faults in Northern Europe), aiming to intersect a postglacial fault near Kiruna, Sweden. Prominent post-glacial faults are widely distributed in northern Fennoscandia, and given their relatively recent movement history, a better

understanding of these fault systems has great scientific and societal relevance.

Another drilling proposal with a strong Nordic component, Volcanic Forcing and Paleogene Climate Change (PVOLC), was approved by ICDP in 2020. Two planned boreholes in northwest Denmark will obtain a complete section through Paleocene-Eocene marine strata, including abundant ash layers. The drill cores will provide data that are critical to improve the understanding of potential causal relationships between the North Atlantic Igneous Province and the global Paleocene-Eocene Thermal Maximum (PETM).

Using the ICDP platform, the earth science community in the Nordic countries and beyond has an excellent opportunity to develop drilling projects of global importance. The work on samples and data collected during ICDP projects stimulates international collaboration, involves students and early-career scientists, have important societal applications and benefits, and commonly results in ground-breaking scientific discoveries. Importantly, all the cores and samples are registered and stored for future studies. After 25 years we can safely conclude that the ICDP program has been highly successful, and we look forward to results from available drill cores as well as new drilling projects in the years to come.

IS4-10

The influence of surface cover and bed rock geology on the snow geochemistry – an example from northern Finland

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The idea of using snow in mineral exploration is due to the needs of environmentally friendly sampling methods for the ecologically sensitive northern areas. Not only the environmental issues, but the low costs of sampling and relieving permission issues encourage researchers to find new methods for mineral exploration. Surface geochemical methods, including sampling plants, topsoil horizons and snow can be considered in the areas where machinery is not allowed. Moreover, surface geochemical methods can provide the information of metal ions derived from the deep-seated mineralization below. The advantages of snow sampling are low volume of sample material, (comparably) light sample material and sampling equipment and therefore the option for low impact sampling campaign by skies or snowshoes.

In the New Exploration Technologies (NEXT) project*, 165 snow samples together with 13 field duplicate snow samples for quality control, were collected in March-April winter 2019. The aim was to estimate with statistical methods the usage of snow as a sampling material for mineral exploration. The samples were collected on the Rajapalot Au-Co prospect in northern Finland, 60 km west from Rovaniemi, operated by Mawson Oy. Stratified random sampling method was used to calculate sampling locations with balanced number of points per soil type and geophysical parameter, but randomly distributed within the strata over the test area. The samples were analysed in the Research Laboratory of the Geological Survey of Finland using a Nu AttoM single collector inductively coupled plasma mass spectrometry (SC-ICPMS) and returned analytical results for 52 elements at ppt level.

Of the analysed elements Ba, Ca, Li, Mg, Mo, Rb, Sr and V passed the strict quality control and were used for the final data analysis. Prior to statistical methods, the geochemical data was transformed to log-ratio scores in order to ensure that results are independent of the selection of elements and to avoid spurious correlations (compositional data approach). The results indicate strong dependency of the snow element composition to the soil type, meaning that there is systematic shift of element pattern if the snow sample was taken above mineral soil or organic soil. Thus, the soil type should be included in models to predict (geological) features below the surface or interpretation of snow data should be performed separately for different soil types. The impact of subsurface features on the snow geochemistry could only be tested indirectly by using geophysical data as proxy for characteristics of the basement rock. Based on linear models, it seems that snow geochemistry could be used as a mapping tool for delineating the areas of major geological units. Given the selection of analytical available elements, snow sampling could serve as a proxy where to continue exploration with different methods rather than directly pointing out the mineralized zones.

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IS4-11

X-ray Computed Tomography of thin section off-cuts to complement 2D e-beam microanalysis

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Production of a rock thin section commonly includes cutting of a hand sample to dimensions similar to the final product but usually up to a centimeter thick. This rock slab is subsequently polished, glued to a glass slide, and cut to a thickness of 0.5–1 mm before grinding and polishing to the desired final thickness (commonly 0.03 mm). The ~9 mm off-cut is either discarded or kept as a reference, though rarely used for further analysis. Yet, its thickness and mirror image to the thin section makes it ideal for X-ray Computed Tomography (X-CT) analysis to complement petrographic microscopy and e-beam microanalysis of the thin section. In this study, 11 thin section off-cuts from the ore zone of the Liikavaara Cu-(W-Au) deposit, northern Sweden, were stacked and fixed in place with adhesive tape and subjected to X-CT analysis at the Geological Survey of Finland. The X-CT scan was performed at ~25 µm voxel resolution for a run time of less than 2.5 h. The software ORS Dragonfly 2021.1 was used for processing and visualization of the data. Results show at least three distinguishable groups of phases, corresponding to: (1) silicates and carbonates; (2) sulfides and oxides; and (3) heavy minerals (e.g., galena, scheelite, Au-, Ag-, and Bi-minerals). The 3D data is particularly valuable concerning the distribution of the commercially interesting heavy minerals. In some off-cuts, heavy minerals are associated with silicates/carbonates and in others with sulfides/oxides. A preferred occurrence of heavy minerals along grain boundaries or as inclusions is easily visible, as well as vein- or foliation-controlled distribution of minerals. This textural knowledge helps with the interpretation of observations made from petrographic microscopy and e-beam microanalysis of the corresponding thin sections. This in turn improves prediction of the processing behavior of the ore and consequently allows for more efficient metal recovery. In

conclusion, the presented method provides a fast and practical way of generating complementary 3D data to 2D analysis using leftover material from thin section production. It also opens up the possibility of follow-on high-resolution analysis on regions of interest through mini-coring, involving core only with a few millimeters diameter.

IS4-12

Geologists on the Silver Screen

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When Geologists gather for a beer after work or around a campfire after a long day in the field, the conversation can easily turn to how our profession is portrayed in movies? Are Geologists' heroes or villains? Do they appear only in supporting roles — their parts limited to entering an office, uttering "Drill here," and promptly leaving the scene — or are they main characters? In an article from 1990 (Geotimes) it was suggested the Geologists on the silver screen are to a great extent the good guys. Only a few Geologists are evil and often misguided souls. This article did not provide any statistical background to support the claim, and therefore, the work presented here took up the task of having this soundly tested through statistics and watching a lot of movies. An article from 1988, "The Physicist as Mad Scientist" in *Physic Today* found that Physicists and Chemists are very often described as mad scientists striving for world domination or the destruction of Earth. Thus, how in contrast are Geologists depicted? And in how many movies do they appear? In our survey, 133 American and British cinema movies were found to include Geologists. To be included, the movie must have been shown in cinemas, and a Geologist must appear in picture, dead or alive, preferably alive. Of the 133 movies, a total number of 190 Geologists show up and of these 84.7 % are good guys. The overall death percentage is 32% but among the evil Geologists, 72% dies. As for the friendly Geologists, the death percentage is (only) 24%. Clearly, it does not pay off to be evil. The best way to survive as a Geologist in a movie is to be a hero. Of the 190 geologists, 43 are heroes and of these 8 suffer a heroic death saving the world or a selection of people. In summary, Geologists in movies are to 85% portrayed as the good guys and 23% are heroes. This is a fantastic outcome and a few more movies will not change the results. In truth and statistics, Geologists are heroes!

IS4-13

Short-term temporal-compositional trends in monogenetic basaltic volcanism: The Coalstoun Lake volcanic field

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Recent eruptions of monogenetic basaltic volcanoes, including the ongoing eruption of Kilauea in Hawai'i, demonstrate the hazardous nature these common volcanic systems can present. Previous studies have shown that magma composition influences the eruption (including flow rate and explosivity), although there remains uncertainty if eruption compositional changes influence lava architecture. This study aims to determine if the late-erupted magmas, being more silica-saturated, reflect

more significant degrees of partial melting and whether this influences the volume of available melt and mass eruption rate. Further to this, the study aims to determine if the compositional variation results from magma ponding and pooling in the crust, in turn influencing a more explosive eruption earlier and later effusive, suggesting a decrease in the mass eruption rate.

This may be answered by a young (600Ka) and little-known well-exposed, intra-plate, 160km long monogenetic lava flow in Coalstoun Lakes, located in Queensland, Australia. We studied the physical and chemical volcanology of the Barambah Basalt and associated volcanic centres around Coalstoun Lakes to elucidate the influence of compositional variation on eruption duration, rate and lava flow architecture of monogenetic basaltic volcanoes.

This study of the lava flows, building on previous work from the early 1900's and 1960/70's, reveals a large flow field consisting of 5 vents, multiple flows and well-preserved flow structures. Preliminary results show the extent of the lava flows, 160 km from 3 eruptive centres, and covering an area of >220 km², based on field mapping and satellite photo imagery. Reinterpretation of 250 hydrogeology drill logs both proximally and medially along the length of the flow field reveal up to 6 discrete flows; individual flow units were identified using two key facies of pahoehoe lava flows; dense core and a highly vesiculated crust, with instances of total thicknesses exceeding >100m metres proximal to the vent.

Samples are very fine-grained, olivine micro-phyric basalts. Proximally to the eruptive centres, samples contain 20% olivine phenocrysts and 15% spinel, with groundmass constituents of 40% plagioclase, <1% clinopyroxene, 3% late stage feldspar growth and up to 20% intersertal glass. More than 100km from the vents, abundances vary to 30% olivine phenocrysts and 10% spinel, and groundmass constituents of 45% plagioclase, 10% late stage feldspar growth, 4% clinopyroxene, and <1% intersertal glass. Whole-rock geochemistry, collected using X-ray Fluorescence (XRF) on 35 samples cement this variability and includes a subtle increase in SiO₂ (48 wt% - 53 wt%), increases in Al₂O₃ and CaO with a concomitant decrease in MgO, and an increase in Mg# from 50.4 wt % to 61.3 wt %.

Few studies have examined links between the existence and magnitude of short-term temporal compositional trends and eruptive volume and mass eruption rate. It is expected that this study will significantly contribute to understanding intraplate, monogenetic basaltic volcanism by monitoring the degree of silica saturation in a lava flow and correlating this to melt source changes and how this influences lava field architecture.

RS2-01

The Copernicus EGMS ground motion map of Iceland

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The European Ground Motion Service (EGMS, a component of the Copernicus Land Monitoring Service implemented and operated by the European Environment Agency), will soon provide InSAR derived measurements of ground displacement over all the Copernicus Participating States. The complete archive of Sentinel-1 data, from 2014 to 2020, has been used

to produce the first dataset, using persistent scatterer interferometry (PSI). Yearly updates will begin this autumn. Using a gridded GNSS velocity model, the InSAR data are linked to the ITRF2014 reference frame. The data will be free and open to all users, presented in an advanced, web-based GUI, and available for download.

EGMS is based upon the experience of national ground motion services. Launched in 2018, InSAR Norway (InSAR.no) offered the first-ever free and open nationwide dataset. Since then, the dataset has been updated each year, and now provides complete deformation time series for over 5 billion locations. The data is used by professionals throughout the country to evaluate a wide range of deformation phenomena, such as ground subsidence, landslides, infrastructure deformation and geomorphological processes. The Geological Survey of Norway (NGU) and the Norwegian Water and Energy Directorate (NVE) have built an operational landslide mapping and monitoring programme largely based upon these data. The data are used for both the identification of unstable slopes and within the hazard and risk classification process. More than 20 discrete corner reflector networks have been deployed on medium and high-risk sites for monitoring.

In this contribution, we present the data produced for Iceland within EGMS. We focus on natural hazards and show how these data could be utilized for systematic mapping and monitoring in Iceland.

RS2-02

15 years of InSAR monitoring of the unstable rock slope Jettan in northern Norway

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The unstable rock slope of Jettan in northern Norway poses a threat to settlements along the Lyngenfjord because of the potential displacement wave a catastrophic failure could trigger. Since mitigation is difficult, the unstable slope has been monitored for nearly 15 years using satellite InSAR and various in-situ instruments, so that people in the hazard zone can be warned and evacuated in case of failure. A proper hazard assessment requires a full understanding of the geometry of the sliding surface and controlling factors of sliding.

We have since 2009 acquired Radarsat-2 and TerraSAR-X satellite datasets over the study area with revisit times of 24 and 11 days. Since 2014, we have collected Sentinel-1 data, with a revisit frequency of every six to twelve days. The collected data has been processed using a variety of advanced InSAR time-series methods. Satellite InSAR has the potential to provide valuable spatial and temporal information about ground displacement, but it is limited by the presence of vegetation or snow coverage. Thus, a network of 8 installed corner reflectors allows for satellite InSAR measurements throughout the year, also when the slope is fully snow-covered. The extensive in situ deformation monitoring at Jettan consists of 10 permanent differential Global Navigation Satellite System (dGNSS) stations is installed in addition to 3 extensometers, 3 lasers, 11 crackmeters, 15 tiltmeters. The in-situ monitoring time goes back nearly 15 years, providing a good opportunity to link satellite InSAR measurements to ground measurements of displacement.

Previous studies of the unstable slope Jettan have shown the presence of different displacement processes, such as deep-seated slope deformation and superficial processes (e.g. solifluction, rock glacier, etc.) related to the periglacial environment where it is located. Coupling InSAR data to displacement phenomena, as well as to driving and controlling factors, can be challenging. We have decomposed a combination of measurements from ascending and descending satellite geometries into vertical and east-west directions. The decomposed 2D product allows for a better interpretation of the displacement patterns.

Our work presents a first analysis of 15 years of InSAR time series linked to in-situ measurements, meteorological data, and mapped slope processes. The compilation of all available data provides new insight into the advantages and limitations of different SAR sensors and InSAR products, and into the spatio-temporal behaviour of Jettan.

RS2-03

Mapping and classifying moving slopes around Iceland using remote sensing

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Landslides are a very serious hazards due to the force of the materials moving downslope. They account for many casualties and infrastructure damages around the world every year. Iceland is prone to landslides, as attested by historical landslides and the deposit landforms visible in many places over the country.

Most landslides will show motion prior to their collapse. This means that special attention should be paid to moving slopes as they may fail in the future. We use remote sensing from satellite to identify moving slope over all Iceland. This is mainly done using deformation time-series derived from Synthetic Aperture Radar interferometry (InSAR) of Sentinel-1 satellites. Specific areas are studied more in details using pixel-offset tracking of archived optical images and TerraSAR-X radar images. All this information is then manually evaluated to map the moving slopes and classify them according to the risk they pose to the public and to the infrastructure.

RS2-04

Monitoring and forecasting quick clay slides, using ground-based InSAR radar, at Gjerdrum, Norway

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The 30th of December 2020, a devastating quick clay slide hit the village of Ask, Gjerdrum municipality, Norway. The landslide, which had a volume of about 1,35 million m³ and a 1250 m long backscarp, caused the death of ten people, destroyed many houses and about 1500 people were initially evacuated, making this the most severe quick clay landslide in Norway in over 100 years.

After the main event, there were several secondary slides from the steep back scarp, and The Norwegian Water Resources and Energy Directorate put up ground based InSAR radars from El-

legi srl to investigate if the technology could be used to detect and predict new slides.

Measuring from the 6th of January to the 24th of February 2021 and from the 7th of July 2021 until now, about 20 avalanches have been detected, with areas as small as 20 m by 20 m. Prior to many of them an area of increased and accelerating velocities has been detected, making the slides possible to predict. Most of the areas have had deformations of about 6-8 mm prior to failure, and an acceleration phase of a few hours. After some of the failures, large masses in the scarp have been remobilized.

Early warning has been possible for many of the events, but the monitoring data needs to be followed closely, due to the short acceleration phase. A few of the slides have been difficult or almost impossible to predict, especially when there have been large movements in the already failed sediments. Radar monitoring in general has challenges when it snows and are atmospheric noise.

This is, to our knowledge, the first-time secondary quick clay slides have been monitored and forecasted in this way. It has been a very valuable tool and is probably the most effective and reliable method for monitoring deformation during search, rescue and mitigation work.

RS2-05

Near real-time photogrammetric monitoring during the 2021 Fagradalsfjall eruption: Results on volume, effusion rate, and lava transport

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The basaltic effusive eruption at Mt. Fagradalsfjall began on March 19, 2021, ending a 781-year hiatus on Reykjanes Peninsula, Iceland. At the time of writing (February 27, 2022), no eruptive activity has been observed since September 18, 2021. To monitor key eruption parameters (i.e., effusion rate and volume), near-real time photogrammetric monitoring was performed using a combination of satellite and airborne stereo images.

By late September 2021, 32 near real-time photogrammetric surveys were completed, usually processed within 3–6 hours. The results are a significant achievement in full-scale monitoring of a lava flow-field providing temporal data sets of lava volume, thickness, and effusion rate. This enabled rapid assessment of eruption evolution and hazards to populated areas, important infrastructure, and tourist centers.

The lava pathways and lava advancement were very complex and changeable as the lava filled and spilled from one valley into another and short-term prediction of the timing of overflow from one valley to another proved challenging. Analysis of

thickness maps and thickness change maps show that the lava transport into different valleys varied up to 10 m³/s between surveys as lava transport rapidly switched between one valley to another.

By late September 2021, the mean lava flow-field thickness exceeded 30 m, covered 4.8 km² and has a bulk volume of $150 \pm 3 \times 10^6$ m³. Around the vent the thickness is up to 122 m. The March–September mean effusion rate is 9.5 ± 0.2 m³/s, generally ranging between 4–8 m³/s in March–April and increasing to 9–13 m³/s in May–September. This is uncommon for recent Icelandic eruptions, where the highest discharge usually occurs in the opening phase. This behavior may have been due to widening of the conduit by thermo-mechanical erosion with time, and not controlled by magma chamber pressure as is most common in the volcanic systems in Iceland.

RS2-06

The Multi-Pairwise Image Correlation (MPIC-OPT) processing chain, an end-to-end online service for surface motion monitoring using optical imagery

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Documenting ground deformation is important for a range of areas in Earth and environmental sciences (such as earthquake, volcanoes, landslides and glaciers/ice sheets monitoring). The availability of optical satellite constellations with a frequent revisit time at medium to high spatial resolution and an open access policy (e.g. Sentinel 2, Landsat 8/9) provides the potential to contribute to surface motion monitoring on a global basis. However, this observational capability also represents a challenge in term of storage capacity and computing resources which together with the complexity of the tuning of the different parameters, may prevent users from exploiting the data. Here we propose a new version of the Multi-Pairwise Image Correlation for OPTical images (MPIC-OPT) algorithm. The new version of the algorithm offers a complete chain to process optical images including data download, image pairs creation and advanced analysis of the displacement field. It offers the choice to compute the ground displacement associated to image pairs with two matching techniques (i.e. MicMac, developed by IGN; GÅ©Folki developed by ONERA). Finally, the Time-Series Inversion for Optical image (TIO) algorithm is integrated to provide displacement time series. The processing chain is accessible through the Geohazards Exploitation Platform (GEP) in the framework of the Thematic Exploitation Platform initiative of the European Space Agency and the runs are performed using the High Performance Computing facility at the A2S/Mesocentre of University of Strasbourg. We present the results of the chain in various areas: to measure the co-seismic displacement of the Ridgecrest earthquakes sequence; to mon-

itor surface displacement of the Slumgullion landslide and the European Alps glaciers (France, Italy, Switzerland). We compare the results of the MPIC-OPT services to in-situ dataset and/or results obtained with similar strategies (e.g. GoLive or ITS-LIVE products, etc.). We discuss the influence of the pairing network and the inversion strategy to retrieve short-term to long-term kinematic regimes in order to define relevant strategies for an operational use of the service for regional monitoring of land-ice motion from satellite images.

RS2-07

The jökulhlaup from the subglacial lake Grímsvötn, beneath Vatnajökull ice cap, in November–December 2021, revealing new insight in to slowly rising jökulhlaups

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The subglacial lake Grímsvötn, beneath Vatnajökull ice cap, has been an important study area since the first attempts to explain the physics of jökulhlaups. The lake, covered by an up to 300 m thick ice shelf, is situated within a caldera of an active central volcano. It collects meltwater produced by geothermal and volcanic activity, in addition to meltwater from the glacier surface. During most of the 20th century the period of water accumulation was typically 4–6 years, collecting 1–3 km³ of water. The jökulhlaups, as observed in the river at the glacier terminus ~50 km south of the lake, typically reached peak discharge of 2,000–10,000 m³s⁻¹ after approximately exponential increase over 2–3 weeks. In October 1996, 3.2 km³ of meltwater from an eruption north of Grímsvötn were collected in the lake. This resulted in hydrostatic uplift of the lake ice dam and sudden release of the accumulated water, reaching a peak flow of ~50,000 m³s⁻¹ at the glacier terminus in less than a day. Due to damage to the lake ice dam during the 1996 jökulhlaup and further undermining from geothermal activity near the dam, the water accumulation and release has been different after this event. Between 1996 and 2018, smaller jökulhlaups typically occurred at 1–2 year intervals with the largest volume of ~0.6 km³ in 2004 and 2010. The jökulhlaup discharge still resembled an exponentially rising discharge, but faster, reaching a peak discharge at the glacier front in 3–5 days after detection of flood water in the river. In 2004 and 2010, the peak discharge was ~3,000 m³s⁻¹. From autumn 2018 until November 2021, ~1 km³ of water accumulated in Grímsvötn. The lake level has been monitored since the 1990s, but now with increased accuracy using online GNSS stations located on the floating ice shelf and repeated glacier surface mapping using Pleiades stereo images. Around mid-November 2021 the GNSS instruments started subsiding, revealing that the lake had started draining. In 3 weeks, the discharge from the lake, estimated from the subsidence rate and the lake hypsometry, gradually increased from a few m³s⁻¹ to a peak discharge of ~3500 m³s⁻¹ on 4 December. A few days later, the lake had drained completely. We present data showing the development at the lake prior to and during the jökulhlaup, and we report on: a) discharge measurements near the glacier front, which combined with the lake discharge allows for an estimate of the temporal subglacial floodwater

storage, b) horizontal and vertical ice motion in the vicinity and above the subglacial flood route during the jökulhlaup, from ICEYE and Sentinel-1 radar images obtained with InSAR (24 hour repeat) analysis and amplitude offset tracking, showing the distribution of flood water and the widespread effect of the jökulhlaup on the horizontal ice motion, c) ice surface motion measured by a GNSS station located half-way between the lake and the glacier margin, spanning the entire jökulhlaup. All this provides new insight into the physical processes occurring during a slow, exponentially rising jökulhlaup from Grímsvötn.

RS3-01

Marine base maps: Multidisciplinary mapping in the Norwegian coastal zone

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Potential conflicts of interest arise as an increasing number of activities compete for space in the Norwegian coastal zone. The spatial requirements of fisheries, aquaculture, tourism, industry, recreation, and marine and coastal infrastructure are often at odds with each other and with the conservation of vulnerable nature types such as spawning grounds and cold-water coral reefs. Spatial planners and other stakeholders require reliable, accessible, and detailed seabed information to help manage these diverse areas in a sustainable manner.

The Norwegian Mapping Authority, the Geological Survey of Norway and the Institute for Marine Research received funding in 2020 to start *Marine Base Maps for the Coastal Zone* – a coordinated pilot project for seabed mapping and data distribution. This three-year pilot involves all three institutions cooperating to produce of a range of maps in three example areas and lay the groundwork for a potential future national coastal mapping programme.

Like Norway's well-established MAREANO programme for offshore seabed mapping, in operation since 2006, the *Marine Base Maps for the Coastal Zone* pilot project is interdisciplinary, with multiple datasets being acquired for a variety of purposes spanning hydrography, geology, biology and pollution. Multi-beam echosounder (MBES) surveys deliver high-resolution data for the production of detailed terrain models and backscatter mosaics. These acoustic data are used in planning the collection of video data, seabed samples, and sub-bottom profiling lines, and are also fundamental to the production of detailed vector maps of sediment properties. MBES-derived raster data such as terrain, slope, rugosity, and backscatter for the study areas are published at the highest resolution permitted by Norwegian Defence Authorities.

Geological thematic maps including Seabed sediments (grain size), Seabed sediments (genesis), Sedimentary environment, and Landforms are produced at 1:20 000 scale through expert interpretation of all available data. Surface sediment samples and short cores from accumulation basins are analysed for organic and inorganic components to evaluate levels of contamination. Biological thematic maps including full-coverage nature types (following the Nature in Norway hierarchic system) and vulnerable habitats are modelled based on sediment maps, hydrographic and oceanographic variables, and the distribution of benthic communities as observed in video and sample data. Maps from the three 400-500 km² pilot areas in Stavanger (South Norway), Giske/Ålesund (Mid Norway) and Skjervøy/Kvænangen (North Norway) are published upon completion. The various thematic maps are available online at e.g. www.ngu.no, www.mareano.no and the pilot project's map portal marinegrunnkart.avinet.no (only in Norwegian).

A proposal for a national mapping programme for all of the Norwegian coastal zone (ca. 100 000 km²), starting in 2023 with an estimated duration of 15-20 years, was delivered to the Norwegian government in November 2021. A recently conducted socio-economic analysis of this proposal estimates considerable benefits related to better and more efficient management of marine areas, justifying an investment cost of 4,5 billion NOK.

RS3-02

The EMODNET-Geology project – harmonizing geological data of the European seas

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Abstract - High-quality maritime spatial planning, coastal zone management, management of marine resources, environmental assessments and forecasting require comprehensive understanding of the seabed. In response to the needs already in 2009, the European Commission established the European Marine Observation and Data Network (EMODnet), which is now in its fourth phase. The EMODnet concept is to assemble existing but often fragmented and partly inaccessible marine data into harmonized, interoperable and publicly freely available information layers which encompass whole marine basins. As the data products are free of restrictions on use the program is supporting any European maritime activities in promotion of sustainable use and management of the European seas.

The whole package of separate EMODNET- projects covers the marine disciplines geology, chemistry, biology, bathymetry, seabed habitats, physics, human activities, as well as a data ingestion project.

In this fourth phase the EMODnet-Geology project is delivering integrated geological map products that include seabed substrates, sediment accumulation and erosion rates, seafloor geology including lithology and stratigraphy, Quaternary geology and geomorphology, coastal behavior, geological events such as submarine slides and earthquakes, marine mineral resources, as well as map products on submerged landscapes of the European continental shelf at various timeframes. All new map products are presented at a scale of 1:100,000 all over but finer where the underlying data permit. A multi-scale approach will be adopted whenever possible.

The EMODnet Geology project is executed by a consortium of 40 partners which core is made up by 24 members of European geological surveys (Eurogeosurveys) backed up by 16 other partner organizations with valuable expertise and data.

Discover Europe's seabed geology at: EMODnet Geology: <https://www.emodnet-geology.eu/>. In the future, when all thematic EMODnet portals are centralized: <https://emodnet.ec.europa.eu/en/geology>

The age and extent of the Andøya Slide (offshore Norway) revisited

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The Andøya Slide has been considered to be the third largest Holocene submarine landslide on the Norwegian continental margin, after the Storegga (largest) and the Trænadjupet slides. Original analyses of GLORIA long-range side-scan sonar data and echo sounder profiles indicated that the size of the Andøya Slide was about 9700 km², and that its run-out distance was approximately 190 km (Dowdeswell et al., 1996; Laberg et al., 2000). It has been interpreted to be of Holocene age, mainly based on its clear outline and “rugged” morphology, as well as exposed pre-Holocene interglacial sediments within the slide scar (Laberg et al., 2000).

The objective of this study is to gain further insight into the extent and age of the slide based on swath-bathymetry data, high-resolution 2D seismic (Chirp) profiles and sediment cores. Our new bathymetric data extends further downslope than previously acquired data, uncovering more of the Andøya Slide, thus allowing for a more comprehensive mapping of the lower slope morphology. The bathymetric data shows that the Andøya Slide is significantly smaller than previously estimated, with a presence on the upper-lower slope of ~2200 km². Integration of our new data with the GLORIA dataset suggests that the size of the Andøya Slide is about 5000 km², i.e. approximately half the size of what was previously assumed. Based on morphological studies and radiocarbon dating of the sediment cores, we find that the slide includes three separate slide events, rather than a single major event. The initial slide event is interpreted to have occurred around the Last Glacial Maximum, as the oldest sample of post-slide sediments are dated to ~21.7 ka cal. BP, indicating a longer and more dynamic failure history for the Andøya Slide.

High-resolution multibeam Sonar and drone mapping of the submarine ikaite columns and structures in Ikka Fjord, SW Greenland

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Ikka Fjord in SW Greenland is renowned for the hundreds of impressive submarine tufa columns and structures found scattered about its shallow length. These life-encrusted, stalagmite-like structures are up to 20m high and composed significantly of the ‘rare’ cold-water carbonate mineral ikaite (CaCO₃·6H₂O). The fjord is the type locality for this mineral after which it is named. Ikka Fjord and the fragile and beautiful columns it contains has been the focus of multidisciplinary studies by scientists from predominantly Nordic countries who have come to refer to themselves and ‘The Ikka Projekt’. The earlier phases of the

investigations of the locality were aimed at understanding the processes behind the formation of the deposits, mapping their distribution and recording the abundant life-forms found living on and within the columns and structures. Recent discoveries of ikaite formation in Arctic and Antarctic sea ice and new laboratory studies has led to a resurgence in interest in Ikka Fjord and ikaite as these findings suggest that this rapidly precipitating carbonate mineral has the potential to be used as a carbon sequestration medium. With much still to learn about the precipitation of ikaite in Ikka Fjord, recent expeditions have been conducted to acquire new samples and to better map the deposits and the marine and terrestrial environment of the fjord. To this end multibeam sonar bathymetry and aerial drone photogrammetric surveys were made in Ikka Fjord in the summers of 2018–19. These new surveys provided highly detailed maps of the floor of the fjord and data that could be used to chart column heights and distributions. The data also identified several hitherto unknown pockmarks on the seabed. A total of 938 individual columns and structures ranging 0.5–20 m in height measured from the sea floor were identified. The results supported previous observations that the columns are restricted to the spatial extents of the Grønnedal-Ikka igneous complex. Column distribution exhibits lineations and variable density over the fjord floor. The tallest columns are observed to reach and then terminate at the levels of a halocline at approximately 2–4 m water depth. If the halocline marks the limit of growth, then majority of columns have reached only 15–50% of their growth potential. The 60 or so columns achieving their maximum growth potential stand in clusters, interpreted as representing exceptionally favourable growth settings. New data collected in 2019 shows a worrying increase in seawater temperature compared with measurements made in 1995 and 2007–2009. Given that the formation and stability of ikaite favours low temperatures, increases in seawater temperature could potentially affect the stability of the delicate columns of Ikka Fjord.

A new 1:50.000 scale map of the Nuussuaq basin: insights into the art of photogrammetric mapping and volcanic processes

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Photogeological mapping using photogrammetric principles is a classical remote sensing discipline used in the topographic and geological map making production. It has been fundamental to the exploration and mapping of the volcano-sedimentary Nuussuaq basin in central west Greenland since the mid 90'ties. Because of Neogene uplift, parts of the basin are nowadays exposed onshore at Disko Island and Nuussuaq peninsula. Here, deeply dissected valleys and coastal sections reveal excellent exposures of the geology in three dimensions spanning 3 orders of magnitude from outcrop scale to seismic scale. The basin has therefore been central to the study and understanding of the complex geological processes working in volcano-sedimentary basins. As well as to the technological development from the early days of analytical photogrammetry, used to produce the first geological map of the area, to the present-day era of digital photogrammetry.

The Geological Survey of Denmark and Greenland and the Greenlandic government is currently producing a new geological map at 1:50.000 scale covering northern Nuussuaq. The map as such is based on a modern 3D photogeological

mapping approach developed at the survey. In the map production we use a combination of high-resolution traditional nadir looking aerial photographs in combination with high oblique stereo-images collected from helicopter. Both scanned achieve data from the mid 90'ties as well as high resolution digital stereo-images collected within the last decade are used in this production. Because of the many years of operation in the area, we now have an extensive image archive of about c. 30.000 images that documents the geology in great detail which within the map area is a prime example of an evolving lava delta.

We describe here the key technological landmarks that helped shape the present-day geological map-making workflow at the survey followed by a description of the present-day mapping set-up and the status of the new 1:50.000 geological map. Finally, we give examples of how thorough scrutinizing of the image data allows us to document complex picritic eruption sites and intrusive patterns.

RS4-02

Mineral Mapping Using Oblique Helicopter-Borne Hyperspectral and Photogrammetric Data Acquisition

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Remote-sensing techniques are particularly well adapted for the investigation of remote and inaccessible areas, either for preparing field work or for supporting thematic mapping in the field. Satellite images allow for the discrimination of rock units in the broader region, and help in effectively defining the best initial targets for regional exploration. For areas and targets identified as potentially prospective, more detailed investigations are usually performed including focused field campaigns.

Unmanned aerial systems (UAS) are particularly attractive to investigate potential deposits in difficult or environmentally sensitive areas but are limited to small-to-medium-sized survey areas, i.e. tens of square kilometers. Using a fixed-wing aircraft or helicopter, aerial surveys can provide information in a rapid, non-invasive manner on areas conducive to mineralisation that may be otherwise difficult to access from the ground. Fixed-wing aircrafts are useful for large-scale and/or lower-resolution surveys, while helicopter surveys are excellent for defining smaller to medium sized targets at higher resolution and can be flown at both lower ground clearance and speed in terrains that would be impossible to follow in a fixed-wing aircraft.

A novel sensors system setup is designed and mounted on a helicopter to gather high-resolution geometric data as well as quantitative information about mineral variations in North-East Greenland. The focus lies hereby on integration of digital photogrammetry with hyperspectral imaging emphasizing both spatial and spectral information domains. Stereo images and hyperspectral data cubes are collected simultaneously from off-nadir viewing angles within a topographically complex landscape.

The highly variable terrain leads to strong illumination and atmospheric absorption variations which must be accounted for in the hyperspectral data processing. A precondition for such correction is an accurate geo-rectification which is done by the PARGE[®] software. Retrieving the unbiased ground reflectance is solved by a physical based atmospheric correction with the DROACOR[®] model. It uses the exact geometric conditions to

retrieve the illumination conditions and reflectances on per-pixel basis from the measured at-sensor radiance data.

The study demonstrates the potential of using helicopters to help understand the geology in poorly accessible areas and to provide information that may help in the future exploration and geological mapping activities.

RS4-03

Fagradalur volcano: Photogrammetric and ground-based geological mapping of a complex and inaccessible caldera structure

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Fagradalur central volcano, Northeast Iceland, was active from 14 Ma (Martin et al., 2011) and is one of the oldest central volcanoes in the Neogene lava piles of Eastern Iceland. The volcano is exposed across the mountain range and peninsula of Fagradalur, where the silicic complex is seen across the steep cliffs of the northern coast. Previous mapping inferred a caldera structure here, as well as noting a welded ignimbrite and breccias in the area (Geirsson, 1993). More recent ground-based geological mapping has brought to light the complex structures in the exposed volcano, this is coupled with remote photogrammetric mapping of the mountains which further unravels the magmatic history of this area.

This mapping has revealed a proposed source of the Virkisvík ignimbrite and Fagradalur lavas. These events may have formed a caldera structure in Fagradalur around 14 Ma, which was subsequently in-filled with intra-caldera mesobreccias, lavas, and ignimbrites.

RS4-04

Monitoring of Surtsey island (S-Iceland) with close-range airborne photogrammetry

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Since 2019 the volcanic island of Surtsey in south Iceland has been monitored with close-range photogrammetry using sensors onboard UAVs and helicopters. The island emerged from the sea in 1963 and the eruption was active intermittently until 1967. Since 1967 area loss accounts 53% and volume loss 29% due to intense coastal erosion and extreme weather conditions. The high-resolution (cm-level) imagery combined with high-precision geodetic measurements allow creation of Digital Elevation Models (DEMs), MESH models and orthoimages used for geological observations of various types through GIS platforms (e.g., differencing of DEMs) and through virtual outcrop platforms (<https://v3geo.com/model/347>). Two DEMs were created using vertical aerial imagery of the island from 1967 and 1974 (available through the National Land Survey of Iceland), and two from close-range photogrammetry surveys from 2019 and 2021, allowing for long-time interval comparisons and short-time interval comparison. The results give a concise picture of the amount eroded and removed or mobilized for sedimentation during these time intervals and demonstrate the efficiency of the method monitoring dynamic environments.

Volcanic tremor intensity and characteristics associated with the Surtsey eruption of 1963-1967

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The formation of Surtsey remains one of the best-documented volcanic islands forming eruptions to date. The volcanic island of Surtsey was created during the 3.5 years of activity. The eruptions occurred in several episodes involving both explosive and effusive activity. Volcanic activity was detected at 6:30 on November 14, 1963, where ocean depth was 130 m before the eruption, at the south-eastern end of the Vestmannaeyjar archipelago. The first explosive phase lasted November-January (eruption of Surtur). Other notable events occurred in December 1963-January 1964 (Surtla - submarine); February-April 1964 (Surtungur – explosive); April 1964 – May 1965 (Surtungur – effusive); May-October 1965 (Syrtlingur – explosive); December 1965-August 1966 (Jólnir – explosive); and Aug 1966 - June 1967 (Surtur – effusive). The eruptive activity was accompanied by considerable seismic activity, both earthquakes, and volcanic tremor.

During the years 1963 to 1967, seismographs from the permanent stations in Reykjavik (REY), Kirkjubæjarklaustur (SID), Vík í Mýrdal (VIK), and Akureyri (AKU) in Iceland were in operation. The scanned analog seismograms of these stations are accessible on the website: <http://seismis.hi.is/>.

The analog seismic records of two stations Reykjavik and Kirkjubæjarklaustur were 1-2 orders of magnitude more sensitive than the old Mainka stations in Vík and Akureyri. Reykjavik and Kirkjubæjarklaustur were located at a distance of 115 and 140 km from Surtsey and used here for tremor observation analysis. Both spasmodic and harmonic tremor was identified, with low (<3 Hz) and higher (3-5 Hz) characteristic frequencies. The first detected tremor was of low frequency and interpreted as a precursor to the eruption. The onset of this tremor indicates that the submarine eruption began in the early afternoon of November 12. During 1964-1967, no clear correlation between tremor and eruption rate is detected. The eruption rate was highest in the first 10 days but then followed by gradual decline and episodic behavior. However, for most of the initial 10 days, seismic tremor is not detected. In contrast, tremor is strongest in December and into January, when the eruption rate is much lower than initially. On a timescale of hours to days for the first three months of the eruption, no obvious correlation is seen between tremor intensity and variations in explosive activity such as episodes of cock's tail explosions, continuous uprush, or several hours long halts to visible activity.

Detecting crustal melts under the Reykjanes Peninsula using MT soundings to assess the risk of future volcanic eruptions

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The 2021 Fagradalsfjall eruption on Reykjanes Peninsula (RP) and the roughly year-long precursory activity have shown that a magma reservoir has been developing in the uppermost mantle, at 15-20 km depth beneath the volcanic fissure. It is highly likely that both melt and exsolved CO₂ from this reservoir have been slowly migrating upwards through the ductile part of the crust, where it gets trapped at the brittle-ductile transition (BDT) at 7-8 km depth. There, the magma may either solidify as an intrusion, penetrate through fissures in the brittle crust to the surface, or migrate laterally upwards along the BDT towards its shallowest points, which are at 4-5 km depth directly beneath the high-temperature (HT) hydrothermal fields on the RP.

Mapping of melt that accumulates at the BDT below the RP is essential to assess the risk of future volcanic eruptions and likely eruption sites. Geophysical methods can distinguish melt accumulation zones from the surrounding medium at 5-10 km depth. Resistivity and S-wave properties are the main physical parameters that can be used for this purpose since both are highly sensitive to temperature anomalies close to the solidus of the rock. It might be problematic to measure the S-wave properties by earthquake tomography with sufficient resolution, and the use of active seismic methods are very costly. On the contrary, measurements of resistivity using the MT method are relatively cheap and likely to detect large magma bodies.

The resistivity structure of the RP is in general like other parts of the Quaternary crust of Iceland, but with two important exceptions: the groundwater is highly saline, and the conductive layer found elsewhere at 5-20 km depth is missing under the RP. In general, the resistivity is high at the surface but lowers sharply with depth to <10 Ωm at roughly 1 km depth due to the saline groundwater and the increasing content of conductive clay minerals. Deeper, the resistivity increases to 30-100 Ωm and stays almost constant to at least 5 km depth, representing temperature in the range of 200-600°C, according to laboratory measurements on rock samples. If a body of considerably higher temperature exists at this depth, it would show up as a moderate low resistivity anomaly. On the RP, such a body has only been observed beneath the Krýsuvík HT field. If a large magma body exists in the uppermost 10 km, it would show up as a volume with resistivity equal to 1-10% of the surrounding rock and easily detectable. No such observation has been reported yet. However, most of the existing MT soundings on the RP have been carried out to explore the HT reservoirs and aim mostly at the uppermost 5 km. Thus, they are not designed to image/detect magma bodies at greater depth.

To explore for possible magma bodies beneath the BDT, we suggest an extensive MT survey covering the entire Reykjanes Peninsula, measuring long enough electromagnetic periods to map the resistivity at least down to 15-20 km depth.

SO₂ flux measurements during the 2021 eruption of Fagradalsfjall

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During the Fagradalsfjall eruption, the flux of SO₂ was measured with ground-based UV spectrometers. A three-instrument network of DOAS instruments (10 km NNW of the eruption site, 6 km to the NW and 4.5 km to the SW) was augmented by traverses directly under the eruption cloud, primarily car-borne but a few measurements were also made by foot and by air-

craft. These measurements are used together with plume height and meteorological conditions to calculate the emission rate of SO₂. The scanning instruments measured the SO₂ flux 4900 times over the duration of the eruption. These measurements include only those where the plume was within +/- 15 degrees of line of site from the eruption to the instrument and the measurements were not obviously impacted by the low solar angle during sunrise and sunset. Additionally, 148 traverse measurements were made. The traverse calculations attempt to include the uncertainty related to wind properties to have the true measurement uncertainty represented in the results.

The measurements reveal significant variations in SO₂ flux over short time periods. The volcanic activity was highly dynamic over the course of the eruption and has been divided into different eruptive phases based on visually observed characteristics including the number of active vents and the frequency of lava fountaining. During the lava fountaining periods, the SO₂ flux measured by DOAS and the seismic tremor are highly correlated with the presence or absence of lava fountaining. We exploit this relationship to use the SO₂ fluxes measured during the high/low activity times together with the amount of time that the continuous seismic tremor measurements indicate to be high/low activity to produce a more precise calculation of the SO₂ emitted during the different eruptive phases. This allows us to calculate a more reliable total flux of SO₂ over the entire eruption. About 6% of the SO₂ emitted during the same length Holuhraun eruption was released during this eruption.

UV1-04

Volcanic activity in Iceland: Magnitude, frequency, styles of activity and principal hazards

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Iceland is one of the most volcanically active areas in the world, built by the combined effects of a major mantle plume and its location at an oceanic plate boundary. About one third of the on-land area of Iceland is classified as being within the volcanically active zones, with about 30 active volcanic systems. The volcanic products are predominantly basalts, accounting for about an order of magnitude more magma than intermediate and silicic eruptions combined. Glaciers cover parts of the volcanic zones, including some of the most active volcanic systems. As a result, magma-water interaction is very common in Iceland, in particular phreatomagmatic explosive eruptions. About 50% of known eruptions occur within the glaciers. One result of the combination of volcanoes and glaciers is that jökulhlaups, outburst floods of meltwater from glaciers resulting from volcanic or the related geothermal activity, are very common. Other prominent hazards are fallout of tephra, lava flows, gas pollution, lightning and occasionally pyroclastic density currents. Volcanoes in Iceland are generally closed systems, implying that lava lakes and other open-vent volcano-type phenomena are only temporary features of on-going eruptions lasting usually not more than weeks or months. Volcanic eruptions tend therefore to be well defined events with clear seismic precursors and usually preceded by inflation and uplift. The majority of eruptions appear to originate from magma reservoirs in the crust, but this is not universal. In the last 50 years, 22 confirmed eruptions have occurred, whereof 9 belong to the Krafla fires of 1975-1984. Over a 100-year-period (1922-2021) the average interval between eruptions in Iceland was 3 years.

The total amount of magma erupted in the same period is about 6 km³ and the combined duration of eruptions is about 7 years (eruptions ongoing ~7% of the time), whereof the Surstey eruption in 1963-67 accounts for 50%. The most intensive eruptions in this period were the Plinian beginning phase of the Hekla eruption in 1947 and the powerful basaltic explosive eruption of Grímsvötn in 2011. The largest was the Holuhraun eruption of 2014-15. The eruptions causing the greatest direct damage were Heimaey in 1973 where a considerable part of the town of Vestmannaeyjar was buried by tephra and lava, and the Gjálp eruption in 1996 where flooding destroyed bridges and roads. Considerable indirect damage resulted from the Krafla fires in 1975-1984. It should also be noted that the record of the last 100 years does not include the largest types of events that occur in Iceland. Examples of such events are the VEI 6 Öræfajökull eruption of 1362 or the massive flood basalt eruption of Laki in 1783-84. If occurring today, events of that magnitude would have a major impact.

UV1-06

Lava flow hazard assessment during the 2021 Fagradalsfjall eruption, Iceland: Results from MrLavaLoba lava flow modelling

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On March 19, 2021, an effusive eruption started at Mt. Fagradalsfjall on the Reykjanes Peninsula, Iceland, ending a volcanically quiet period of ~780 years. Its location, in the backyard of the capital Reykjavik and the international airport, made this eruption a big tourist attraction both for the Icelandic population and international tourists. Therefore,

timely and frequent lava flow hazard assessment were needed to evaluate and inform authorities on potential risk.

To meet this need we used the probabilistic lava flow simulation code MrLavaLoba (de' Michieli Vitturi and Tarquini, 2018) which is freely downloadable from the web (<http://demichiel.github.io/MrLavaLoba/>). Different simulation strategies were deployed during the unrest and eruption depending on specific purposes. Overall, the purposes were three-fold; (a) Pre-eruption simulations based on the deformation signals caused by the intrusion, to investigate potential infrastructures in immediate danger in case of lava effusion (b) Near real-time simulations addressing areas of danger for lava flow inundation in the short-term (two weeks) and (c) Simulations addressing areas of danger for lava flow inundation in the long-term (months to years).

Overall, MrLavaLoba code proved useful for both short-term and long-term scenarios as well for barrier testing. The fast run time and the flexibility to implement new topography (e.g. models of barriers or an updated lava thickness map) were key during the near-real time monitoring. Furthermore, due to the landscape made of nested valleys, it was extremely useful that MrLavaLoba code include the final lava flow volume and change the topography throughout run, in order to monitor the fill and spill of valleys. This would not have been feasible with other existing probabilistic codes.

Fault structures in the Fagradalsfjall area and tectonic framework of the 2021 eruption in the Reykjanes Peninsula Oblique Rift, Iceland.

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The structure of the plate boundaries in Iceland is relatively complex. Two of the plate boundary segments are highly oblique to the over-all plate velocity vector between the North America and Eurasia Plates, i.e. the Reykjanes Peninsula and the Grimsey oblique rifts. They contain both volcanic systems and seismogenic strike-slip faults. Oblique spreading leads to extensive volcanism and large earthquakes, a combination that is otherwise uncommon in Iceland. The fissure swarms of individual volcanic systems contain normal faults and fissures, arranged en echelon along the plate boundary. The fissure swarms fade out as they extend into the plates on either side. These volcano-tectonic rift structures on the Reykjanes Peninsula are overprinted by sets of parallel, N-S striking transcurrent faults that generate the largest earthquakes in the zones, up to M 6.5. Their surface expressions are en echelon fracture arrays and push-up structures. The distance between them varies from 0.3 to 5 km. They are most prominent in the areas between the overlapping fissure swarms, and together they form a bookshelf-type fault system taking up the shear component of plate movements across the oblique rift zones. The Fagradalsfjall volcanic system is located between the fissure swarms of the Svartsengi and Krísuvík fissure swarms. It lacks its own fissure swarm, that are otherwise one of the characteristics of Icelandic volcanic systems. We present maps of surface fracturing structures of the area and interpret them as the result of strike-slip displacement on underlying N-S faults. About 20 faults are implied along a 10 km long section of the plate boundary. In addition to these bookshelf-type faults, several areas have been identified where earthquakes appear to line up along ENE-WSW-striking, fault-like structures. These structures have so far not been seen at the surface despite thorough search, with one possible exception. Taken together, the N-S and the ENE-WSW faults form a conjugate set of faults. The implied tectonic stress field has a horizontal maximum principal stress with a N45°E orientation, and a minimum principal stress with a N135°E orientation, perpendicular to the fissure swarms on the peninsula. It is postulated that bookshelf faulting is one of the characteristics of unstable or immature plate boundaries.

Degassing of thick basaltic flow during crystallisation and segregation of residual melt

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During lava flow emplacement and cooling, crystallisation and degassing take place and interact with each other. Crystallisation increases volatile concentration within the residual melt, until saturation and formation of a gas phase. This leads to melt segregation by gas filter pressing to lower pressure. This process results both in the formation of segregation structures

filled with evolved material, such as vesicle cylinders (VC), horizontal vesicle sheets (HVS) and megavesicles (MV), and in the outgassing of the lava. In order to study the condition under which these structures form, diverse segregation products and their associated host lava (HL) were sampled in thick olivine tholeiite lava from Reykjanes Peninsula. The outgassing is investigated by sampling the gas emitted at the Fagradalsfjall 2021 lava field. Major-trace element concentrations (including the toxic metals Pb, Cd, Bi, As...) were analysed by ICP-MS and ion chromatography, both in the different segregation products and in the gas phase emitted from cooling lava and the crater itself.

The whole-rock data indicate that the segregation structure material is formed by at least 40 % of fractional crystallisation for the HVS and up to 60 % for the MV, based on their enrichment in the Zr and Th (fully incompatible elements) with respect to the HL. The mineral proportions (mode) and compositions of the segregations are consistent with such crystallisation extent. The analysed VC product display evolved composition but is clearly shifted from the liquid-line-of-descent, translating more complex formation processes (potentially involving HL crystal contamination and/or liquid escape). The HVS and MV samples are both extremely enriched in the chalcophile elements Bi, Sb and Pb with an enrichment factor up to 7.5 for lead in the MV, e.g., much higher than Zr (2.58) or Th (2.48), which can thus not be explained by fractional crystallisation alone. The same chalcophile elements are notably low in the VC, with enrichment factor around 1. Diluted gas plume sampled at the Fagradalsfjall 2021 lava field and crater exhibit significant concentration of these toxic chalcophile metals, with Pb, As, Tl, Zn and Ag and Tl between 6 and 205 ng.m⁻³ at the crater.

These results strongly support the idea that segregation processes occur after a significant crystallisation of the host lava and that the residual melt continues to fractionate while rising through the lava flow (from VC to MV). The strong chalcophile-element enrichment in the most evolved segregation products (MV) suggests the circulation of a gas phase within these structures, carrying volatile species from the HL to the HVS to the MV, and eventually escaping the lava flow through cracks, as observed in our gas-phase measurements at Fagradalsfjall.

Diverse mantle components with invariant oxygen isotopes; the 2021 Fagradalsfjall eruption, Iceland

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Continuous and dense sampling of the products from active eruptions provide unprecedented insight into volcanic activity, magmatic processes, and the underlying mantle sources that are impossible to achieve from studying ancient deposits where younger and more voluminous products cover first erupted deposits. The Reykjanes Peninsula (RP) in Western Iceland is not only a volcanically active subaerial plate boundary functioning as the onshore extension of the Reykjanes Ridge, but also hosts about 70% of Iceland's population, including the Greater Reykjavík area, the Reykjanes geothermal power plant, and Keflavík international airport. The 2021 Fagradalsfjall eruption

was the first on the Reykjanes Peninsula in 781 years and the erupted products (basaltic lavas) offer unique insights into the composition of the mantle underlying Iceland, in particular its oxygen isotope composition ($\delta^{18}\text{O}$ values) and trace element ratios. The Fagradalsfjall basalts show compositional variations in Zr/Y, Nb/Zr and Nb/Y values that span roughly half of the previously described range for Icelandic basalt magmas and thus signal involvement of multiple distinct mantle sources in magma genesis. Remarkably, Fagradalsfjall $\delta^{18}\text{O}$ values are invariable and indistinguishable from “normal” upper mantle, in contrast to significantly lower $\delta^{18}\text{O}$ values reported for erupted materials from Central Iceland. Thus, despite differing trace element characteristics, the melts that supplied the Fagradalsfjall eruption show no evidence for ^{18}O -depleted mantle or interaction with low- $\delta^{18}\text{O}$ crust, and may represent a useful mantle reference value in this part of the Iceland plume system.

UV2-04

Geology of a Neogene caldera cluster in the Borgarfjörður eystri – Loðmundarfjörður area, Northeast Iceland

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The Borgarfjörður eystri-Loðmundarfjörður area, Northeast Iceland, is home to several volcanic centres characterised by large volumes of silicic, as well as intermediate volcanic rocks. The volcanic centres of Njarðvík/Dyrfjöll, Breiðuvík, Kækjuskörð, and Herfell formed in the Miocene between 14 and 12.2 Ma and are dissected by glacial erosion that exposes a total of 1700 m of the volcanic stratigraphy. We present the first comprehensive geological map and volcanostratigraphy of the area, including a summary of the geology, based on more than 40 years of fieldwork. We identify regional marker horizons that comprise lavas of intermediate (icelandite) and mafic (olivine basalt and porphyritic basalt) composition. The volcanostratigraphy, including the marker horizons, new paleomagnetic data, and previous radiogenic dating, give insight into this little-studied phase of magmatic activity that predates the Reyðarfjörður volcanic system to the south. The area includes spectacular exposures of collapse calderas in Njarðvík, Dyrfjöll, Breiðuvík, ignimbrite-producing vent structures in Kækjuskörð and Herfell, sub-volcanic intrusions, such as volcanic vents, sills, and cone sheets, and unique caldera-lake sediments. We conclude with open questions and invite the research community to visit and study this remarkable area.

UV2-05

Caldera volcanoes in Iceland: A record of caldera formation and eruptive history in Breiðdalur volcano, east Iceland

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Caldera forming eruptions are among some of the most dangerous and impressive volcanological phenomenon in the world. We know, from the geological record, that caldera forming eruptions happen in Iceland; caldera structures are visible in many of the active volcanoes and deposits from post-glacial caldera formations can be found in the tephra record (e.g., Askja c 14 Ka). Caldera collapse is coupled with sub-Plinian to Plinian explosive eruptions and subsequent PDC's, leaving a record of proximally thick and more distally thin ignimbrite and tuffs. Proximal caldera formations are often obscured, either in active volcanoes by more recent eruptions, or in ancient volcanoes by levels of erosion, younger intrusions, and weathering of fissile volcanoclastic sequences.

The Breiðdalur caldera offers a rare cross-section through different parts of a Neogene caldera, allowing for the piecing together of the complex eruptive history of this sequence. The first sequences to overlie basaltic lavas, which are assumed to be the caldera floor, are proximal pumice-fall deposits and ignimbrites. To the east these are themselves directly overlain by an erosive ignimbrite, highly altered mafic lavas, and a thick silicic lava. In the central sequences they are overlain by lacustrine siltstones; silicic and mafic tuffs; a 200 m thick layered ignimbrite sequence with an erosive base; and above this a continued sequence of lacustrine siltstones, tuffs, and mafic scoria deposits. The final sequence in the central section is a thick sequence of altered pumice tuff proximal fall deposits.

The intra-caldera sequence displays a high (c. 70°) dip to the southwest, reverse faulting, and soft-sediment deformation structures. These structures indicate a tectonically active area, even during quiescence periods, and may also indicate slight resurgence. The caldera was clearly not formed and in-filled by a single catastrophic event, but rather by a sequence of explosive silicic eruptive events interspersed with periods of relative quiescence. During these relatively lower energy periods, sediments formed in caldera lakes, though these periods still had explosive and effusive mafic eruptions and smaller silicic events.

Our work emphasises the complex nature of caldera sequences and the need for continued work on ancient structures to understand our geological history and our present volcanological hazards. This work utilises UAV mapping of the Breiðdalur volcano and highlights the usefulness of remote sensing alongside ground-based geology.

UV2-06

Photogrammetric investigation of Vestfirðir (NW peninsula) of Iceland: New insights to the structure of the Miocene lava pile and the enigmatic lignite horizon

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A significant compositional change up the Vestfirðir lavas of NW Iceland has been linked to a jump of paleorifts of Iceland from W of E of Vestfirðir, and it has been found to occur sharply at a widespread lignite horizon in the lava pile (Hardarson et

al., 1997). These authors also suggested that the lavas dip towards their paleorifts: to the W below and to the E above the lignite horizon. Some observations appear to support this (McDougal et al., 1984; Hardarson et al., 1997), whereas other indicate the lavas to be almost flat lying in some regions (Kristjansson et al., 2003; Kristjansson 2014). The official geological map of Iceland (Jóhannesson & Sæmundsson 2014) indicate that the lignite itself has an easterly dip. It is essential for the understanding of the Miocene geological development of Iceland to determine if the development of the large Vestfirðir lava plateau can be interpretation within the Palmason model (Palmason, 1980) where off-rift lavas dip towards the rift due to subsidence caused by increasing mass load towards the rift.

We have studied parts of the Vestfirðir lavas by digital photogrammetry using stereo images acquired using a consumer grade digital camera while conducting field work. The camera was operated in a handheld manner from a car while driving or on foot walking in approximately straight lines roughly parallel to the investigated outcrops. The images were prepared for quantitative 3D analysis in Anchor Lab software 3D Stereo Blend following the workflow of Sørensen & Dueholm 2018. A combination of GNSS data, levelling points and control points were used to georeferenced the images.

The images were subsequently analyzed stereoscopically to constrain local and regional inclination of the lavas below and above the lignite horizon. Using this methodology, we were able to trace and measure the overall orientation of the different lava flow packages within the study area. We present results from areas along Súgandafjörður and Öndufjörður in Vestfirðir. Overall, the lavas show very restricted dips of few degrees. This confirms what some studies have previously found for this part of Vestfirðir but is contrary to the suggestion by others of a general change of dip of the lavas with stratigraphic level.

From our mapping we also demonstrate that the lignite horizon does not descend to sea-level in two along fjord profiles. Therefore, this marker horizon is suggested to either pinch out towards east or alternatively that it continues eastward beyond where it has been previously mapped. Our results have implication to the understanding of Vestfirðir and the data will be discussed within the framework of the Palmason model.

UV2-07

Paleomagnetism and rock magnetism applied to volcanology – prospects for Iceland

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The magnetic characteristics of erupted materials can be used for studying volcanic processes. Since the ~1950s many tools in paleomagnetism and rock magnetism have been developed to answer pressing questions about volcanoes. In some cases, these tools are the most effective or the only way to do this. Abundant magnetic minerals in tephra cause an increase in magnetic susceptibility making it easy to detect the tephra layers from less magnetic materials in sediment cores. Complementary relative or numerical dating of volcanic products and deposits is possible through comparison of the paleomagnetic direction and intensity with regional paleosecular variation reference curves. In a similar manner, remanence and rock magnetic properties can act as a cross-correlation tool between different units. Progressive thermal demagnetization can help distinguish between hot and cold deposits, and given suitable

conditions (emplacement temperature less than that of magnetic blocking temperature) provide emplacement temperature estimates – both important for hazard aspects. Finally, anisotropy of magnetic susceptibility can constrain subsurface magma flow directions for dykes and conduits, as well as surface lava and ignimbrite flow dynamics. Paleomagnetic methods can thereby assist volcanologists in hazard assessment and in refining the spatiotemporal models of volcanoes and volcanic complexes. Here, we will provide a review of the current state of the art in paleomagnetic and rock magnetic methods for studying volcanoes, show some recent examples and discuss the future potential of these methods for studying Icelandic volcanoes and their products.

UV2-08

Characterising ice-magma interactions during a shallow subglacial fissure eruption: northern Laki, Iceland, a case study

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Iceland has the largest variety of subglacially formed volcanic edifices worldwide, given the extensive glacial cover during the Pleistocene and its frequent volcanic activity. As substantial parts of the volcanic zones are presently ice-covered, fissure eruptions beneath glaciers are common.

Phreatomagmatic activity and flood deposits have been hypothesised for shallow subglacial fissure eruptions, at or within a glacial margin. However, to date, no historical examples that did not immediately break through the ice, resulting in dry magmatic activity, have been directly observed. Also, at dynamic ice-margin settings, no extensive resultant formations from shallow subglacial fissure eruptions formed in older historic eruptions have been studied until now.

The final fissure from the 1783–84 CE Laki basaltic flood lava event in the Síða highlands of Iceland, fissure 10, provides a perfect natural laboratory to understand the eruptive dynamics of a shallow subglacial or intraglacial fissure eruption. Fissure 10 is a 2.5 km long formation, which constitutes the final phase of activity on the 29.5 km long Laki crater row, formed as eruptive activity from the Laki eruption propagated under Síðujökull, an outlet glacier from the Vatnajökull ice-cap. The resultant eruptive sequences display evidence of the increasing influence of ice when traced along strike from SW to NE, with the eruption transitioning to a predominantly phreatomagmatic phase with increasing degrees of lateral confinement. The sequence is dominated by volcanoclastic units, formed by multiple phreatomagmatic and magmatic phases suggestive of fluctuating water levels, intercalated with hackly jointed intrusions, hackly jointed lobate lava flows and debris flows. Repeating units of agglutinated spatter and spatter-fed lava flows cap the sequence, suggesting decreasing influence of external water with stratigraphic height and towards the end of the fissure's eruptive activity. A thin layer of glacial till coats the top of the fissure 10 sequences. The margin of Síðujökull has since fully receded from the formation.

Our model for the eruptive dynamics of the northern Laki fissure 10 formation is based on field mapping, a drone photogrammetry survey, petrological observations and EMP analysis of glassy tephra and lava selvages to gain a full understanding of the activity and how eruptive activity progressed. The Laki eruption benefits from a wealth of previous studies on the magmatic phases from the other 9 subaerially eruptive fissures, to the SW of fissure 10, allowing for the effects of the glacier on this fissure's activity to be isolated and defined.

Fissure 10 allows for an approximate reconstruction of the ice margin and glacier slope at the time of eruption, adding valuable information on the extent of the glaciers in SW-Vatnajökull in the late 18th century, and during the Little Ice Age. These shallow subglacially erupted deposits are the only fully accessible intraglacial eruptive vents, from a known historical eruption, on Earth. Detailed mapping and petrological analysis of deposits like these is important for interpreting landforms in paleo-ice margins, where transitional activity occurs.

UV2-09

Early Holocene explosive volcanism in Iceland

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Volcanic eruption frequency in Iceland is high and is estimated to exceed 20 events per century on average during the Holocene. The majority of the eruptions are mafic (~90%) and predominantly explosive (~70%). The dominating explosive volcanism in Iceland allows for the history and behaviour of volcanic provinces to be studied in detail through tephra stratigraphy.

The tephra stratigraphy of the Middle and Late Holocene in Iceland is relatively well known, mostly based on studies of numerous soil/sedimentary profiles across the country. The focus of this study is to obtain a more comprehensive overview on Early Holocene tephra stratigraphy and explosive eruption history. For this purpose, records from soil, lacustrine and marine archives extending beyond 7200 years with a regional coverage of Iceland have been studied.

The cumulative tephra record from the archives will be used to answer questions about the most active volcanoes, what was the level of activity and how does the Early Holocene explosive activity compare to Middle and Late Holocene activity.

UV2-10

Late Quaternary Tephrochronology of Sweden: A look back and prospects for the future

Stefan Wastegård, Simon A. Larsson

Stockholm University, STOCKHOLM, Sweden

Late Quaternary Tephrochronology of Sweden: A look back and prospects for the future

Stefan Wastegård and Simon A. Larsson, Department of Physical Geography, Stockholm University, Sweden

Stockholm University (SU) has a long and successful history of tephrochronology, starting with the ground-breaking thesis of Sigurdur Thorarinsson in 1944, considered as the foundation of modern tephrochronology. Since that, three PhD theses on tephrochronology have been presented by scientists at Stockholm University, most recently in February 2022 by Simon Larsson, and almost 100 papers on tephra applications have been authored or co-authored by researchers from SU.

In this talk, I will give a comprehensive overview of the state-of-art of tephrochronology of Sweden and I will also present some prospects for the future.

UV3-01

Explosive hydromagmatic eruptions during the emplacement of the North Atlantic Igneous Province: A story of volcanic ash

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The North Atlantic Igneous Province (NAIP) comprises extrusive and intrusive rocks along the east and west coast of Greenland, on plateaus and ridges in the North Atlantic, and in the Faroes and British Isles. The province was emplaced 63–52 Ma during the early stages of the opening of the Northeast Atlantic Ocean. The most voluminous activity was focused between ~56 and 54 Ma, leading to the emplacement of the bulk of the flood basalts and to the widespread deposition of volcanic ash layers. The Danish ash series is a succession of more than 180 of these layers outcropping in northwest Denmark, deposited during a ~1.3 Myr period from about 55.9 Ma to 54.6 Ma. While some of the earliest ashes are heavily altered and a mix of magma compositions, most of the later ashes are composed of almost pristine tholeiitic basalts.

The thicknesses of the ash layers (up to 16 cm) and the long distances from potential source volcanoes (>700 km) suggest large and explosive eruptions, which are highly unusual for low-viscosity basaltic magmas. To explain this widespread dispersal of fine ash, we propose that magma-water interaction triggered explosive hydromagmatic eruptions, enhancing the fragmentation efficiency and increasing the proportion of fine ash produced. Hydromagmatic activity is governed by a complex interaction of several factors, such as the magma composition, the relative amounts of magma and water, and the depth of subaqueous eruptions. However, the style and extent

of hydromagmatic volcanism within the NAIP remains poorly characterised. We analyse the residual volatile concentrations in pristine matrix glasses and combine with textural observations of ash morphology and vesicularity throughout the stratigraphy of the Danish ash series. Together, these data allow us to evaluate the degree of magma-water interaction during the fragmentation process and model the changes in volatile degassing over time (a proxy for the pressure of magma-water interaction and quenching). We also compare bulk geochemical analysis of the ashes with all available data from the NAIP literature in order to improve our constraints on the position and environment of the source volcanoes.

Overall, we show that the extensive ash deposits in northern Denmark record a period of major hydromagmatic activity in a shallow marine environment (<200 m water depth). This explosive activity was likely triggered by the opening of the North-east Atlantic Ocean as spreading of the seafloor submerged the central axis of the North Atlantic Igneous Province between Greenland and the Faroe Islands.

UV3-02

IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism and Paleoclimate Implications

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The NE Atlantic conjugate volcanic rifted margins are characterized by extensive breakup-related magmatism which is concomitant with the global hot-house climate in the Paleogene. Injection of magma into organic-rich sedimentary basins in the Vøring and Møre basins has been proposed as a driver for the Paleocene-Eocene Thermal Maximum (PETM) at c. 56 Ma. International Ocean Discovery Program (IODP) Expedition 396 in August and September 2021 drilled a total of 21 boreholes in the Norwegian Sea to study the nature of the breakup magmatism and the associated global climate changes. In total, more than 2000 m of cores were recovered during 48 days of operations, including more than 350 m of basalt, 15 m of granite, and 900 m of late Paleocene to early Eocene sediments. A comprehensive suite of wireline logs was collected in eight boreholes. Most of the sites were located on recent industry-standard 3D seismic reflection data, whereas additional high-resolution 2D and 3D P-Cable site survey data were acquired across six sites. The Expedition 396 probed the key elements of a typical volcanic rifted margin and the associated sedimentary archive. Of particular importance is the Modgunn Transect, drilling five holes through the upper part of a hydrothermal vent complex with a very expanded PETM interval dominated by biogenic ooze and volcanic ash deposits. The expedition also recovered an unprecedented suite of basalt cores across a volcanic rifted margin, including both subaerial and deep marine sheet flows with inter-lava sediments and spectacular shallow marine pillow basalts and hyaloclastites. We also recovered the first cores of sub-basalt granitic igneous rocks and upper Paleocene sediments along the mid-Norwegian continental margin. Successful drilling, combined with high core recovery of target intervals

of all ten sites, should allow us to achieve the expedition goals during post cruise work.

UV3-03

Core-log-seismic integration of a volcano-sedimentary sequence penetrated at the Kolga High Seaward Dipping Reflectors, mid-Norway: initial results from IODP Expedition 396

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International Ocean Discovery Program (IODP) Expedition 396 drilled 21 holes at 10 sites spanning the mid-Norwegian volcanic rifted margin in 2021. Sites U1565 and U1566 penetrated the western flank of the Kolga High, a structural high in the north-western part of the Møre Margin close to the continent-ocean boundary. Two boreholes at Site U1565 recovered deeply weathered granite, revealing the previously unknown nature of the high. One kilometer to the west, Site U1566 penetrated a ~120 m Seaward Dipping Reflector (SDR) sequence beneath a thin Quaternary sediment cover. Coring revealed a basaltic lava flow dominated sequence with inter-layered volcanoclastic and siliciclastic sediments, the latter containing granitic clasts eroded from the nearby high. The base of the volcanic sequence was recovered in the cores and marks a sharp transition from sub-aerial lava flows into deeply altered granite similar to Site U1565. ~27 m of granite was recovered which include multiple granite-derived sandstone stringers of variable orientation, a feature provisionally attributed to infill of a deep sub-aerial weathering profile in the granite.

Shipboard petrophysical and wireline data for Site U1566 were collected in order to characterize the SDR sequence and compared to available seismic data. Whole-Round Multisensor Logger measurements were collected on cores for natural gamma radiation, bulk density, magnetic susceptibility, and P-wave velocity at 2.5 cm spacing. 588 P-wave caliper measurements along with 2219 point magnetic susceptibility measurements were made on the working-half sections. In addition, a total of 102 discrete samples were taken for moisture and density (MAD) analysis including 2 cm cubes and 34 additional mini-core samples. Wireline data including gamma, density, P- and S-wave velocity, resistivity, magnetic susceptibility and image log data (micro-resistivity and acoustic) were collected over the main volcano-sedimentary sequence along with VSP.

The volcanic sequence is characterized by an average bulk density of ~2.3 g/cm³, grain density of ~2.9 g/cm³, and average Vp of ~3.7 km/s with vertically stacked fluctuations in physical properties typical of variably compound to simple lava flows showing asymmetrical log profiles with individual flow lobes rarely exceeding ~3 m in thickness. Selected mini-core samples

of siliciclastic inter-layers spanning the volcanic and granitic sequence reveal average grain densities and porosities of 2.63 g/cm³ and 30 % respectively. Recovered lava flow margins range from variably altered vesicular pahoehoe to rubbly aa flow margin breccias. Primary vesicular porosity exceeds 40 % in fresh unaltered flow margins and decreases to < 10 % where alteration and secondary mineralization are pervasive.

The nature and formation of SDR sequences is an area of intense research spanning all global volcanic rifted margins. Results from U1566 reveal unique insights into the formation of SDRs on the mid-Norway margin revealing that the Kolga High was exposed sub-aerially during SDR onset. In addition, the site provides the first evidence for siliciclastic sedimentation during SDR eruptions as continental breakup progressed. The results from U1566 support drainage, at least locally, towards the developing breakup axis giving key new data for appraising SDR formation and development in the area.

UV3-04

Preliminary results of the PORO-CLIM seismic experiment: Constraining NAIP magmatic productivity through time.

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While the post breakup history and magma productivity of the North Atlantic Igneous Province is reasonably well constrained by numerous seismic refraction experiments around the region, the earlier pre-breakup history of volcanism remains more speculative and is primarily based on sampling of pre-breakup volcanic rocks in only a few areas. The Porcupine and Rockall rifted margins juxtapose an earlier hyperextended margin to a later magma-rich margin and provides a unique opportunity to constrain the lateral extent of the impacting Iceland in latest Cretaceous to Paleogene as well as the full record of mantle potential temperature as the NAIP initiated. In May 2021 we conducted a seismic reflection/refraction program over oceanic crust south of the Rockall Plateau and Trough where it transitions from a magma rich to magma poor margin in the Porcupine Basin. Using crustal thickness as a proxy for mantle potential over crust that varies from Late Cretaceous through Eocene age, the experiment places important constraints on the size of early plume impact in the North Atlantic. In this talk, preliminary results of the experiment will be presented.

UV4-01

Shallow magma degassing drives short-period lava fountaining at Fagradalsfjall, Iceland

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Lava fountains are a globally widespread manifestation of basaltic volcanism. They are thought to result from collapse of a foam layer at the top of a magma reservoir. Recharge of the foam can drive cyclic eruptions at the surface. Remarkably periodic lava fountaining persisted for several weeks during the 2021 eruption at Fagradalsfjall, Iceland. However, the repose between successive fountains was much shorter (7-8 min) than documented elsewhere, for example at Kðlauea and Etna (days to weeks). Assuming a similar mechanism applies to each case, the contrast begs the question of what controls the timescales of foam collapse and recharge. Here, we report variations in relative abundances of magmatic volatiles emitted into the atmosphere from the Fagradalsfjall vent measured using open-path infrared absorption spectroscopy. Through application of degassing models for these species and consideration of physical models for foam collapse we show that gas segregation must have occurred at very shallow depths, a few hundred metres below the surface. This explains the short interval between fountaining events at Fagradalsfjall. Thus, the fountaining behavior exhibited at Fagradalsfjall represents a new end-member for lava fountaining, which can be driven by gas segregation at shallower depths than was previously recognized as possible. Similar to geysers, which are driven by collapse of steam accumulated in a bubble trap, we suggest that there is a correlation between the depth of gas accumulation, the fountain height, and the frequency of fountaining: a shallower depth of gas accumulation leads to shorter fountains (both in terms of height and duration) and a shorter interval between fountaining events.

UV4-02

Highlighting gas accumulation as a driver of recent Hekla's eruptions using the short-lived radionuclide ²²²Rn.

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The volcanic activity of Mt. Hekla changed after 1970 CE, when the quiescent time became regular with a low-magnitude eruption every 10 years. Each eruption initiated with a short explosive phase, followed by lava production of uniform composition (ca. 54% SiO₂). Ground deformation and strain measurements are interpreted to reflect magma storage zone at 11 km or deeper (Sturkell et al., 2013), where volatile accumulation and resulting magma buoyancy may have led to an autocyclic eruptivity according to Hautmann et al. (2017). In their model, the gas accumulation is the driver of the last four eruptions at Mt. Hekla, with magma recharge only after a pressure fall in the magma chamber during or after an eruption. The gas phase would be principally composed of CO₂ since water remains soluble in the melt of pressure corresponding to 11 km depth. This model can be tested by measuring volatile short-lived radionuclides in pumice and lavas of the Hekla volcano.

The inert gas, radon, which is present in low abundance in magma needs a carrier gas such as CO₂ to migrate up through the magma plumbing system. It will accumulate at the top of a magma chamber together with CO₂ if the crust above is hermetic. The most abundant Rn isotope is the ²²²Rn, a decay product of ²²⁶Ra in the middle of the ²³⁸U decay chain. Due to its short half-life of only 3.8 days, ²²²Rn decays rapidly through very short-lived radionuclides to ²¹⁰Pb, which half-life is 22 days. In contrast to radon, lead is readily dissolved in the melt. Accumulation of CO₂ and ²²²Rn should therefore lead to production of ²¹⁰Pb in the first magma erupted and thus a ratio of (²¹⁰Pb/²²⁶Ra) ≳ 1. Note that ²²⁶Ra does not decay in a measur-

able way for the short period of this study, given its relatively long half-life being 1600 years. Therefore, the activity of ^{210}Pb is only driven by disintegration.

First tephra from the 20th century Hekla eruptions have been sampled and are being analysed with by gamma and alpha spectrometry. The ^{226}Ra contents were measured in several historical lavas by Chekol *et al.* (2010) and we use their average for each eruption to calculate the ($^{210}\text{Pb}/^{226}\text{Ra}$) values. Pumice from the 1970 and 1991 eruption yields ($^{210}\text{Pb}/^{226}\text{Ra}$) of 5.05 ± 0.22 and 2.96 ± 0.16 (2SD), respectively, calculated at the time of the eruption. The excess of ^{210}Pb is produced by the disintegration of ^{222}Rn , confirming a gas accumulation before these two eruptions. Therefore, the radioactive disequilibrium between ^{226}Ra and ^{210}Pb concurs with the model of autocyclic behaviour of Hekla's magma chamber.

UV4-03

Magma plumbing system of mass extinction-related Large Igneous Provinces: Insights from Synchrotron Light X-ray microtomography

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The fossil examples of magma plumbing system from Large Igneous Provinces (LIPs) may shed light on the causal relationship between magmatic activity and the most catastrophic mass extinction events in Earth's history. Among the Big 5, the worst biotic crises throughout the Phanerozoic, the end-Triassic mass extinction is synchronous with the activity of the Central Atlantic Magmatic Province (CAMP) [1] and the Cretaceous-Paleogene boundary extinction occurred during the emplacement of the Deccan Traps [2]. The mechanism linking exceptional magmatic activity and biotic crises likely consists in the volcanogenic greenhouse gases, especially CO_2 . Magmatic volatiles have a fundamental role in triggering climatic and environmental changes at global scale [3], as well as in influencing magma migration and governing eruptive dynamics [4]. CO_2 -rich melt inclusions within crystal clots of clinopyroxene in basaltic rocks from the CAMP and the Deccan Traps indicate both early CO_2 exsolution during magma ascent and its abundance in the magma plumbing system [5]. Bubble-bearing melt inclusions and glomerocrystic aggregates in basaltic samples from both these LIPs were imaged by Synchrotron Light X-ray microtomography at Diamond Light Source (United Kingdom). Several mineral phases, glass and bubbles, occupied by the volatile phase, were distinguished and characterized based on their different density. The 3D reconstruction of analysed volumes, in terms of both entire crystal clots and single melt inclusions, allowed investigating the distribution of melt inclusions within crystal clots and estimating the glass/bubble ratio within the melt inclusions. The latter operation is fundamental

to constrain the original concentration of volatile species in the melt prior to gas exsolution and glass shrinkage. The X-ray microtomography data of these LIPs unveiled the microstructural features of bubble-bearing melt inclusions and their host glomerocrystic aggregates. A multi-phase mush constituted the deep magma plumbing system of LIPs, where interstitial melt and CO_2 exsolved from it may have migrated through a porous crystalline framework, interacted with crustal material and driven magma ascent and eruption. Hence, the magma plumbing system of LIPs played a key role in the transfer from the mantle to the surface of carbon, which is likely responsible for the most devastating mass extinctions in Earth's past.

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UV4-04

A new multi-scale, multi-modal and multi-dimensional workflow for the rapid characterization of volcanic materials – a study from the 2021 La Palma eruptions

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Geologists, especially volcanologists, are always faced with the challenge of how to bridge the scales of observations found in nature, especially going from field-scale observations (3D-4D) down to laboratory-based imaging and analysis (3D-2D). Using concepts and practices borrowed from allied areas (for example, oil and gas reservoir characterisation and material science), we have developed a new workflow that takes full advantage of the range of geo-analytical techniques that are available today (including optical, e-beam, x-ray beam, and laser beam). By using all these complimentary techniques, we have been able to upscale and downscale, as well as maximise the discovery and analysis of features of special interest to the understanding of the eruption history. This includes mapping the 3D distribution of phenocrysts and vesicles, as well as the 2D surface analysis of rock surfaces to quantify exact micro-chemical mineral compositions and other textural features, such as mineral associations, grain sizes and grain shapes. A special feature is to be able to map rock surfaces that are significantly larger in area than that typically covered by a standard petrographic thin section, using scanning micro-XRF technology.

Our case study is based on samples recently collected from the 2021 eruptions of Cumbre Vieja, La Palma, Canary Islands,

Spain, where the value of a fully integrated approach was needed as a back-up to rapid response petrology efforts. Work is on-going, but early results suggest there is added value of such an approach, with a much-improved understanding of the eruptive histories on La Palma during 2021.

UV4-05

Insight into a shallow magma plumbing system: examples from the exhumed Torfufell central volcano, Eyjafjarðardalur, N-Iceland

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The region surrounding Eyjafjörður, N-Iceland, is composed of sequences of gently tilted basaltic lava flow successions, ranging in age from about 12 Ma near the mouth of the fjord to Early Pleistocene age by the southernmost valley head. Several extinct central volcanoes are identified in the region, including the Torfufell volcano which is the focus of this study. Torfufell, located in the southern part of the Eyjafjarðardalur valley, has been dissected by rivers and glaciers which have exposed extrusive rocks and shallow intrusions and provided a window into the shallow magma plumbing system associated with the volcano. These intrusions were identified via detailed geological mapping of the Torfufell volcano and surrounding strata pile. The composition of the magmas utilizing the plumbing system ranges from basalt to rhyolite, with early plumbing system activity delivering through eruption a sequence of thin basaltic δ' a lavas. Later activity was typified by delivery of rhyolite magma through effusive and explosive eruption events and less frequent occurrences of smaller andesite to dacite magma delivery. The silicic intrusions commonly feature finely crystalline to aphanitic groundmass, narrowly spaced columnar jointing, sparse vesicles and chilled margins. These features are indicative of rather fast cooling, consistent with emplacement at shallow levels within the crust, further supported by the low-temperature secondary mineral assemblages that typify the succession. Silicic sills are exposed at several levels below the base of the silicic/intermediate extrusive products thus largely intruding the basaltic lava part of the succession. As the sills are most commonly conformable with the basalt lava succession and its sedimentary inter-beds, it is evident that the magma intrusion was largely guided by the sub-horizontal layering of the strata. However, the exposure also demonstrates how the sills changed stratigraphic levels, both discordantly at gentle inclination and at steep angles through dyke-like segments. These sills are connected to sub-cylindrical conduits as well as dykes within fault zones. The exposures provide excellent cross-sections through these conduits, including brecciated intrusion margins as well as flow banded pitchstone that grades into stony rhyolite towards the center. Silicic dykes are concentrated in the northern part of Mt. Torfufell, trending from ENE-WSW to ESE-WNW and tending to form arcuate alignments with an implied center within the NW sector the mountain. These orientations differ significantly from the trend defined by regional dykes and thus are considered to have formed within a stress field associated with a shallow magma chamber beneath the volcano. The exposures of the Torfufell volcano demonstrate how sill intrusions contributed to the upper crustal magma transport and storage within the volcanic system and show how the silicic magma ascended through transgressive sills and erupted via sub-vertical dykes as well as discrete conduits that were approximately cylindrical at shallow depths.

UV4-06

Reconstructing silicic magma intrusion and eruption in the Reyðarártindur pluton, Southeast Iceland

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New magma arriving inside a volcano's roots requires the creation of space, primarily by the deformation of the surrounding host rock. If the host rock cannot make space to accommodate the incoming magma, then an eruption may be triggered. Therefore, assembly dynamics and the type of emplacement mechanisms influences the eruption potential. The exposure of the Reyðarártindur pluton in Southeast Iceland represents a unique field example that gives insight into both the primary construction of the magma chamber and eruptions from the chamber. Structural analysis of the host rock, 3D reconstruction of the pluton shape, and examination of the geochemical architecture of the pluton allow us to decipher the sequence of events.

The pluton was emplaced into sub-horizontal basaltic lava flows of Neogene age. The exposed pluton is constructed largely of a single rock unit, the Main Granite. Two additional units occur only as enclaves: the Granite Enclaves, and the Quartz Monzonite Enclaves. The pluton wall contacts are sub-vertical and discordant to the host lavas, while the roof contacts with the overlying basalts are concordant and mostly sub-horizontal. Adjacent roof exposures occur with vertical offsets of up to 200 m, which create structural highs and lows. The 3D reconstruction of the pluton shape shows an elongated rhomboid with steps in the roof and a minimum volume of 2.5 km³. The basaltic lavas overlying the pluton roof are punctured by steeply-dipping to sub-vertical (70-90°) fractures/faults that are arranged in conjugate sets. Notably, the maximum fault offset measured was only 5 m and no large faults are observed at the pluton walls or above the steps in the roof. In the locations of Rílitungnahamrar-Falkáhnnaus and Fagralág, the pluton roof displays depressions associated with large dykes. Within these dykes, the rock is partially to wholly tuffitic, and geochemical compositions range from quartz monzonite to granite. We interpret these dykes as eruption-feeding conduits from the pluton.

We consider that the pluton was emplaced by piecemeal floor subsidence which began with multiple horizontal intrusions of the Main Granite at different localities at different depths, hence the stepped pluton roof. Continued magma supply would have promoted the thickening and subsequent merging of individual intrusions by the subsidence of multiple blocks of the intrusion floor. Rather than facilitating pluton emplacement, the conjugate fracturing/faulting in the roof instead suggest upwards pressure from the magma chamber and testify to overpressure. Overpressure eventually culminated in eruption, evidenced by the exposed conduits. The mingling of magmatic units within the conduits indicates that injection of new magma into the reservoir triggered the overpressure/eruption. The build-up of any magmatic overpressure in the reservoir indicates that magma recharge was not fully accommodated by piecemeal subsidence. Hence, the sequence of events deciphered from Reyðarártindur shows that eruption would have been preceded by recharge into the pluton and small-scale seismicity in the pluton roof, both of which would likely be detectable with modern-day volcano monitoring techniques.

ORAL
UV4

UV4-07

Lithological controls on sill development in sedimentary basins: Observations from the San Rafael Volcanic Field, Utah.

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Sills and dykes have been a studied topic for decades, and many studies have indirectly investigated sill propagation and architecture by using numerical models. Such studies are important to investigate how igneous intrusions behave at the time of the emplacement, but these often ignore the complexity observed in real magmatic intrusions.

Our study investigates how sedimentary and lithologic heterogeneity may infer strong controls on sill propagation and evolution, which will significantly change distances ranging from e.g. 1 km- to 100 m. A key question is how such heterogeneity will influence the large-scale architecture of sills, and how the overall emplacement features in a single sill changes once it propagates through different lithologies. Understanding how sedimentary heterogeneity influence sill development on such scales may lead to better forecasting of volcanic eruptions, subsurface resources and general basin understanding.

Our dataset consists of 3D models with corresponding logs and thin sections gathered from of three large localities: (I) *Cedar Mountains*, a 5.5 km long cliff-face showing complex sills with multiple geometries, (II) *Cathedral Valley*, a 250 m long cliff face showing a complex sill consisting of multiple splays, and (III) *Mussentuchit Valley*, a 1.3 km long meandering valley showing a 3D exposure of a 12 m thick sill. The sills in *Cedar Mountains* and the *Cathedral Valley* occurs within red silty sandstones with interbedded mudstone, while the *Mussentuchit Valley* sill intrudes mainly within thinly bedded and cross-bedded sandstones.

Observations from the field area shows that the sills in San Rafael Swell prefers and exploits locally occurring discontinuities, such as flooding surfaces containing silt, and undulating anhydrite veins. This suggests that sill tips prefer weak discontinuities and thus alter their initial propagation path to follow local lithology. This implies that certain local stratigraphic intervals exert strong controls propagation paths of sills and evidently their resulting geometry.

UV4-08

Streitishvarf composite dyke, a snapshot of magma mixing and silicic magma ascent through the shallow crust

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Magma mixing and mingling is an important process in magmatic systems, as it is a significant driving force behind volcanic eruptions. Volcanic and igneous products can bear the fingerprints of magma mixing in their mineral cargos, or incomplete

mixing (mingling) seen as enclaves of a second magma. These rocks then give us an insight into the processes ongoing prior to eruption, from the deep crust to the surface. Streitishvarf dyke is a well exposed composite dyke, consisting of mafic dyke margins and a rhyolitic core, with a distinct mixing and mingling zone (hybrid zone) between the two. It offers a world-class snapshot of silicic magma ascent and mixing and mingling between silicic and mafic magmas in the crust. The dyke can be traced for 15 km N–S and for around 700 m vertically.

Our findings reveal that the magmas were sourced separately and intruded as one dyke after a brief and high-energy mixing process. Geochemical trends across the Streitishvarf dyke show that the hybrid zone is best explained by binary mixing of mafic magma, represented by the outermost margins of the dyke, and the rhyolitic magma that forms the core of the dyke. However, the chemical profile across the dyke indicates this mixing is stepwise; involving sequential mixing that started with the basalt and rhyolite end-member compositions to form the basaltic icelandite. This step was followed by mixing of the newly formed basaltic icelandite hybrid with the silicic magma and subsequently intruded along the same dyke pathway; a process that was repeated in succession, making each segment of mixed magma more silicic with time until the final rhyolite magma with discrete enclaves of mafic material.

The mixing of magmas of contrasting compositions is clearly an important volcanic mechanism globally, within Iceland it is likely to be a significant driver of large silicic eruptions which have important, potentially catastrophic, impacts on local, national, and international populations and climates. Events such as the Veidivötn eruption at Torfajökull volcano are thought to be driven by a mafic dyke intersecting a silicic magma reservoir and causing the silicic magma to mobilise along the dyke. Thus, the Streitishvarf dyke is presumably analogous to the cross-section of the dyke feeding that eruption at around 1 km depth.

UV4-09

Pit crater depressions in the Galilee, Israel: volcanic-tectonic landforms?

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Pit craters are enigmatic closed depressions, common across the solar system. In Mars they cover ~25% of the surface, and have potential importance for future expeditions. Here we use geologic and geomorphic surveys coupled with K-Ar dating of related basalts, to constrain the formation processes and age of pit craters in the Galilee, Israel, which may serve as analogs to similar extraterrestrial landforms. The circular morphology and lack of ejecta indicates collapse into subsurface voids. The studied landforms are closely associated with normal faults, fractures, and 2.25 Ma volcanism, including a dike which separates two depressions from one another. This association indicates that the depressions formed mainly by collapse into inflated dike voids which were deflated and emptied at the end of the magmatic event. We don't rule out the possibility that some of the subsurface voids formed by dilational normal faulting. We show that this process explains also the formation of modern pit craters at active volcanic centers such as Hawaii and Etna.

Posters

EC1 – Physical and biological impact of climate change

P01

Acid sulfate soils and their impact on surface water quality on the Swedish west coast

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Acid-sulfate soils (AS-soils) are in literature described as the “nastiest soils in the world” due to their potential negative impact on the environment. This is due to their ability to lower the soil pH drastically into an ultra-acidic range, a state that allows toxic metals to mobilize and potentially leak out of the soil matrix posing a threat to surrounding ecosystems and freshwater bodies. In northern Scandinavia, several fish kills have been reported due to leaching AS-soils allowing for these areas to be the focal point of prior investigations. However, seasonally lowered local groundwater levels caused by altered temperature and precipitation pattern in Scandinavia increases the need for additional research in southern Scandinavia. Therefore, this study investigates the existence of AS-soils and their impact on the water chemistry in an area without previous investigations in Halland, SW Sweden.

To investigate the existence of AS-soils, samples taken from different soil profiles in an agricultural area and water samples from the agricultural drainage system were analyzed in pH and metal concentrations. Soil type and soil pH were determined every 0.1 m down to a maximum depth of 3 m. Soil samples were collected from relevant and interesting depths for aerobic incubation, metal- and sulfur analysis. To estimate potential metal emissions after a period of low groundwater levels, in situ surface water sampling was conducted from smaller ditches draining the agricultural area into a nearby canal. Additional hydro-chemical parameters, such as pH, redox potential, and electric conductivity were simultaneously measured in situ and groundwater data from nearby wells were retrieved. The concentrations of several metals, such as Al, Cu, Fe, and V were analyzed using an inductively coupled plasma mass spectrometry (ICP-MS) instrument in both soil and water samples and the total organic carbon (TOC) in the water samples were determined.

The results prove, for the first time, the existence of active AS-soils in a coastal area of western Sweden. The discovery was made in an area of drained wetland and peatland in layers of gyttja clay and sand. The results also provided a clear indication of leaching acids to the surface water, through elevated concentrations of numerous metals, along with a pH of 3.82 - 6.64 in the surface water. Several metals such as Al and Mn, were highly elevated, in some cases close to 100 times higher than the background levels. No signal was found in the groundwater data retrieved, presumably due to the great difference in depth between private wells and the AS soil layer.

The elevated concentrations of metals and the low pH in the surface water are a direct consequence of the discovered active AS soils in the area. Therefore, this is the first case study proving the existence of AS-soils and highlighting their environmental impact on surface water quality on the Swedish west coast (i.e. outside the Baltic Sea Basin).

EC2 – Glacier and glacial processes

P02

Streamlined subglacial bedforms in Bárðardalur, north Iceland: a signature of a palaeo-ice stream within the Iceland Ice Sheet

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Ice streams are important constituents of ice sheets as they drain massive amounts of ice and sediments to the margins and leave distinct geomorphological signatures on the ice sheet bed. Elongated subglacial bedforms, including drumlins and mega scale glacial lineations (MSGs), have been firmly linked to fast ice flow. They are considered an important geomorphological signature of ice streaming, and their internal composition and structure shed light on the processes prevailing on ice stream beds. For this project, drumlins and MSGs in Bárðardalur, north Iceland, are studied with the aim of revealing the formational processes and implications for palaeo-ice streaming within the Icelandic Ice Sheet (IIS). Detailed morphological mapping and spatial analysis of the drumlins and MSGs were carried out and their sedimentological and internal architecture was studied in three sections. The results reveal that drumlins and MSGs in Bárðardalur are primarily composed of fissile diamict, with rafts and lenses of sorted sediments that show ductile deformation, which potentially indicates that high subglacial water pressure enhanced the fast flow. Roughly 30% of the landforms have an elongation ratio of ≥ 10 and are classified as MSGs, supporting the conclusion of a palaeo-ice stream bed.

This research elucidates the existence and scope of ice-streams in the IIS and contributes towards further understanding of drumlin and MSG formation under actively streaming ice.

EC3 - Palaeoglaciology and palaeoclimate; the Nordics and beyond

P03

Tephra constrains natural and anthropogenic changes in postglacial Icelandic lakes

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Iceland is an ideal setting to investigate naturally occurring shifts in climate and environment due to; *i*) its sensitive climatic location in the middle of the North Atlantic, *ii*) the geochronological (and correlative) potential of tephra visible in various sedimentary archives and *iii*) the lack of human influence until the documented settlement c. 871 AD. As Iceland was uninhabited during the majority of the Holocene, the island is a model location to study natural climatic variation and its impact on the landscape as well as to disentangle the complex effects humans and land-use have on the Earth-system following settlement. While studies have investigated Iceland's climatic and environmental history through the last 10 ka BP, key knowledge gaps remain, particularly during the transition from Late Glacial to Early Holocene (15–10 ka BP). Iceland's coastal areas became ice free c. 14.5 ka BP however, as of yet only few sedimentary records extend back beyond c. 10 ka BP. Here we introduce a new project within *Queen Margrethe's and Vigdís Finnbogadóttir's Interdisciplinary Research Centre on Ocean, Climate and Society* (ROCS). The aims of this project are twofold: *i*) to better understand the glacial, sea level and volcanic history of Iceland following its dynamic deglaciation during the Late Glacial–Early Holocene and *ii*) investigate the human impact and land-use on the pristine natural environment following settlement. This investigation is based on a strategic network of tephrochronologically constrained lake records from around Iceland which span the Late Glacial and Holocene. While these lake records are high resolution multiproxy recorders of natural and anthropogenic shifts through the last 14 ka BP, the application of environmental DNA on the sediment sequences allows for an unprecedented understanding of species migration, vegetation establishment / resilience, as well as human impact and land-use.

P04

³⁶Cl as a dating tool for deep ice

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The ¹⁰Be/³⁶Cl ratio has the potential to be a dating tool for old ice, as it decays with an apparent half-life of years and is thought to remove production and transport effects affecting the individual radionuclide concentrations in ice cores. Chlorine, however, suffers from post-depositional loss at low accumulation sites in Antarctica, which requires a better understanding for accurate dating. As previous research suggests little to no chlorine loss occurs during glacial times, the ¹⁰Be/³⁶Cl ratio was determined for glacial samples from Epica Dome C in Antarctica to test its potential as a dating method. Additionally, the chloride and Cl/Na-ratio record was established for the site. The project is ongoing, but first results indicate a reasonably good fit between the measured and expected ¹⁰Be/³⁶Cl decay curve during glacial times. At the beginning of the Holocene, the ratio surprisingly returns to a low value similar to that of the last glacial maximum, which is accompanied by a peak in the chloride concentration, which may therefore serve as a possible predictor for ³⁶Cl loss. Similar patterns are observed in the Cl/Na ratio, which indicates chloride loss when it is lower than the marine sea salt value. These preliminary results encourage us to continue our ¹⁰Be/³⁶Cl measurement campaign and to better understand the process of the chlorine loss as well as possible predictors to correct for it.

P05

Detection of Rogen moraines throughout Norway through use of an unsupervised machine learning approach

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Recognition of geomorphological features such as Rogen moraines can be approached using a simple unsupervised machine learning approach. Rogen moraines are thought to be related to subglacial hydrology, and thus their identification contributes to understanding related subglacial processes during past glacial periods. We make use of an unsupervised learning approach as Rogen moraines typically occur in distinct regions, across large areas of past-glaciated land, making their automated detection parameters easy to define. However, as Rogen moraines form across wide swaths of terrain, their manual delineation is time consuming, therefore automated methods are important for the extensive mapping of Rogen moraines. We aim to make use of existing maps of Rogen moraines as training and testing data, within Norway, Sweden and Canada. We detect moraines using several terrain parameters derived from a high-resolution digital terrain model: slope, several metrics of curvature, and a 40-300 m filtered digital elevation model. We also mask areas in which Rogen moraines

cannot form using a general slope and Laplacian curvature surface and a detailed high resolution lake map. Previous works in detecting Rogen moraines and related landforms from digital elevation models have been limited to large-scale features due to available DEMs being ≥ 50 m resolution, while Norway's concurrent high resolution (1-10 m) products allow small scale features to be easily detected. We find this clustering method to show promising results in regard to Rogen moraine detection, and thus intend to attempt to map these throughout Norway.

P06

A time-transgressive perspective of glacial erosion beneath the Eurasian ice sheet

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Ice sheets play an important role in sculpting landscapes across geological timescales. However, constraints regarding the efficacy and controls on glacial erosion are poorly known, in particular for polar ice sheets over timescales of 100,000 years and more. The Eurasian ice sheet shaped the North Atlantic passive margin and north-western European continental shelf through kilometre-scale denudation processes, sediment transfer, and related uplift during repeated glacial cycles over the Quaternary, whilst broad swathes of inter-fjord uplands and the terrestrial hinterland, including the Baltic Shield, survived multiple glaciations relatively unmodified. Recently, these views have been challenged by new cosmogenic measurements that indicate glacial erosion and extensive modification of high plateaus between the fjords of western Scandinavia. Erosion of these low relief/high altitude surfaces has been linked to long-term glacier equilibrium altitudes, yielding a distinctive bimodal erosion/elevation distribution and associated hypsometric curve that has been interpreted as a glacial buzzsaw mechanism, implying that on geological timescales there is a climatic control on mountain elevation.

We assimilate geological data with ice sheet modelling to investigate the time-transgressive erosional patterns during the last ~110 ka glacial cycle beneath the Eurasian ice sheet. Our results demonstrate extreme rates and a complex spatial variability of glacial erosion ranging from 0 to >5 mm per year across contrasting topographic settings and geological provinces. Bedrock lithologies and thermomechanical boundary conditions are key factors determining long-term erosion rates, and we find limited support for the supposition that polar ice sheets are ineffective agents of landscape development. Though our analysis lends limited support for a bimodal signature of erosion across western Fennoscandia over the entire glacial cycle, we find a thermomechanical control on erosion across high-elevation plateaus during deglaciation phases. Whilst climate perturbations can dramatically impact bulk erosion over short, sub-millennial timescales, we find evidence for a nuanced hierarchy of interdependent environmental controls based on lithology, topographic relief and climate, all of which are critically modulated by the evolving thermomechanical configuration of the ice sheet. Moreover, the highly selective subglacial erosion across shield margins, along with episodes of extreme rates driven by abrupt disequilibrium within the clima-

te-cryosphere-landscape system, provide essential context to contemporary process studies that evidence exceptionally high rates of erosion as ice sheets respond to increased meltwater flux and deglaciates under abrupt climate warming.

P07

Changing palaeoenvironment and bottom currents in the western Fram Strait – preliminary lithostratigraphic results

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Marine sediment cores are an invaluable tool for reconstructing past sedimentary environments and oceanographic conditions in the climate-sensitive Arctic region. This work focuses on multi-proxy analysis of a sediment gravity core recovered from 3393 m water depth at ca. 81° N, 3° W in the western Fram Strait, offshore NE Greenland. The analyses include magnetic susceptibility, x-radiography, line scan imaging, grain size analysis, and x-ray fluorescence core scanning. The processes affecting marine sedimentation in the western Fram Strait are complex and influenced by changing conditions onshore Greenland and in the Arctic Ocean. This includes the growth and decay of the Greenland Ice Sheet; changes in the intensity of the East Greenland Current, which carries Arctic Water from the Arctic Ocean through the Fram Strait; as well as the Transpolar Drift, which results in the export of ice from the Arctic Ocean. Additionally, intermediate and bottom water masses also exchange water between the Arctic and Atlantic oceans through the Fram Strait.

The preliminary results from this core provide insights into variations in sedimentary processes and bottom-current activity, as well as the history of ice-rafted debris deposition offshore NE-Greenland through time. Establishing a chronology remains challenging; however, based on preliminary correlations with other dated sediment cores, the core covers sediments dating to at least MIS 8. Upcoming paleomagnetic data are expected to improve the age determination of the core. Within the core, cyclic changes in the sediments, including changes in colour, grain size, elemental composition, and magnetic susceptibility, suggest repeated changes in environmental conditions in MIS 7 and 6, and 4 and 3. Additionally, there are periods with increased deposition of ice-rafted material around 28 cal ka BP, MIS 5 and MIS 8, and there is evidence of increases in bottom current activity in the sediments older than MIS 8 at the bottom of the core.

The drainage of the Central Jämtland Ice Lake - a revival of de Geer's bipartition hypothesis?

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Here we present, for the first time, geomorphological evidence of a catastrophic drainage of the early Holocene ice-dammed Central Jämtland Ice Lake, marking a definite bipartition of the Scandinavian Ice Sheet in the interior of Sweden.

At the end of the 19th century, it was concluded that in the late stages of the deglaciation an extensive system of ice-dammed lakes, the Central Jämtland Ice Lake Complex, formed between the Scandinavian mountain range in the west and the eastward retreating ice sheet margin. The initial stages of the Central Jämtland Ice Lake Complex consisted of a series of smaller ice-dammed lakes that drained westward, across the present-day water divide, and into the Atlantic Ocean. Then, as the ice-margin retreated, the ice-dammed lakes successively coalesced to form larger lakes, of which the largest was named the Central Jämtland Ice Lake.

Some years later, in the early 20th century, in his efforts to establish the varve-based "Swedish time scale" of the last deglaciation, Gerhard De Geer chose an exceptionally thick and coarse-grained varve in eastern Jämtland as the zero-year varve of his time scale; marking the end of the Ice Age and the boundary between the Finiglacial and the Postglacial subdivisions of the late Quaternary. De Geer believed this varve to stem from the opening of an eastern outlet and the final drainage of the Central Jämtland Ice Lake into the Baltic basin and, therefore, this zero-varve should represent the first definitive bipartition of the receding Scandinavian Ice Sheet.

However, the correlation between the zero-varve and a drainage of the Central Jämtland Ice Lake was only assumed and, at the time, no erosional features from the supposed enormous drainage had been found. In fact, from the middle of the 20th century and onwards, the very existence of the Central Jämtland Ice Lake was challenged, and its palaeo-shorelines instead explained as formed in numerous marginal lakes within and around stagnant ice. Consequently, the draining of these lakes was believed to have been a more gradual process through a disintegrating dead ice-sheet.

About a century and a half after its first discovery, we now present geomorphological evidence in agreement with the original reconstruction of the Central Jämtland Ice Lake being a c. 3500 km² large and open lake, dammed by a coherent and actively retreating ice-margin. Most notably, we have found the "missing" extensive erosive features along with large sediment deposits relating to the catastrophic glacial lake outburst flood that followed when the damming ice margin broke in two. When this dam broke, the drainage was effectively reversed, from its western outlet across the present-day water divide to an eastern outlet and into the Baltic basin.

The glacial landscape of central Jämtland, Sweden; societal and scientific implications of a new map

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The central part of the former Scandinavian Ice Sheet was located over Jämtland and has left a complex landform and stratigraphic archive, which has been studied by geologists for more than a century. This archive shows numerous glacial configurations based on cross-cutting glacial landforms, sub-till sediments, and subglacial till sequences, which presents challenges for land use because, for example, risk indicators for earth mass movements may be obscured.

Jämtland covers a large part of central Sweden and was initially mapped for surface deposits and landforms by the Geological Survey of Sweden (SGU) during the 1960s. However, societal use of geologic information has changed over the past decades, most notably the need for digitalization, which has also driven a demand for higher spatial detail, and for society relevant derivatives of geologic data. Regional authorities in Jämtland, including land-use planners, highlight a lack of high-resolution data that informs geohazard assessment, groundwater resources, and urban infrastructure development.

SGU has therefore recently undertaken detailed mapping of the Quaternary landforms and sediments of Jämtland. To map such a large area effectively and efficiently, we have combined several strategies. We generate our digital Quaternary surface deposits maps from observations of surface characteristics, vegetation, and landforms observable on LiDAR-derived elevation models and aerial orthophotography. We then 'ground truth' these observations against field data collected during the 1960s mapping campaigns and from our own field campaigns. Our fieldwork is focused on field control (quality check) and collection of new geological observations and conceptual understanding (e.g., stratigraphy), rather than providing the initial data to support mapping.

During 2020 and 2021, we have published new maps covering more than 10 000 km² of Quaternary surface deposit maps and 50 000 km² of Quaternary geomorphology. Our mapping has generated important new findings including: 1) Glacial landforms indicate large temporal and spatial variations in ice-flow directions during the Weichselian. We have divided these landforms into chronological groups based on their stratigraphic relations, including a likely new group of glacial lineations formed by an east-flowing mountain-centered ice sheet. 2) During mapping, several observations of multiple tills have been recorded from west-central Jämtland. The till fabrics agree well with the landform record and are possibly explained by local variations in ice-flow patterns. 3) The sediment stratigraphy contains units that may initiate mud and coarse-debris flows and should therefore be further assessed from a geohazard perspective. 4) During deglaciation the ice sheet retreated eastward, onto the piedmont, which dammed large lakes against the mountains. Our mapping has notably increased the detail of ice-dammed lake extents, enabling reconstruction of the final ice-sheet retreat.

In conclusion, our mapping has generated results that motivate further scientific investigation to help us better understand past and modern ice sheet dynamics. Moreover, our maps and data now support better decision-making regarding appropriate land use, particularly in a mountainous region undergoing rapid climate warming.

P10

Deglacial and post-glacial sedimentary processes south of Kvitøya, northern Barents Sea

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Under today's warming climate, the Greenland and Antarctica ice sheets marine-terminating margins experience thinning and retreat. To better predict the future evolution of the ice sheets requires knowledge of how marine-terminating ice margins behave over timescales longer than the observational climate records. We provide one such reconstruction from the former marine-based Barents Sea Ice Sheet.

We present swath-bathymetry and TOPAS sub-bottom profiler data, in addition to multi-proxy analyses of four sediment gravity cores retrieved from water depths of c. 250-550 m in troughs south of Kvitøya, NW Barents Sea. Mainly two types of landforms dominate the morphology: Elongated ridges semi-parallel to the strait (~2-5 m high) interpreted to be recessional moraines representing re-advances or still-stands of the ice front during its retreat. Also, several hill hole pairs (~4-11 m high) are observed indicating a complex retreat pattern.

The lowermost lithological unit in each of the gravity cores retrieved across the GZW is composed of muddy diamicts, interpreted to be a subglacial till. Laminated mud overlying the diamict is interpreted to represent sedimentation from meltwater plumes that emanated from a nearby ice margin. The uppermost unit in all cores is defined by massive, olive brown marine mud containing scattered clasts. This unit is interpreted to be deposited from suspension settling and ice rafting in a glacier-distal environment like at present.

Radiocarbon dates provide minimum ages for the formations of the recessional moraines, and, thus, age constraints on both the timing of ice retreat and significant changes in environmental conditions in this part of the Barents Sea.

P11

Reconstructing the flow evolution of the Fennoscandian Ice Sheet using new high-resolution digital elevation models: a multi-scale mapping approach.

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We are exploiting the recent expansion in availability and coverage of very-high-resolution (1–2 m) digital elevation models (DEMs) within the domain of the former Fennoscandian Ice Sheet to reconstruct its flow pattern evolution from the glacial landform record. Data-driven reconstructions of palaeo-ice sheets based on their landform records are required to validate and improve numerical ice sheet models. In turn, these models can be used to better predict the future responses of the Antarctic and Greenland ice sheets to climate change.

The Fennoscandian Ice Sheet reached its maximum extent at 21–20 ka. Previous data-driven reconstructions over the whole ice sheet domain (encompassing Fennoscandia, northern continental Europe and western Russia) have necessarily relied upon landform mapping from relatively coarse (decametre-scale) data, predominantly satellite images and aerial photographs. However, 1–2 m/pixel resolution LiDAR DEMs have recently become available over a large portion of the ice sheet domain above contemporary sea level. They reveal previously unobserved landform assemblages which record past ice sheet flow, including fine-scale cross-cutting and superposition relationships between landforms. These observations are likely to reveal previously unidentified complexity in the ice sheet's flow evolution. However, the data richness and the large ice sheet domain amplify labour-intensity challenges of data-driven whole-ice-sheet reconstructions; it is not possible to map every flow-related landform (or even a majority of them) manually in a timely manner. We therefore present a new multi-scale sampling approach for systematic, comprehensive ice-sheet-scale mapping, which aims to overcome the data-richness challenge while maintaining rigor and providing informative data products for model-data comparisons.

We have mapped >200 000 subglacial bedforms and bedform fields in Finland, Norway, and Sweden using our new multi-scale mapping approach, and present an in-progress map of 'landform linkages'. Landform linkages summarise the flow directions revealed by the landform mapping but do not extrapolate over large distances between observed landforms. Landform linkages therefore provide a reduced data product that is useful for regional-scale flow reconstruction and model-data comparisons, and remains closely tied to landform observations. The landform linkages will be reduced into longer 'flowlines' which we will use to generate 'flowsets' describing discrete ice flow patterns within the ice sheet. We will use cross-cutting relationships observed in the detailed landform mapping to ascribe a relative chronology to overlapping flowsets, where relevant. We will then combine the flowsets into a new reconstruction of the flow pattern evolution of the ice sheet.

DATED-2: Revisiting the chronology and time-slice reconstruction of the last Eurasian ice sheets

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DATED-1 comprised a fully-documented empirical reconstruction of the changing extent of the last Eurasian ice sheets 40-10 ka (at 1000-year resolution after 25 ka) based on an assessment of all relevant chronological data (Hughes et al. 2016). All uncertainties within the underlying data are synthesised and expressed in terms of distance; deviation between maximum and minimum limits, and their relative proximity to the extent considered 'most-credible', indicates the degree of uncertainty along the ice margin at each time-slice. Explicitly reporting all uncertainties in this way provides a straightforward means to compare geological data with results from numerical modelling of past ice extent. This process also created an archive of published dates (and associated data necessary for their interpretation, quality, and recalculation) relating to the build-up and retreat of the Eurasian ice sheets. Both the time-slice reconstructions and underlying chronological dataset are available via the online data repository PANGAEA (<https://doi.org/10.1594/PANGAEA.848117>). Here we present progress towards the second-generation Eurasian ice sheets' synthesis, DATED-2, which brings the chronological dataset and reconstructions up-to-date; including all new chronological information published since the DATED-1 census 9 years ago. We highlight the main changes required to satisfy this new chronology, and discuss implications for, and obstacles to, constraining the build-up and deglaciation of the last Eurasian ice sheets using empirical geological data.

EC4 - Permafrost and periglacial processes

Permafrost history in northern Fennoscandian peatlands since the mid-Holocene

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Increased permafrost temperatures have been reported from the circum-Arctic region as a result of global warming, and widespread degradation of permafrost peatlands has occurred in recent decades. Since peatlands are important soil organic carbon reservoirs the ongoing permafrost thaw can result in extensive greenhouse gas emissions. The timing of permafrost aggradation in these ecosystems could have implications for the soil carbon lability upon thawing, and an increased understanding of the permafrost history and dynamics is therefore needed in order to better project future carbon feedbacks. In this study we have performed high resolution plant macrofossil and geochemical analyses, and AMS radiocarbon dating of active layer cores from four permafrost peatlands in northern Fennoscandia. In the mid-Holocene all four sites were wet fens, and at least three of them remained permafrost-free until a shift in vegetation towards bog species was recorded during the Little Ice Age. At the two continental sites in Tavvavuoma, northern Sweden, permafrost aggradation occurred around 700 cal. a BP in Riba and 400 cal. a BP in Dávva. Similar ages were reported from the two coastal sites in Finnmark, northern Norway, where permafrost developed around 850 cal. a BP in Karlebotn and 400 cal. a BP in Lakselv. In Karlebotn the vegetation succession shows a period of dry bog conditions also between 3300-2900 cal. a BP, followed by a rapid shift towards species growing in very wet fens or open pools, possibly suggesting that permafrost was present around 3000 cal. a BP but quickly disappeared and was replaced by a collapse scar fen (thermokarst).

UV1 - Monitoring volcanoes and assessing their hazards

P14

The causes of unexpected jökulhlaups, studied using geothermal reservoir modelling

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Jökulhlaups (glacier outburst floods) are considered the most common type of volcanic hazard in Iceland, and result from the accumulation of meltwater during long-term geothermal activity beneath glaciers, or very rapid melting over a short period of time. Jökulhlaups may occur without visible precursors or prior warning, varying in size from being persistent leakage to floods that have caused considerable damage like the jökulhlaups in Múlakvísl and Kaldakvísl in July 2011. Little has been known about the onset time of water accumulation/melting, whether water accumulated before the flood, and how these events are related to intrusion of magma. This study categorises known ice cauldrons within Icelandic glaciers based on their volume, rate of formation, and longevity. Geothermal reservoir modelling was used to explore possible heat sources which generate ice cauldrons. Five scenarios were simulated: (1) Subglacial eruption – freshly erupted magma in direct contact with the ice at the glacier base; (2) Intrusion into homogeneous bedrock – magma intrudes into a bedrock of homogeneous properties; (3) Intrusion into high permeability channel – similar to scenario (2) but a high permeability channel extends from the intrusion to the glacier-bedrock boundary, e.g. zone of high permeability at a caldera fault; (4) Sudden release of pressure – a hot reservoir is topped by caprock, with a high permeability pathway from depth up to the glacier-bedrock boundary, representing a sudden breach of a pressurised reservoir; and (5) Intrusion into a very hot reservoir – similar to scenario (3) but the reservoir is near boiling point, from previous repeated intrusive activity. This work improves our understanding of sudden and unexpected jökulhlaups, which is helpful for hazard assessments and response plans for unrest in glaciers near inhabited areas, tourist spots, and power plants.

UV2 – Volcanism in Iceland

P15

Tephra dispersal and volume of the Surtseyan phases of the 1210-11 CE Younger Stampar eruption, Reykjanes, SW-Iceland

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The 1210-11 CE Younger Stampar eruption started the 1211-1238 CE Reykjanes Fires, which featured 4-5 discrete events: the 1210-11 CE eruption, itself consisting of 3 phases, followed by 3 offshore eruptions in 1223, 1226-7 and 1231 CE, with a possible fourth in 1238 CE. The 1226-7 eruption is regarded as the source of the Medieval tephra, which is a well-known marker layer in SW Iceland. The first phase of the 1210-11 eruption was a Surtseyan event just offshore of Reykjanes, forming the Vatnsfellgígur tuff cone. Hitherto, tephra fall from this cone has not been identified on land. Thus, it is assumed that plume dispersal was westwards over the ocean. Within weeks to months, this phase was followed by a second Surtseyan phase ~500 m offshore, forming the larger Karlsígur tuff cone and a tephra layer with an apparent E to SE dispersal. This was closely followed by subaerial activity forming the 4km-long Stampar spatter cone row and lava flow field¹. The two tuff cones are olivine tholeiite basalt and consist of alternating pyroclastic surge and tephra fall units, intercalated with units from simultaneous deposition from surge and fall. The 3.5m-thick Vatnsfellgígur cone section consists of 8 units, with a general transition from surge to hybrid to fall characteristics, whereas the 5.5m-thick Karlsígur section hosts 9 units and displays at least 2 surge, 1 fall and 2 hybrid units. Cone volumes are $\approx 0.006 \text{ km}^3$ and $\approx 0.044 \text{ km}^3$ for the two cones, respectively. The only widespread tephra layer from the 1210-1238 Reykjanes Fires inferred to be present on land is the Medieval tephra². This scenario is challenged by the identification of two consecutive tephra layers from the 1210-1238 Fires in sediment cores from Lake Hestvatn³, ~100 km E of Reykjanes. The 0.2-cm thick upper layer has a calculated sediment accumulation rate (SAR) age of 1226 CE whereas the 0.4 cm-thick lower layer has a SAR age of 1211 CE. The presented arguments suggest that the Medieval tephra might consist of two tephra sectors, one with an E-SE dispersal axis that hugged the southern coast of the Reykjanes Peninsula (RP); another with a more northerly dispersal axis extending over the northern sector of the RP. Using existing data, new dispersal maps were constructed for the 1226 Medieval eruption and the Surtseyan phases of the 1210-11 Younger Stampar eruption. The volume of each was obtained via exponential, power-law and Weibull empirical models using the AshCalc v1.2 software. The results indicate tephra fall volumes for the 1226 (Medieval tephra) eruption of $\approx 0.06 \text{ km}^3$ and $\approx 0.05 \text{ km}^3$ for the second Surtseyan phase of the 1210-11 Younger Stampar eruption. This implies a total volume (cone+tephra fall) of 0.1 km^3 for the latter and presumably, comparable volumes for the former eruption. Whilst these inferences require verification via further studies, they highlight the importance of such research because events similar to those of the 1211 or 1226 Surtseyan eruptions could have unfolded in 2021 had the Fagradalsfjall eruption shifted by a few kilometres south to an offshore setting.

Eruption styles and environments at Katla in the last glacial period

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Eruptions at Katla volcano occur through the Mýrdalsjökull ice cap. Throughout the Holocene, phreatomagmatic explosions of basaltic and silica magma have been the most common eruption style, and the resulting tephra are well recognised marker horizons from south Iceland across the North Atlantic. During the last glaciation, the ice cap was greater in extent and thickness, and a diverse range of glaciovolcanic products are preserved. We present detailed maps of three formations showing that eruption styles during this time were variable, probably reflecting a combination of locally variable hydrological conditions in the ice sheet, effusion rate, and lava rheology.

Morinsheiði is a subaqueous basaltic sequence on the west flank of Katla, dominated by pillow lava and pillow breccia, intercalated with lobate lava and sheet lava. Minor subaqueous density current deposits underlie the lava units beneath a peperitic contact zone. Successive explosive eruptions and effusive eruptions took place in a sustained meltwater lake. While the base is unclear, the top of the formation rises 550 m above the Markarfljót valley and is where Eyjafjallajökull and Mýrdalsjökull ice caps would once have converged. A substantial glacier thickness at this time allowed for meltwater to accumulate and pond throughout several eruptive phases.

Two rhyolitic nunataks are mapped on the northwestern and eastern edges of Mýrdalsjökull. The Enta nunatak is comprised of a rhyolitic lava ridge and dispersed rhyolitic domes and spines, intercalated with and intruding silicic tephra. Younger silicic tephra and a segment of a basaltic cinder cone make for complex contact relationships with the ice-bound lavas. The Kötlujökull nunatak is formed of a tabular ridge with a clastic base capped by lava with lobate margins. Breakout lobes descend the steep slopes. These sites are 1350 m and 950 m asl, respectively. At both sites, fine hackly and columnar jointing indicate an ice-confined environment, but there is little evidence for ponded water. Our new maps provide greater insight into the form of Katla and the glacial conditions that prevailed during the late Pleistocene.

UV3 – Volcanism in the North Atlantic

P17

Pre-Holocene volcanic ash in sediments near Jan Mayen

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Volcanic ash attributed to Jan Mayen has been found in many distal sites in the North-Atlantic region however, descriptions of tephra horizons in the proximity of Jan Mayen are few and this study aims to increase the knowledge of tephra producing eruptions from Jan Mayen. In this poster we show some preliminary results from investigations of the pre-Holocene intervals of two sediment cores retrieved from the sea floor less than 50 km from Jan Mayen. The Holocene interval of these cores has already been studied and our preliminary examinations of the pre-Holocene intervals include: XRF core-scanning, radiocarbon ages, tephra concentrations (for selected intervals), tephra geochemistry and CT-scanning of the core sections. These results provide valuable insights into the pre-Holocene volcanic activity of Jan Mayen.

P18

Peculiar seismicity in 2021 in the Snæfellsnes and Borgarfjörður area, Iceland

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Seismicity in volcanic systems can be caused by various processes, such as magma movements, fluid pressure changes, tectonic stresses, or other external forcing. When seismicity picks up in a previously aseismic region, within or near volcanic systems, a natural question is whether the new seismicity relates to magma movements or not.

The Snæfellsnes Volcanic Zone (SVZ) in western Iceland still has volcanic activity, although it has not been a major part of the plate boundary in Iceland for several million years. Within the zone there are three volcanic systems, from west to east; Snæfellsnesjökull, Lýsuskarð and Ljósufjöll. The only historic eruption in these systems was in Ljósufjöll about 1000 years ago in Rauðhálsahraun. Seismicity in the SVZ has been minimal since the start of seismic observations in Iceland. In the Ljósufjöll volcanic system, seismicity prior to 2021 consisted of approximately one earthquake per year with a magnitude of 0-3. Since May 2021, seismic activity in the Ljósufjöll area increased substantially: In a small area (approximately 5 km in diameter) between Langavatn and Grjótárvatn lakes, in the south-central part of the Ljósufjöll volcanic system, 84 earthquakes of magnitude 0-3 were recorded over the year 2021 by the national seismic network.

A similar increase in activity was observed at the end of 2021 by Póreyjartungur, which is a region southeast of the SVZ and west of the Western Volcanic Zone. The increase in seismicity follows time-wise the Fagradalsfjall eruption and rifting episode that took place on the Reykjanes Peninsula, approximately 80-100 km away from the regions of increased seismicity. Although a causal relation between these events may be tentative, GNSS measurements from continuously recording stations west Iceland show a SW-NE extension across the region along with the events on the Reykjanes Peninsula. In this study we further try to understand this intraplate activity by using InSAR data from the Sentinel 1 satellites. These methods give an increased insight into the seismic activity in off-rift systems, such as the Ljósufjöll system, and its causes.

P19

Education in climate induced geohazards, risk, and mitigation

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The GEOMME partnership for 'climate-induced geohazards mitigation, management, and education in Japan, South Korea, and Norway' is a newly established collaboration between six institutes in Norway, Japan, and South Korea. The research partners are, in Norway, (1) the Norwegian Geotechnical Institute (NGI; coordinating institute), (2) UiT The Arctic University of Norway (UiT), in Japan, (3) the National Research Institute for Earth Science and Disaster Resilience (NIED) and (4) Niigata University, and, in South Korea, (5) the Korea Institute of Geoscience and Mineral Resources (KIGAM) and (6) the Korea Advanced Institute of Science and Technology (KAIST). The partnership will run until 2026 with the objective of developing novel and collaborative activities in geohazard education and research. During the 5-year project period, activities will rotate between four thematic areas: (I) Geohazards and risk in a changing climate, (II) Natural hazards and risk over large spatial scales, (III) Advanced experiments, modelling, and monitoring, and (IV) Green solutions in hazard- and risk-mitigation practice. In addition to research activities, the GEOMME partners will co-develop four courses on these themes and conduct other forms of educational outreach – for students and practitioners.

Within this framework, UiT is co-developing and coordinating an intensive, research-, and field-based course in autumn 2022, with partners at Niigata University. The graduate-level course will introduce geohazard types, processes and triggers and examine climate-change impacts in different physiographic regions – with special emphasis on the Nordic and East Asian contexts. The main focus areas of the course are: connecting climate and geohazards, analyzing temporal changes in hazard frequency, and projecting geohazard frequency under future climate scenarios. The course will discuss geohazard-related climate-change adaptation and will investigate methods to incorporate climate change into geohazards assessments and modelling. The course will be two-weeks (5 ECTS) and co-taught by partner institutions within GEOMME. Field activities will be conducted in the rapidly changing Arctic of northern Norway. We welcome levels from masters and beyond!

The GEOMME partnership is financed by the Research Council of Norway (project number 322469) and coordinated by the Norwegian Geotechnical Institute.

P20

Long-term volcanic hazard assessments in densely populated regions in Iceland

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Long-term hazard assessments are suitable for long-term planning during the quiescent time between eruptions. Iceland has several populated areas that could be particularly vulnerable to close by eruptions including the communities on Heimaey and on the Reykjanes Peninsula. The spatial likelihood of vulnerability to eruptive hazards has been explored in relation to the location of homes and other critical infrastructure focusing on tephra fall, gas dispersion and lava flows. Eruption scenarios were defined based on past activity and the spatial probability of future vent openings were calculated based on mapped features and surficial expressions of activity. Lava flow simulations were performed to capture a range of possible eruption strengths and vent locations. Tephra dispersion and deposition simulations were performed to capture a variety of weather conditions and vent locations where tephra may be produced from submarine eruptions. Likewise, gas dispersion simulations were also performed to capture a variety of weather conditions and vent locations. The simulation results are used to assess the regional vulnerability of critical infrastructure to the considered hazards. These results can be used to provide suggestions regarding more/less advisable locations for future infrastructure development and can be included in cost/benefit analyses by decision makers.

P21

Mapping potential release areas and modelling runout distances of permafrost rock slope failures at regional scale for hazard assessment

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High mountains and high latitude environments are highly affected by climate change, which notably results in glacier retreat and permafrost degradation. The latter may cause rock slope failures, sometimes provoking far-reaching cascading processes like debris flows or displacement waves threatening human lives and infrastructure. Developing knowledge about their triggering mechanism and propagation is thus required to determine adaptation strategies.

Permafrost-related rock slope destabilizations have been most widely investigated in the European Alps, providing knowledge for other mountain and Arctic environments. In the French Alps, permafrost mapping and extensive rockfall inventories provide relevant data for statistical analysis of their triggering conditions and mobility. Using this database and in accordance with the GAPHAZ guidelines for hazard assessment (GAPHAZ, 2017), the aims of this study are (i) to propose a mapping approach of susceptible release areas of rock slope failures and resulting runout distances at a regional scale (French Alps, 10⁵ km²), and (ii) to identify hotspots for further hazard assessment.

An inventory of 1389 rockfalls (> 10² m³) recorded in the Mont Blanc massif between 2007 and 2021 was used for a statistical analysis of the topographical (slope) and the permafrost (Mean Annual Rock Surface Temperature) conditions within which they have occurred. These conditions are used in a multi-criteria GIS approach to identify the potential unstable slopes at a regional scale.

Then, the potential release areas are used as input to map the propagation of potential events, using a model based on a normalised area dependant energy line principle (NELA model, adapted from DETALE model for permafrost-affected areas). The calibration of the NELA model was done with 3630 Alpine rockfall events covering all possible volume ranges (from Interreg Espace Alpin project; Rock the Alps). The validation of the modelled propagation was based on 48 events from the Mont Blanc database.

In a next step, the resulting maps of release and propagation areas will be crossed with human assets (mountaineering routes, high mountain infrastructure, tourism areas) and lakes (that can provoke cascading hazards) in order to identify areas which could be impacted by rock slope failure-related hazards at a regional scale.

GAPHAZ 2017: *Assessment of glacier and permafrost hazards in mountain regions*. Prepared by Allen, S., Frey, H., Huggel, C. et al. Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). Zurich, Switzerland / Lima, Peru, 72 pp.

POSTERS
GAI

IM - Igneous and Metamorphic Geochemistry

P22

The effect of water and chlorine on growth textures, nucleation delay, and crystallization order of plagioclase and clinopyroxene in mafic melts

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Auto-metasomatism in the form of epidotization and scapolitization indicates that the unzoned pegmatites of the mafic-ultramafic Hamn intrusion crystallized from a melt that was enriched in water and chlorine. Dynamic (kinetic) and equilibrium experiments were performed at 1150 °C and 300 MPa, using an internally heated pressure vessel, to determine the effect of water and chlorine on the texture, nucleation delay, and crystallization order of plagioclase and clinopyroxene in a mafic melt. Each experimental run included 5 noble metal capsules filled with powder of gabbro-norite doped with different amounts of distilled water and chlorine in the form of AgCl. The equilibrium experiments in combination with thermodynamic modeling (MELTS) provided a reference frame for the liquidus temperatures, phase assemblages, and mineral composition for the varying water concentrations to parameterize the dynamic experiments. These lasted 100, 250, and 1800 minutes, were performed under controlled oxygen-fugacity conditions and were quenched rapidly subsequently. The textures of the experimental run products were analyzed with a scanning electron microscope, whereas the chemical composition of the glasses (melt) and minerals was determined with an electron microscope. The experimental results indicate that water as well as chlorine increase the nucleation delay of plagioclase. A nucleation delay of clinopyroxene could not be observed. Further, the nucleation delay seems to increase the crystal size of plagioclase.

P23

Zircon U-Pb-O-Hf isotope constraints on the origin of the Ketilidian Orogen in South Greenland

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The Paleoproterozoic Ketilidian orogen in South Greenland (1.85-1.73 Ga) is interpreted to be the result of northwards-dipping oblique subduction of an oceanic plate beneath the Archaean continental crust of the North Atlantic Craton. The Ketilidian orogen is part of the subducted-related magmatism and accretionary orogenic belt named the Great Paleoproterozoic Accretionary Orogen that existed along an active margin stretching through Laurentia (North America and South Greenland) to Baltica (Northeast Europe), which was part of

the formation of the supercontinent Columbia/Nuna. Thus, the orogeny represents part of an important episode of crustal growth and preservation in Earth's history. The Central Domain of the orogeny is dominated by the plutonic remnants of a magmatic arc (the Julianehåb Igneous Complex (JIC), ca. 1.85-1.80 Ga), which in time grew sufficiently large and stable to subsequently uplift and unroof, to generate rocks interpreted to represent erosional fore-arc deposits that are preserved to the south in the Southern Domain. Between ca. 1.80 Ga and 1.76 Ga, the fore-arc underwent metamorphism at amphibolite to granulite facies conditions, and subsequently was intruded by post-tectonic granites (including rapakivi variants) of the Ilua Suite (1.75-1.73 Ga). We present new zircon U-Pb SIMS ages for granitic and metasedimentary rocks sampled at a regional scale in a traverse stretching NW to SW through the Central and Southern Domains of the Ketilidian Orogen in South Greenland. The U-Pb results are part of an ongoing larger investigation including O-Hf isotope compositions in zircon analysed by SIMS and LA-MC-ICPMS respectively, combined with whole rock geochemical and isotope data. Our intention is to present the combined results of the zircon U-Pb-O-Hf work. Preliminary $\delta^{18}\text{O}$ results suggest the JIC was derived from melting of a primarily juvenile source. Samples from the Southern Domain have a higher $\delta^{18}\text{O}$ signature suggesting the zircons grew from a magma derived from a mixed source. This study will provide the first thorough geochemical and petrogenetic investigation of the timing, across arc variations, and source components involved in the formation and evolution of South Greenland as well as evaluate its contribution to one of the worldwide peaks of continental crustal growth.

P24

Mesozoic granites of southern Indochina: timing and metallogenic implications.

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The Late Permian - Early Jurassic Indosinian Orogen is an arc-accretionary orogen involving the collision of a succession of microcontinental fragments rifted from Gondwana and accreted onto the Indochina Block and South China (e.g. Metcalfe, 2013). This complex long-lived Phanerozoic system, which persists today in the Banda and Sunda Arcs, is commonly used as a modern analogue to the Palaeoproterozoic Svecofennian Orogen in Fennoscandia. Multiple stages of granitic magmatism have occurred in this region, including the granites of the Southeast Asian Tin Belt in Thailand and Malaysia. After the Indosinian, granitic magmatism continued in both the western (the Western Province of the SE Asian Tin Belt) and eastern (the Da Lat zone of southern Vietnam) margins of the Indochina Block during the Middle- to Late-Cretaceous (Nguyen et al., 2004; Searle et al., 2012; Shellnut et al., 2013). While these marginal areas are relatively well-studied, considerably less is known about how these processes affected the interior of the Indochina Block. However, multiple small (<3 km in diameter) granite intrusions have been identified in eastern Cambodia and southwestern Vietnam (Kong, 2012; Waight et al., 2021). These intrusions vary geochemically with I-, S-, and A-types as well as transitional varieties occurring, with many intrusions bearing magmatic Mo and/or Cu mineralisation. In this study, granites from the Kandal and Takeo Provinces of southeastern Cambodia, as well as the An Giang Province of southwestern Vietnam have been investigated. Six individual granite in-

trusions, both mineralised and unmineralised, along a roughly linear path ~120 kilometres north to south were dated. Results indicate that within this limited geographic area at least two distinct periods of magmatism occurred: Early Jurassic and Late Cretaceous, each with associated Mo-mineralisation. The tectonodynamic and metallogenic implications of this will be discussed.

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P25

Geochemical variability of the Fjallgarðar Volcanic Ridge: The spatial and temporal evolution of off-axis Quaternary basaltic magmatism in Central East Iceland

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Understanding lateral shifts, or jumps, of mid-ocean ridge segments is typically hindered by the lack of mid-ocean ridge segments above sea level. Rift zones in Iceland are viewed as non-stationary and undergo frequent, small-scale lateral, sudden shifts in position (Sæmundsson, 1974), making Iceland an ideal location to study the mechanism by which volcanic activity proceeds from a dying rift to a new segment. This project focuses on the evolution of the Fjallgarðar Volcanic Ridge (FVR), which has been interpreted as a possible dormant precursor of the present Northern Rift Zone (NRZ) (Helgason, 1989).

The FVR extends 190 km from the northern extent of the Vatnajökull ice cap in Central-East Iceland to the Slétta peninsula in the North. The volcanic strata are characterized by subglacial, basaltic hyaloclastites and pillow lavas, and are thought to have formed during a ~200-300 ka period of dyke-fed fissure eruptions in the Brunhes geomagnetic polarity chron.

The FVR is thought to be the precursor of the NRZ because of its proximity and parallel orientation to the median line of the present NRZ (Helgason, 1989). However, the true cause, duration, and timing of magmatic activity at the FVR remains largely unknown.

This project explores the geochemical and petrological variability of different sections along the FVR to understand the tectonic context in which the FVR formed. We identify the composition of the mantle source and a range of processes (e.g., melt extraction and transport, crustal assimilation, rifting, isostatic rebound in response to deglaciation) that affect the spatial and temporal variability of subglacial and subaerial erupted products.

We present preliminary data obtained from samples collected from parts of the FVR in August 2021, including major and trace element analyses on whole rock powders, glasses, and minerals from the entire length of the FVR, and their variations with distance from the assumed plume centre close to Vatnajökull. Furthermore, we discuss how these results compare to previous work conducted by Helgason (1989).

Our planned and ongoing work includes: (i) Sr-Nd-Hf-Pb isotope geochemistry on volcanic glass and whole rock powders (ii) determining the mantle source, (iii) identifying magma evolution processes, and (iv) establishing a preliminary model of magma storage and transport in the crust through application of mineral-melt thermobarometry and diffusion modelling.

P26

Petrogenesis and origin of reef-style PGE mineralization in the Penikat layered intrusion, northern Finland – New constraints from in-situ Sr isotope and trace element systematics of plagioclase

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The Penikat mafic-ultramafic intrusion is one of the numerous 2.44 Ga large layered intrusions in northern Finland. It hosts several horizons of subeconomic reef-type PGE mineralization, which can be followed over the >20 km strike length of the intrusion. The intrusion is traditionally divided into five megacyclic units (MCU I to V (top), each characterized by peridotitic/pyroxenitic rocks at the base followed by gabbroic successions. The three most significant PGE reefs are all found within MCU IV; the *Sompujärvi reef* at the base of the MCU IV, the *Ala-Penikka reef* within the MCU IV, and the *Paasivaara reef* at the uppermost part of the MCU IV.

In-situ Sr isotope and trace element compositions of plagioclase are utilized to constrain the petrogenesis of the Penikat intrusion and its PGE reefs. Over 40 samples from the Ala-Penikka block were selected for in-situ analyses to construct an Sr isotope profile of the intrusion. Selected samples were further analysed for trace elements. In addition, trace elements were measured from few representative samples from a pothole structure hosting a thickened Ala-Penikka PGE mineralization. In-situ Sr isotope and trace element analyses were carried out by laser ablation (MC/SC)-ICP-MS at the Finnish Geosciences Research Laboratory at Geological Survey of Finland (GTK), Espoo. Major element compositions of the studied plagioclase grains were analysed by electron probe microanalyser (EPMA) at the Centre for Material Analysis, at the University of Oulu.

The initial Sr isotope compositions of plagioclase are relatively homogeneous ($Sr_{(0)} \sim 0.7020$ to ~ 0.7040), yet subtle stratigraphic variations can be observed. The results show a mild decrease in $Sr_{(0)}$ compositions upwards from MCU I to MCU IV and the MCU IV records the lowest most $Sr_{(0)}$ values within the Penikat intrusion. A marked transgressive shift towards more radiogenic signature is observed at the transition zone between MCU IV and V, at the stratigraphic position of the Paasivaara PGE reef. This transition coincides with enhanced erratic variations in plagioclase An content. The trace element characteristics of the plagioclase grains from different stratigraphic levels, including the pothole structure, are generally similar. Notably, plagioclase in mineralized pegmatoidal rocks of the pothole structure do

not seem to deviate from other rock types of the MCU IV. The MCU V, however, records somewhat elevated LREE abundances in comparison to plagioclase from MCU IV.

The results indicate that there are different types of magmas involved in the genesis of the Penikat intrusion. In particular, the Sr-isotope data supports involvement and mixing of magmas with contrasting isotopic lineages in the genesis of the Paasi-vaara PGE reef. A contribution of late-stage volatile rich fluids in the genesis of the pothole structure and related pegmatoids and PGE mineralization can't be unambiguous demonstrated from the trace-element signatures.

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P27

Ancient, primordial source of water in the Iceland plume source?

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The Icelandic mantle plume has been shown to sample some of the oldest and perhaps, the least-modified constituents of the Earth [1]. It has been proposed that material associated with the proto-Iceland plume at Baffin Island may have tapped a primordial water source [2]. There are, however, very limited hydrogen isotope data for mantle-derived materials currently available from the neovolcanic zone of Iceland, with only a few existing data points restricted to highly degassed subaerial lava flows, which provide limited insights into the importance of this inferred primordial water reservoir at present. This is important as hydrogen isotope studies of other high-³He/⁴He hotspots (e.g., Hawaii-Loihi) do not resolve dD values any different from those found in the majority of mid-ocean ridge basalts (MORB) [3].

We report new water abundance and hydrogen isotope data for a suite of geochemically well-characterized subglacial (n=54) from Iceland using SIMS to obtain water abundance and thermal conversion elemental analyser (TC/EA) IRMS and NanoSIMS (n=19) to obtain hydrogen isotope values. Most samples come from glassy pillow rims that were likely instantly quenched during eruption and are therefore relatively undegassed with respect to water.

Water contents in the basaltic glasses vary from 0.07 to 1.0 wt.%. In general, high-MgO samples tend to have low H₂O contents whereas samples with lower MgO display higher H₂O. TC/EA δD values of the glasses span a wide range of values,

from -118‰ to -65‰. Most NanoSIMS δD values (n=17) cover a similar range, from -124‰ to -69‰. However, two samples from Central-Iceland (Hnöttóttaalda and Kistufell) yield somewhat lower values with NanoSIMS, -142‰ and -160‰ (respectively). No simple relationship is observed between H₂O and δD, and in general, degassing-induced modification of δD values does not appear to significantly affect this dataset. Irrespective of H₂O contents, most samples display δD values below estimates for the depleted MORB mantle. Although δD values do not show any systematic relationships with indicators of magmatic evolution, the most primitive (MgO ~10%), least degassed samples, display some of the lowest δD values observed.

δD-³He/⁴He relationships facilitate identification of possible primordial water sources. Interestingly, high-³He/⁴He samples generally display much lower δD values than expected for the depleted MORB mantle. In this case, high-³He/⁴He (> 17R_A) basalts from Central Iceland, which sample domains of the Iceland plume least modified by recycled materials [1], extend to some of the lowest values observed in this dataset (down to -118‰ for TC/EA and -160‰ for NanoSIMS). Such low values, which are consistent with estimates for the North Atlantic depleted mantle end-member [4], closely resemble those found in enstatite chondrites meteorites [5] and suggest the presence of ancient, primordial water in the Iceland plume source.

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ER1 - Geothermal research and utilization

P28

Bømoen Plus Village A sustainable utilization of a groundwater resource for drinking water, energy extraction and storage

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AIM

This project will lay the foundation for the development of a future "Plus" village that is largely self-sufficient with regards to energy, water, and aggregates from local geological resources.

Development and use of the different geological resources may conflict with each other, and the project will form a management plan for an optimized use of groundwater for drinking water supply, energy extraction and gravel excavation.

The study area Bømoen, Voss, Western Norway, is comprised of a large glaciofluvial deposit with an area of more than 2 000 000 m². Until recently the area was used for military purposes but is now open for civilian use. The plan is to develop the area for small scale industry and residential housing. The focus up until this stage has been to bring together different people and institutions to agree on the future development of the area.

METHOD

The aim is to perform hydrogeological exploration; ground penetrating georadar, drilling, logging. Along with groundwater modelling and field testing this will demonstrate the resource potential for the stake holders. The tools created through this project will be used for management of the resources along with land development.

The aquifer will be used as a source of energy and drinking water. A possible solution is to use the aquifer as both an energy source and storage. By pumping groundwater through a heat exchanger, thermal energy can be transferred and magnified through processes such as compression to both heat and cool air or water. The process is the same as that commonly used in refrigerators, air conditioners or heat pumps. In winter, energy (stored as heat) in groundwater can be extracted and transferred to heat a space. The aquifer can be used as a "battery" that may either be charged (heated) or used (cooled) as source for energy for seasonal needs, such a system is called ATEs (Aquifer Thermal Energy Storage).

RESULTS

Results so far indicate an average thickness of 10-15 m of water bearing sand and gravel. The groundwater temperature is stable at ca. 6 °C. Work related to a reserve water supply for the municipality of Voss has shown significant potential for groundwater extraction. Each drill well can give over 10 l/s of water. By accounting for water's heat capacity and 4 degrees extraction through a heat exchanger this will give a well an effect of 167 kW. Based on yearly heating needs of Norwegian buildings one well can then supply heat for 100 residences.

CONCLUSIONS

Large groundwater resources.

Possible with multiple use of the water for both drinking water and as energy a source.

Cooperation and management plan is necessary for a sustainable use of the resource

Acknowledgments. The project is a collaboration between the Research Council of Norway, Norwegian University of Science and Technology, the Geological Survey of Norway, Bømoen AS, Voss Municipality, Voss Energi AS COWI Fonden and COWI AS.

P29

Carbon Capture and Storage (CCS) – the potential for mineral carbonation in the Swedish onshore bedrock

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The paper/pulp industry is responsible for 5 % of the world's total industrial energy consumption, and 2 % of the direct CO₂ emissions (Trudeau et al. 2011). Companies are now looking to offset their carbon footprint by reducing their use of fossil fuels and implementing the BECCS technique, bio-energy with carbon capture and storage. In the recently started BECCS project INSURANCE (Utilization of industrial residues for an efficient geological BECCS), the aim is to advance the CO₂ capturing technique through the use of enzymes and the industry's own waste streams and to investigate the potential for onshore geological storage for BECCS in Sweden. The project is a collaboration between the research groups biochemical process engineering and ore geology which will deal respectively with the CO₂ capture and targeting geologically suitable storage sites, together with the packaging company BillerudKorsnäs.

As a case study, the BillerudKorsnäs-owned Karlsborg paper/pulp plant, outside Kalix in northern Sweden will be used. The plant itself, is located on metavolcanic rocks of mainly basaltic origin mimicking the geological conditions of the Icelandic CarbFix project. These Swedish rocks are however compared to the Icelandic equivalents metamorphosed and deformed. In addition to this case study, there will also be a national perspective and investigation of mafic and ultramafic rocks around other existing major paper/pulp plants throughout Sweden for potential implementation of BECCS.

The first step of the project will be to investigate relevant factors such as mineralogy, textures, permeability and porosity. Subsequently, aqueous carbonation experiments will be carried out using the enzyme-captured CO₂ coupled to geologically favorable sites in close proximity to CO₂-emitting industry plants. The rock samples will be tested in an experimental reactor with the reactive medium simulating geologically realistic pressure/temperature conditions for CO₂ injection sites in the bedrock, to quantify the rates of how efficiently the silicate minerals can liberate divalent metal cations and produce carbonates. Basaltic rocks in Sweden and across many places around the world are metamorphosed and deformed and will thus behave differently to CO₂ sequestration compared to younger, more porous and highly reactive basaltic formations that previously have been studied for probable CCS projects (Matter et al. 2011; Marieni & Oelkers 2018). In this project, the overall aim is to improve the capturing technique and the methodology for evaluating the potential for CO₂ sequestration through mineral carbonation in metamorphosed and altered basaltic rock formations.

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P30

Geochemical modeling of H₂S injection and its implications on geophysical monitoring techniques at Nesjavellir geothermal power station, Iceland

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Geothermal brine pumped to the surface as part of geothermal energy production contains significant concentrations of non-condensable gasses, such as hydrogen sulfide (H₂S). To reduce H₂S emissions from the production process, H₂S-rich wastewater is injected into the subsurface at Nesjavellir power station, Iceland. The wastewater is assumed to interact with the highly reactive basaltic host rock to mineralize pyrite. Pyrite, and other iron sulfides, have electrical properties detectable in theory by induced polarization (IP), a geophysical method. In order to implement effective geophysical monitoring of H₂S sequestration at the Nesjavellir power station, geochemical reaction path models must first constrain the injection fluid-basalt interactions and determine expected secondary mineralization. These geochemical models quantify pyrite precipitation, thus establishing a necessary foundation for forward modeling the IP response.

In this study, injection fluids and drill cuttings were sampled in November 2021 from boreholes at Nesjavellir and analyzed for their chemical composition. The injection fluids (T = 40-73°C) were found to be alkaline, and their H₂S concentration ranged from 74.41 to 79.54 ppm. The host rock was of basaltic composition with 0.05±0.01 wt. % sulfur. The chemical compositions of the injection fluid and host rock were subsequently implemented into a geochemical reaction path model to investigate the formation of sulfide minerals upon progressive basalt interaction with the injection fluid.

Here we present preliminary results of the geochemical reaction path models detailing (1) fluid and rock compositions from injection wells at the Nesjavellir power station, (2) secondary mineral precipitation, (3) and volume estimates of pyrite formation. The results yield an increase in the sulfur content of the rock upon progressive reaction of basalt with the injection fluid over the modeled temperature range (30-80°C). Sulfide mineralization in the altered basalt accounts for this increase in sulfur, with pyrite mineralizing at reaction temperatures of 30-80°C and pyrrhotite mineralizing at temperatures >40°C. Preliminary estimates suggest lower sulfur volumes than predicted in previous literature studies. We investigate these discrepancies to discuss how differences in model parameters (e.g. H₂S fluid concentration, injection fluid pH, rock composition, temperature, etc.) impact pyrite mineralization.

These preliminary results provide insight into the mineralization of iron sulfides and other secondary minerals at temperatures ranging from 30-80°C. Although constraining the pyrite quantity is only one parameter in the IP forward model calculation, it is an essential first step to evaluate the capacity

of IP to enhance the monitoring efforts of H₂S sequestration via mineralization at Nesjavellir.

P31

Carbon Fixation using Seawater for Sustainable Large-Scale Carbon Capture and Storage – Using stable isotopes in a field-scale pilot

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Carbon capture and storage has been identified as a key strategy to limit global warming to 1.5°C by 2100. Subsurface carbon mineralization is the safest method of carbon capture and storage; this process consists of injecting dissolved CO₂ into the subsurface, reacting with mafic or ultramafic minerals (e.g., basalt) to release cations (e.g., Ca²⁺, Mg²⁺, Fe²⁺), and precipitating into carbonate minerals. However, existing methods of mineral carbonation are water intensive (e.g., with >25 metric tons of freshwater required for each ton of dissolved CO₂ injected at 25 °C and 25 bar CO₂ pressure). Sustainably implementing mineral carbonation carbon storage on the Gigatonne scale will require alternate solvents for CO₂ dissolution depending on the location, and seawater is an attractive replacement¹. While efficient carbon mineralization has been demonstrated in seawater experimentally in conditions relevant to mineral carbonation², no field-scale seawater investigations of mineral carbonation have been undertaken to date.

Stable isotopes of calcium (d⁴⁴Ca) and magnesium (d²⁶Mg) can be applied to compare the efficiency of mineral carbonation in seawater to that in freshwater, however the most reliable estimates will require accurate isotopic fractionation factors (Đ) for carbonate mineral precipitation at relevant conditions. Here, we measure d⁴⁴Ca and d²⁶Mg for mineral carbonation in seawater at varying temperatures and CO₂ partial pressures to understand how these variables impact the calculated Đ for carbonate precipitation. We also compare estimates of carbon mineralization using d⁴⁴Ca and d²⁶Mg to alternative methods (acidification and non-dispersive infrared (IR) CO₂ gas analyzer, furnace and solid state IR, mass balance calculations). We apply these findings to baseline d⁴⁴Ca and d²⁶Mg values taken from a future pilot injection site on the Reykjanes peninsula, Iceland, to evaluate the carbon mineralization potentials, and model the evolution of d⁴⁴Ca and d²⁶Mg signatures for carbon mineralization. Findings of this work will be used in conjunction with post-injection measurements of d⁴⁴Ca and d²⁶Mg to evaluate the efficiency of mineral carbonation in seawater. This study highlights key variables to consider when using d⁴⁴Ca and d²⁶Mg to investigate subsurface processes, and lays a foundation for the first field-scale investigation of carbon mineralization in seawater.

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² Voigt, Martin, et al. „An experimental study of basalt–seawater–CO₂ interaction at 130° C.“ *Geochimica et Cosmochimica Acta* 308 (2021): 21-41.

ER3 - Hydrology, hydrogeology, and weathering

P32

Does solar activity have an impact on freshwater ecosystems?

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Lake Thingvallavatn is one of the largest and deepest lakes in Iceland. It is mostly fed by groundwater springs which are in the northern part of the lake. The water is cold and unusually clear, which makes it unique and very popular tourist attraction, especially for divers. The outlet of the lake is in the southern part of the lake and the residence time is around one year. Monitoring of the water chemistry of Lake Thingvallavatn started in 2007[1]. Before that, the river flowing out of the lake, Sog, had been monitored since 1998. The lake is oligotrophic and primary productivity is limited by nitrogen due to relatively high concentration of phosphorus in the inlet water, compared to what is needed by plants and algae. Dissolved silica is an important nutrient for diatoms, but its concentration is high enough, so it never becomes limiting for diatom productivity.

The result of the monitoring has shown an interesting fluctuation in dissolved silica concentration in the lake. It is a steady fluctuation with an indication of oscillation time around 10-11 years. The total concentration change is relatively large, and the only plausible explanation is variable activity of diatoms with time, and thus variable biological uptake of dissolved silica from the water phase. The study shows that there is a strong negative correlation between the annual number of sunspots and the annual average concentration of dissolved silica in the lake, suggesting that solar activity can enhance biological activity and consequently cause increased uptake of silica by diatoms from the water phase. Research on diatoms in the lake has been conducted in the outlet of the lake since 2015 until present. The time sequence of the diatom data is shorter than the monitoring of the lake water chemistry, but the results indicate that the biomass in the diatom spring bloom (April-May) is higher in years with high number of sunspots. The reason for this correlation between solar activity and diatom activity is unclear. A possible direct effect could be an increase in solar irradiance at times of high solar activity, potentially providing irradiation into deeper levels of the lake, where nitrogen is not limiting for primary production. Solar activity has been shown to vary systematically of the solar cycle, both regarding the total irradiance and its relative components, UV radiation versus visible and other frequencies. [2],[3] This hypothesis is in accordance with evidence found in sediment cores, which suggest a correlation between variable solar irradiance and biomass.[4]

[1] Eydís Salome Eiríksdóttir and Sigurður Reynir Gíslason, 2020. *Efna- búskapur Þingvallavatns. Náttúrufræðingurinn* 90, pp. 65-79.

[2] Willson, R. C. et al., 1981. *Observations of Solar Irradiance Variability. Science.* 211 (4483), 700–2.

[3] Haigh, J. D. et al., 2010. *An influence of solar spectral variations on radiative forcing of climate. Nature.* 467 (7316): 696–9.

[4] Castagnoli G. C. et al., 1999. *700 Year record of the 11 year solar cycle by planktonic foraminifera of a shallow water mediterranean core. Adv. Space Res.* 24, 233-236.

P33

Element enrichment in synmagmatic fractures at the Sandfell laccolith, Fáskrúðsfjörður, Iceland

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Useful minerals containing rare Earth elements (REE) and metals are sourced from magma bodies, but exactly how these elements initially leave the magma is not well known. Here we present textural and chemical analyses of mineral-filled fracture bands within the rhyolitic Sandfell laccolith exposed in eastern Iceland (Fáskrúðsfjörður). The fracture fillings showcase dynamic and complex textures and imply multiple energy levels during precipitation. The dominant mineral phases are Fe- and Mg-oxides, Mn carbonate, and La/Ce oxide. The textures they present are comb, laminate, radial, and a rounded reworked clastic texture filling the tips. Microtomography images of hand-samples show the fractures are stretched-penny shaped, and contain 80 vol% fillings and 20 vol% void space. The connectivity of fractures within one band is limited to 1-3 neighbours, via small oblique fractures joining two main fractures together. μ XRF measurements revealed distinct halos of 0.8 wt% Fe depletion surrounding each fracture, and within the fracture-fill a strong enrichment in an unusual suite of elements including Fe, Mn, Cl, Zn, Cr, Y, Ce, and La. This is an unusual suite of elements, some of which are commonly immobile in aqueous fluids. There is also no evidence for hydrous alteration surrounding the fractures at Sandfell. Our working hypothesis is that the formation of the fractures provided a degassing pathway through the impermeable magma. However, the nature and the composition of the magmatic volatiles are as yet unknown. Complexities of the fractures in each band grade from single orientations (as shown here) to multiple orientations in one band, and finally into a complete breccia. The minimal connectivity between fractures in single-orientation bands suggests fluid would have travelled through the length of one to three fractures until intersecting with another fracture band system, while precipitating minerals along the way. Given the ubiquitous occurrence of the fracture bands within the entire laccolith, the small-scale process of mineral extraction and deposition compounds into large amounts of mass transfer overall. The fractures at Sandfell may be a snapshot of the initial process of removing incompatible elements from silicic magma.

P34

Paleoproterozoic Rajapalot Au-Co system associated with evaporites: Chemical composition and boron isotope geochemistry of tourmaline, and sulfur isotopes of sulfates, Peräpohja belt, northern Finland

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The Paleoproterozoic Raja Au-Co deposit in the Peräpohja belt, northern Finland is part of the wider Rompas-Rajapalot Au-Co mineralized area. Tourmaline is abundant mineral within the area, spatially associated with Au-Co deposits. Four texturally distinct tourmaline types were identified Raja Au-Co. All tourmaline types are classified as dravite and belong to the alkali-group and are $\delta^{11}\text{B}$ values and fractionation modelling indicates that at least two distinct fluids were responsible for the tourmaline formation with initial end member $\delta^{11}\text{B}$ values of the fluids at -8‰ and -1‰. Possible sources for boron rich fluids are Svecofennian orogeny related (ca. <1.9 Ga) metamorphic fluids and magmatic-hydrothermal fluids related to the late-orogenic ca. 1.78 Ga granitoids. A distinctive rock unit with bright purple anhydrite layers and white gypsum veins has been intersected by drilling. Anhydrite has $\delta^{34}\text{S}$ values in a narrow range from 8.1 to 9.8 ‰. Gypsum has slightly heavier $\delta^{34}\text{S}$ from 10.6 to 12.2 ‰. Significant similarities in textures and sulfur isotope values to well-known evaporite successions of the Onega basin, western Russia, strongly indicates the presence of evaporitic strata within the Peräpohja belt. The close spatial relationship of the Au-Co deposits and the evaporitic rocks indicates their important role as potential fluid and ligand source for the multi-stage metallogeny of the belt.

Trace element and isotope analyses of sulphide minerals in mineral deposit fingerprinting: A case study from the Petäjäseltä Au occurrence, northern Finland

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Geochemical and indicator mineral research methods are commonly used in mineral exploration in the glaciated terrains. Transported cover sediments such as unconsolidated till and upper soils are typically used in targeting the source areas and detecting sub-outcropping mineralizations. Pyrite is one the most common sulphide in various mineral deposits and during glacial transport, pyrite grains are refractory against weathering and can survive the transport. Trace element composition of pyrite is known to vary in different geological and ore-forming processes, thus making it potential mineral for fingerprinting. Advanced analytical techniques such as LA-ICP-MS allows detailed trace element and isotopic analyses with spatial resolution of few tens of microns.

In this study, we present results from in-situ trace element and sulphur isotope compositions of pyrite in heavy mineral separates and gold occurrences collected from the Petäjäseltä study area, in the Central Lapland belt, northern Finland. Pyrite compositions from heavy mineral separates are compared with pyrites from the gold occurrences, and capability of using pyrite for fingerprinting is evaluated. The study is a part of the first author's PhD project within the EIT Raw Materials funded 'Enhanced use of heavy mineral chemistry in exploration targeting' (MinExTarget) project. The goal of project is to develop effective indicator mineral concentration procedure and fingerprinting techniques using various minerals in tills which can be used in the greenfield exploration stages. Furthermore, the project develops a new service for mineral exploration by a novel combination of the available technologies of automated mineralogy and mass spectroscopy.

Metallogenic model of the sediment-hosted Cu deposits in the Kåfjord area, Alta-Kvænangen Tectonic Window, northern Norway

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Sediment-hosted Cu deposits account for about 20-25% of the global Cu production, 80% of the global Co production and 12% of the global Ag production. At the moment, the global production is mostly attributed to the Central African Copperbelt in Zambia and the Democratic Republic of Congo, the Polish Kupferschiefer deposits and the Chu-Sarysu Basin in Central Kazakhstan.

The Precambrian Alta-Kvænangen Tectonic Window (AKTW) in northern Norway also hosts numerous Cu occurrences. Some of those occurrences have been previously mined, but their mineralogical, geochemical and stable isotope characteristics have not been a subject of detailed investigations and therefore the relevant ore-forming processes are still poorly understood. This study brings new field observations as well as results of petrographical, geochemical, fluid inclusion and stable isotope investigations focused to the Cu mineralization in the Kåfjord area of AKTW.

The Kåfjord area hosts Cu occurrences in sedimentary lithologies of the Storviknes formation and in mafic lithologies of the Kvenvik formation. Both formations are regionally folded, with Storviknes formation lying stratigraphically above Kvenvik formation. The Cu mineralization predominantly occurs in form of epigenetic quartz-carbonate-sulphide veins. The mineralization hosted by the Kvenvik formation is characterized by a predomination of chalcopyrite and pyrite over other sulphide minerals. In contrast, the ore mineralization hosted by the Storviknes formation consists mostly of bornite and digenite with covellite and chalcopyrite as minor phases and shows an enrichment in Pb, Se, Te, Bi and Ag.

Syn-ore carbonates from the epigenetic veins in the Kvenvik formation show positive $\delta^{13}\text{C}$ values, indicating an influence of ^{13}C -rich carbonate layers formed during the Lomagundi-Jatuli Event. The $\delta^{13}\text{C}$ vs. $\delta^{18}\text{O}$ values of the epigenetic veins in the Storviknes formation reflect a marine carbonate signature. The $\delta^{34}\text{S}$ values of sulphides suggest that sulphur was predominantly derived from marine evaporites.

The fluid inclusion study revealed that the ore-forming fluids were NaCl-CaCl₂ aqueous solutions with salinities between 30 and 40 wt.% NaCl equiv. The homogenization temperatures range from 190 to 235°C. These high-salinity moderate-temperature fluids had a great capability to leach and transport copper in forms of Cu-chloride complexes.

The Kåfjord area of AKTW displays geological and geochemical characteristics typical for classical examples of sediment-hosted Cu deposits, with the Storviknes formation identified as the high-grade zone and the Kvenvik formation characterized as the low-grade zone.

ER6 - Basin analysis and sedimentology

P37

A possible Proto-Fram Strait gateway into the Arctic Ocean? – preliminary results from the Sedimentary Record of the early Cenozoic Buchananisen Group on Prins Karls Forland, Western Svalbard

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Our modern climate system is strongly influenced by the thermohaline circulation through the Fram Strait, where warm, Atlantic surface water flows into the Arctic Ocean, while cold, Arctic surface water returns southwards into the Greenland Sea. Even though it is generally accepted that the Fram Strait opened in the Miocene following the onset of seafloor spreading between Greenland and Svalbard, the precise timing and nature of this opening, and thus the onset of its influence on the climate system, is still poorly understood. This includes the hypothesis of an older gateway (Proto-Fram Strait) in this area, allowing for inflow and outflow of water masses from the Arctic Ocean also in the early Cenozoic.

A key area to study the hypothesis of an older gateway is the eastern side of the Fram Strait: onshore Prins Karls Forland, West of Spitsbergen. Here, the sedimentary infill of the Forlandsundet Graben is cropping out on the western and eastern side of Forlandsundet. A first field campaign during the summer of 2021 was focused on the sedimentology, paleoenvironmental reconstruction and age constraints of the early Cenozoic formations of Prins Karls Forland. We present the preliminary results of this fieldwork, including sedimentary logs and lithofacies of this basin infill, which range from terrestrial to deep marine deposits. We also discuss these results in relation to the possible opening of a Proto-Fram Strait.

P38

Work life relevance of earth science educations, the why and how.

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Through the iEarth centre for excellence in education (SFU) initiative the universities of Bergen, Oslo, Tromsø and the university centre in Svalbard's geoscience departments collaborate on various projects in developing earth science education. One of the objectives of iEarth is to enhance the work life relevance of earth science education. For this reason, we have established a national internship course for students in geosciences.

Over the last 10-15 years the employment market for geoscientists worldwide has changed rapidly. From more or less a

petroleum dominated future career for the majority of geoscientists, the situation today is in flux, with geoscientists going on to work in a broad variety of private and public sectors.

The culture within academia is to a various degree following the trends in the employment market. Students are vividly reporting on a mismatch between competence learned and competence asked in the employment market. Through various projects Norwegian universities are testing new ways of matching students with career learning and the potential for work life practice or internships during their studies. This raises the question of whether an increased focus on the characteristics of the job market, knowledge and training in work relevant skills and competence may lead to a better alignment between academic studies and future careers in earth science. The presentation showcases novel ways of matching work life practice and geoscience education, including the development of new 'generic skills' within the Earth Sciences such as programming and geomatics, providing practical workplace experience through internship placements, and striving to foster better dialogues and transfers of knowledge through student-active learning techniques.

P39

Architecture, fluid flow and deformation along a rift-bounding fault system, the Helmsdale Fault (Scotland)

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Within rift systems, the juxtaposition of clastic sediments at the hanging wall of basin-bounding normal faults to the crystalline basement is a recurrent structural setting in which hydrocarbon reservoirs can be found. Due to the large relevance that these normal faults exert on controlling the migration and trapping of fluids, it is important to understand their mechanical and petrophysical evolution during the slip history, with particular regards to porosity/permeability changes within the fault zone and in the surrounding rocks.

In this contribution we will report detailed field and microstructural observation along the Helmsdale Fault, a normal fault zone located in NE Scotland. The Helmsdale Fault was mostly active during the rift climax phase in the North Sea during Late Jurassic, and possibly underwent minor reactivation with a sinistral transpressive slip during the Tertiary. The study area includes a fairly continuously outcropping section of c. 5 km along the coast north of Helmsdale. The hanging wall consists of Upper Jurassic Boulder Beds (alternating clastic siltstone layers and debris flow and fault scarp deposit) that show widespread cementation and calcite veining sub-parallel to the main fault displaying numerous crack and seal events along the same structures. Within the footwall, extensive fracturing and veining in the Helmsdale Granite result in meter thick fault cores comprised of successive stacking of millimetre to centimetre thick calcite veins.

Ongoing analysis aim to provide information on formation temperatures of the calcite veins, composition of the associated (hydrothermal) fluids and control of structural complexities along the fault zone on fluid flow. The results will be compared with other nearby fault systems such as the Upper Jurassic Brae system in the Viking Graben or the Vingleia Fault Complex in the offshore Mid Norway.

IS2 - Computers and geosciences: Developments in modelling, machine learning, visualization and data repositories

P40

Automatic delineation of bedrock from sediments in geological maps using Deep Learning techniques

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Regional geological maps provide an important foundation for many fields in geology. Manual mapping of both bedrock and soils are time consuming and require extensive work both with remote sensed data and during field work. The first step in both bedrock and soil mapping is to delineate bedrock from sediments. This is normally done manually based on high resolution optical remote sensing images or Light Detection and Ranging (LiDAR) data, where bedrock can readily be discerned from sediments. Although a quite straightforward task to perform for an experienced geologist, it is very time consuming. There is thus much to gain from more time- and cost-efficient solutions. We therefore propose an automated approach to delineate sediments from bare bedrock.

We have tested deep learning, fully convolutional neural networks, and managed to automatically differentiate bedrock from sediments in southwestern Norway. A U-Net model was applied on two different sets of explanatory variables consisting of (a) terrain variables and (b) remote sensed Landsat 8 scenes. The results show very good visual match in the study area, with training accuracy 96-99% and validation accuracy at the average of 75% for terrain variables and 81% for Landsat 8. The resulting errors consisted mostly of false positive results. We conclude that our approach can be used to differentiate bedrock rapidly and precisely from sediments and thus can be a valuable tool for cost-efficient geological mapping of both bedrock and sediments.

IS4 - General contributions to geoscience

P41

Tephra records from NW Iceland: tephrochronology on a narrow spatial scale and new 14C dates

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Tephra horizons in Iceland, the results of frequent explosive volcanic eruptions, offer unique potential to accurately date natural and anthropogenic events and processes, as archived in sedimentary records, and correlate between study sites. Since its birth in the first half of the 20th century, tephra research has established a chronological sequence of widespread tephra layers of known age and source, many of which cover the majority of Iceland. These are often referred to as "marker tephra layers". The extensive research extends to marine, lacustrine and terrestrial sediments and soils and perhaps the source of layers that can be used as "marker tephra" is close to exhaustion. A problem here is that many layers which appear as distinct horizons may have limited spatial distribution or originate from volcanic systems where eruptions are frequent and produce tephra with (near-)identical geochemical composition. A possible way to circumvent this problem is to establish detailed records over narrower spatial scales, where tephra horizons can be dated and placed into an established marker tephra record. Advances to the tephrochronological record can also involve the refining of age-determinations of known layers. Radiocarbon dates for a number of marker tephra layers were established before the AMS technique was developed or were performed using materials that have since proven ill-suited for this purpose. Here we present tephra records from a series of sites in Austur Húnavatnssýla. Our results demonstrate the presence of a basaltic Katla tephra, radiocarbon dated to around 6600 cal. yr BP, that can be observed as a distinct horizon in the region. Further, we present new radiocarbon dates for the marker tephra layers Ssn2 (Snæfellsjökull) and Hekla 5.

P42

Identification of Marine Geohazards with the use of NEANIAS service

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Seafloor mapping has been encouraged by many national and international initiatives and culminated in the declaration of the Decade of Ocean Science for Sustainable Development (2021-2030) by the United Nations, 2017. Knowing the depth

and the type of seafloor is crucial for understanding the marine environment. Moreover, coastal management, habitat loss, underwater cultural heritage, marine resources and offshore installations have underlined the need for charting the seabed. However, one of the most important fields of application of seafloor mapping is the recognition and characterization of geohazard features to perform a comprehensive seafloor geohazard assessment. Therefore, bathymetric data are fundamental for various scientific and professional communities, but handling and processing these data requires specific knowledge mainly possessed by researchers operating in the field of hydroacoustics.

NEANIAS Underwater thematic services implement Open Science procedures through the European Open Science Cloud (EOSC). The services produce user-friendly, cloud-based solutions addressing bathymetry processing, seafloor mosaicking and classification. More specifically, the Bathymetry Mapping from Acoustic Data (UW-BAT) service provides a user-friendly and cloud-based edition of the well-known open-source MB-System, via Jupyter notebooks. The goal is to reach a broader audience of users interested in ocean mapping, like geoscientists, biologists, oceanographers, environmental engineers, technicians, renewable energy planners, and more. This service produces bathymetric grids and maps after processing the data through a flexible and fit-for-purpose workflow by implementing sound speed corrections, applying tides, filters and choosing the required spatial resolution. MB-System is used worldwide in many institutes and universities as a bathymetry and backscatter post-processing tool for multibeam data sets. It is on a technology readiness level (TRL) 6, has been validated using different data sets from various vendors and is under constant maintenance through the open-source community. Nevertheless, due to its numerous software dependencies, MB-System requires a certain knowledge of the operating systems Unix/Linux and the command line-based installation and execution of the different packages.

Therefore, NEANIAS UW_BAT service, by exploiting cutting-edge technologies, provides highly accurate results, regardless of the level of expertise of the end-user, and reduces the time and cost of the processing.

P43

The Atmo-Stress service: a new web-designed software to reconstruct stress trajectories

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The reconstruction of stress and paleostress trajectories of an active tectonic area is essential to study: *i*) its evolution and kinematics, and *ii*) seismic and volcanic hazard assessment.

Here, we present the so-called Atmo-Stress service, available at <https://atmo-stress.neanias.eu/>, a brand-new software developed in the framework of the NEANIAS Project (<https://www.neanias.eu/>), EU H2020 RIA. This is an open-source cloud service, present on the GARR Kubernetes platform, that will allow to reconstruct stress trajectories in plain view, based on the already existing software *Lissage*, by Lee and Angelier (1994).

The service considers a specific type of stress (e.g., σ_{Hmax} , or σ_{Hmin}) as input data, and will use these data to interpolate the stress trajectories over the whole area in plain view. Input data can be derived from different sources (e.g., field data, focal mechanism solutions, in-situ geotechnical measures), and they must be uploaded as .txt or .xls file format, that should provide the geographic coordinates, the stress azimuth and the angular error. Interpolation can be carried out using two different methods (Polynomial and Distance Weight), at the user's choice, and can be conducted from a local to a regional scale. Results can be downloaded as grid or trajectory maps and are compatible with both GIS software and Google Earth.

Given its usefulness in tectonic and volcanic active areas, the service is designed for both academics and non-academics purposes and can be used in different fields, like research activity, oil and gas industry and natural hazard prevention and management planned by national institutions, such as Civil Protection.

P44

The Goldschmidt Laboratory – a new infrastructure for microanalyses and high precision geochronology in Norway

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The Goldschmidt Laboratory is a national infrastructure funded by Norwegian Research Council, and is an integrated laboratory for microanalyses, high-resolution imaging, and high-precision geochronology. The Goldschmidt Laboratory comprises a high-end scanning electron microscope SEM laboratory at the University of Oslo (UiO), and U-Pb TIMS and Ar-Ar NGMS laboratories, located at UiO and Geological Survey of Norway (NGU), Trondheim respectively. The SEM laboratory at UiO consist of a Hitachi tabeltop SEM and a Hitachi FE-SEM with Bruker EDS and HR EBSD collectors and a Delmic Sparc CL system. The SEM lab is already in operation and can be accessed by international user through the EXCITE network, a European infrastructure initiative for scientists using electron- and X-ray imaging techniques. New state-of-the-art mass spectrometers from IsotopX have been installed in Oslo and Trondheim during the Autumn 2021, and is currently starting to operate. At UiO a new ISO4+ clean lab is currently being constructed, and the U-Pb TIMS laboratory should be operational by the early summer 2022. The new clean lab combined with the latest mass spectrometer detector technology will allow analyses of small concentrations of Pb at increased precision, applicable to e.g. small grain sizes, grain fragments, and young rocks. At NGU, the Ar-Ar NGMS is equipped with CO₂ Diode and a UV excimer laser from Teledyne Photon Machines, allowing geochronological analysis where high spatial resolution is required (150 -1µm spots) The Goldschmidt Laboratory will be also open for international projects, and applications to use the laboratories should be submitted through our booking system on our web site (<https://www.mn.uio.no/geo/english/research/goldschmidt/>).

P45

SEducate plugin for sedimentology courses

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Active learning in education, which focuses on a student-centered learning environment has been shown to improve students' learning outcomes through increased engagement in the classroom. In sedimentology courses however, there are few documented uses of active-learning methods. Moreover, the ones that exist are primarily focused on virtual field trips based on digital outcrop models and core or field photography. Far rarer still are teaching resources that are appropriate for an introductory course curriculum to teach students the foundations of sedimentology such as making observations, performing interpretations and analysis of different depositional environments. The sEDucate project aims to narrow this knowledge gap by creating tailored sedimentary log exercises for an interactive and active-learning environment that will engage and provide feedback to students in a geographical information system (GIS).

Here we present the current progress of the SEducate project including a set of algorithms written in the python programming language for creating tailored sedimentary log exercises and assessments for students. The algorithms allow for the creation of seven different environments: floodplain, fluvial, shallow marine, deep marine, eolian, alluvial and lacustrine. Each log creation adheres to the grainsize distributions, lithology, sedimentary structures, and bed boundary conditions for the different environments. Based on the classification of modern sedimentary environments mapped from satellites, we can create several random logs that correspond to the observed environments which a student may use to interpret. This allows students to learn to describe and interpret sedimentary logs but also to learn the subtleties in defining the lateral transition in sedimentary environments.

Current and future work deals with building a user-friendly QGIS plugin. A future goal is to incorporate more complex sea-level, tectonic and paleocurrent scenarios in the creation of the tailored sedimentary logs. When completed, the new QGIS plugin will be implemented in a wide range of exercises and assessments as either individual or group-based work and complement existing sedimentology course curriculums for an active-learning environment.

P46

Improving teaching quality through student-based course evaluation

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This poster will focus on experiences with student-based course evaluations. Course evaluations by the iEarth student organization at the University of Bergen have been conducted through discussions between iEarth students and groups of 5-7 students. This form of evaluation has been developed and improved since 2020. The guidelines of these discussions are a set of questions put together in cooperation between iEarth students in Bergen and the educational staff. The iEarth students are currently trying to implement this type of evaluation in other universities across the country.

A non-formal discussion among fellow students is valuable since the students often express a lot more opinions and experiences compared to a digital standard evaluation form. This helps to realize that they can contribute to improvements regarding teaching, and how important this is. This is also assumed to encourage them to give feedback directly to the teacher. The iEarth students conducting the evaluation are usually at different stages of their education, so experiences can be shared, and knowledge can be transferred. The evaluation ends in a report with the collected data that is presented and discussed with the course responsible.

P47

Student and staff co-creation – How to develop geoscience education together

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A teacher can improve a course; students and teachers working together can revolutionise it.

It all started in Spring 2020 when a group of students asked the teachers for a meeting to discuss the introductory course in geology and geography, GEO1110, at the University of Oslo. The outcome of the meeting was that five students from three different years got employed as student consultants to collaborate with the teachers to improve the course.

We started with looking at the course structure to ensure the course's modules were built on each other, and on the students' previous knowledge. As the course ran, we had continuous meetings to discuss what was working and what could be improved further.

Both the students and staff involved in the project felt they were a part of something important. The student consultants understood that they could contribute to improving their own education, and they arranged extra afternoon lectures in Geographic Information System (GIS) and field report writing. The high degree of student involvement in the course seemed to inspire the course's students when they arranged their own field trip and invited fellow geophysics students. The co-creation project also initiated a course representative project that now is running in many of the Bachelor courses at the Department of Geosciences, UiO.

What started as a meeting initiated by frustrated geoscience students is now about to revolutionise how the students and teachers together develop geoscience education.

P48

Photogrammetric 3D Modeling for Geological Tunnel Investigation in Rapakivi Area

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This study reviews photogrammetric application for geological tunnel documentation both in scientific and engineering purposes. Photogrammetry is one of the digital mapping methods effectively to create 3D surface models and to provide information of geological structures for various geotechnical and rock mechanical construction projects. This study comprehends an operating railway tunnel of 180 m length without a shotcrete lining in anorogenic 1.6 Ga rapakivi area in southeast Finland.

The rapakivi granite is homogenous and unfoliated crystalline bedrock domain showing distinct jointing pattern which makes the objective very approachable. The aim is to create a structural geological 3D model which acts as a basis for discrete fracture network (DFN) model and further analysis. Possibility to map and gather geological information in a 3D environment considerably improves the output models.

Methodology covers of taking over 4 000 overlapping images inside the railway tunnel covering the whole cross section. A software Agisoft Metashape was used to perform photogrammetric processing of the digital images and to generate 3D spatial data. Point cloud data was processed with the CloudCompare software. Finally, trace lines and planes of joints and fractures were digitized from the georeferenced point cloud.

The purpose of the study is to create a structural geological 3D model of the area to enhance the engineering and scientific understanding of the site. The created photogrammetric 3D model had excellent quality for example to detect joint spacing, moist rock surfaces and to inspect existing tunnel structures. A total of 1 200 joints and fractures were measured with CloudCompare including dip and dip direction. Observed joint orientations reflect typical orthogonal cross joint pattern for rapakivi granite (trending SW-NE and NW-SE and dipping 75-89° with additionally horizontal jointing). Several nearly vertical faults were detected with moist surfaces.

This study concludes the importance of digital geological documentation in tunnel construction projects. After the tunnel is reinforced with shotcrete the initial geological 3D model plays a prominent role for afterward rock mass investigation and guiding for example post grouting design. The geological 3D model also acts as a fundamental basis for fracture network characterization and hydrogeological modeling which then can be applied to future DFN models.

P49

The relationships between metamorphic conditions and aggregate properties of meta-granite and -gabbro

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Granitic rocks are common raw materials for rock aggregates aimed at the construction of roads and railroads. Gabbroic rocks typically make up a secondary component of the same bedrock but are occasionally blended during the production stage of crushed aggregates. Although the performance of a rock material relies on both its constituent minerals and its fabric, i.e., texture and structure of the rock, determinations of technical properties rarely emphasize the geological processes that produce the different textures, fabrics, and mineral assemblage.

This study evaluated the variation in resistance to fragmentation (Los Angeles-value, LA) and wear/abrasion (Micro-Deval-value M_{DE}) for the fraction 10/14 mm of metamorphosed granite and gabbro at different metamorphic conditions. Samples were collected along a 150 km profile across the Eastern Segment of the Sveconorwegian Province in Scandinavia, where metamorphic conditions grade from epidote amphibolite- to high-pressure granulite-facies. The degree and type of metamorphic recrystallization vary with both temperature and the availability of hydrous fluid.

The investigated felsic and mafic rocks show systematic variations of the technical values as a function of macro-fabric and microtexture, reflecting the metamorphic temperature gradient from east to west. The lowest-grade rocks in the east and the highest-grade rocks in the west recrystallized under relatively dry conditions and show uneven-grained fabrics and high-complexity of grain boundaries. Under these conditions, meta-granite and -gabbro have the highest resistances to brittle fragmentation and wear. By contrast, rocks that recrystallized and deformed under mid- to upper-amphibolite-facies conditions have high LA-values and M_{DE} -values. The influx of water during the recrystallization resulted in even-grained and non-complex fabrics. For example, most analysed amphibolites are suitable as unbound layers only. Partially molten rocks, such as stromatic migmatite gneiss and migmatitic amphibolite yielded the poorest technical performances.

RS1 - Remote sensing of the cryosphere

P50

Monitoring ice-calving at the Astrolabe glacier (Antarctica) with seismological and Sentinel-2 satellite data

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Better understanding the global (e.g. ice mass balance, ice motion) and local (e.g. fissures and calving processes, basal melting, sea-ice interactions) dynamics of tidewater Antarctic outlet glaciers is of paramount importance to simulate the ice-sheet response to global warming. The Astrolabe glacier is located in Terre Adélie (140°E, 67°S) near the Dumont d'Urville French research station. In January 2019, a large fissure of around 3km has been observed in the western shore of the glacier which could lead to a calving of ca. 28 km². The fissure has progressively grown until November 2021 when an iceberg of 20 km² was released by the glacier outlet.

The location of the glacier outlet at the proximity of the Dumont D'Urville French research station is an asset to collect in-situ measures such as GNSS surveys and seismic monitoring. Satellite optical imagery also provides numerous acquisitions from the early 1990 till the end of the 2021 thanks to the Landsat and Sentinel-2 missions.

We used two monitoring techniques: optical remote sensing and seismology to analyze changes in the activity of the glacier outlet. We computed the displacement of the ice surface with MPIC-OPT-ICE service available on the ESA Geohazards Exploitation Platform (GEP) and derived the velocity and strain rates from the archive of multispectral Sentinel-2 imagery from 2017 to end of 2021. The images of the Landsat mission are used to map the limit of the ice front to retrieve the calving cycle of the Astrolabe. We observe that the ice front is significantly advanced toward the sea (4 km) since September 2016 and such an extension is not observed in the previous years (since 2006) although minor calving episodes occurred. The joint analysis of the seismological data and the velocity and strain maps are discussed with the recent evolution of the glacier outlets. The strain maps show complex patterns of extension and compression areas. The number of calving events detected in the seismological dataset significantly increased during 2016-2021 in comparison with the period 2012-2016. Since the beginning of 2021, both dataset show an acceleration. The number of calving events increased exponentially from June 2021 to the rupture in November 2021 and the velocity of the ice surface accelerate from 1 m.day⁻¹ to 4 m.day⁻¹ in the part of the glacier that detached afterward. We discuss the recent evolution of the glacier with the meteorological data available. This calving event is the first one of this magnitude documented at the Astrolabe glacier.

RS3 - Earth observations for marine and coastal environments

P51

Evidence of Weichselian slide events preserved in the northern Storegga Slide area, off Mid-Norway

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This study is focusing on data from the north-eastern part of the Storegga Slide area, and the morphologies/features preserved both within the failed and the undisturbed areas of the upper continental slope. The new analyses are based on swath-bathymetry data (10 & 15 m cell size, MAREANO) and a number of high-resolution 2D seismic lines (TOPAS/Chirp, University of Bergen & MAREANO). The most prominent feature in the dataset is the slide scar related to the 8.2 ka Storegga Slide mega-scale event, which have affected the southern part of the study area, apart from a small raft/block of ~3.3 km² with undisturbed sediments. We observe evidence of three events older than 8.2 ka, two on the upper and one on the lower slope, here named as Nyegga, Lillegga, and Halten Slide. The Nyegga Slide has previously been identified as a glaciogenic debris flow (GDF). The headwall of the Nyegga Slide is located along the present-day shelf edge, and a run-out distance of ~24 km has been estimated. Furthermore, Nyegga Slide seems to have affected an area of ~175 km². Based on the age estimation of seismic reflectors established by Reiche et al. (2011), has this event been dated to ~20 – 21.8 ka. The Lillegga Slide has been partly eroded by the 8.2 ka Storegga Slide event. The Lillegga Slide has been tentatively dated to 19 – 21 ka (weighted towards the older part of the estimate). On the lower slope (at ~1000 m water depth) we have found a third slide, the Halten Slide, which looks significantly older than 22 ka. The age of this slide is still uncertain, but tentative estimated to be 30 ka or older. In addition, are a series of furrows/cracks observed on the seafloor outside of the Storegga Slide scar (previously described by e.g. Gravdal et al., 2003; Hjelstuen et al., 2010; Reiche et al., 2011). The cracks are a few meters deep and several kilometers in length. The cracks can be followed several 10s of meters below the seabed (continue beyond the seismic range), and affect both GDFs, glaciomarine sediments, and the lower part of the Holocene unit. The development of the cracks is likely related to the removal of sediments during the 8.2 ka Storegga Slide failure, and their size and number highlight a clear potential for future events in the Storegga Slide area.

POSTERS
RS3

P52

MAREANO – Mapping the Norwegian sea floor

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The Norwegian seabed mapping programme MAREANO (www.mareano.no) has since its establishment in 2005 mapped over 287 660 km² in the Norwegian and Barents Seas. This national, interdisciplinary programme is a collaboration between the Geological Survey of Norway (NGU), the Institute of Marine Research and the Norwegian Mapping Authority. MAREANO investigates predefined vulnerable and valuable bottom areas, and produce thematic geological and biological maps, contributing to a sustainable and knowledge-based management and commercial development of the Norwegian sea floor.

Geological seabed maps made by NGU include maps of sediment grain size and genesis, sedimentary environments, and landforms. The maps are delivered based on terrain and stratigraphical analyses of detailed bathymetry maps, backscatter, sediment samples from the seabed (grabs, boxcores and multicores), video footage and high-resolution seabed sediment profiles.

In this study we present data from Garsholbanken, a glacially influenced sedimentary environment on the mid-Norwegian shelf. The sea floor geomorphology is dominated by glacial landforms, including moraines, mega-scale glacial lineations and hill-hole pairs.

RS4 – Use of Remote Sensing for geological mapping

P53

Geomorphological Mapping of a Paraglacial Slope Instability at the Southeastern Tindfjallajökull Glacier, Iceland

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A paraglacial slope instability has been detected by an outlet glacier at the southeastern part of Tindfjallajökull glacier, Iceland. A geomorphological mapping of the slope and the outlet glacier was conducted in order to determine the scale, possible causes and consequences of the deformation. A comprehensive literature review on paraglacial induced mass movement activity was conducted along with remote sensing methods for geomorphological analysis of the area throughout the 20th century. It was concluded that the process investigated resembles a paraglacial induced Deep Seated Gravitational Slope Deformation that has the potential to turn into a rapid slope failure. Further research is needed in order to confirm these findings and special emphasis should be put on field monitoring of the area while the process is still active. Results indicated that the retreat of the outlet glacier has an effect on the slope's stability. The glacier is expected to continue its retreat at an exponential rate as global climatic warming is expected to continue. Climate change has and will most likely cause these processes to become more common in the future with a possible increase in paraglacial environments. In some cases, these processes are cause for concern as secondary effects such as Glacial Lake Outburst Floods (GLOFs) or tsunamis can pose severe natural hazards.

Author Index

NAME ABSTRACT NO

A

Aakala, TuomasEC1-05
 Aaltonen, IsmoER5-12
 Aasly, KurtAG1-06, PL-2
 Abersteiner, AdamIM1-04
 Adamczyk, AleksanderEC2-05
 Aðalgeirsdóttir, GuðfinnaPL-3
 Ahlberg, AndersIS4-04
 Ahmed, MahidIS1-02
 Aiuppa, AlessandroIM1-14
 Alexanderson, HelenaEC3-20
 Allaart, LisEC3-15
 Alsan, GökhanRS2-01
 Alvarez Zarikian, CarlosUV3-03
 Alvarez Zarikian, Carlos A.UV3-02
 Amon, LeeliEC3-14
 Andersson, Joel B.H.ER5-04
 Andrew, DugmoreEC2-02
 Anell, IngridER6-09, EC3-09
 Annesley, R. IrvineIS2-01
 Aradóttir, NínaEC2-03, EC3-04, EC2-04
 Arellano, SantiagoUV1-03
 Ari Halldórsson, SæmundurGT6-01
 Armadillo, EgidioER1-04
 Arnadóttir, Erna ÓskEC3-12
 Askew, Robert A.RS4-03, UV2-08, UV2-05, UV4-08
 Atakan, KuvvetIS2-05, IS2-04
 Augland, Lars EivindER6-10, IM1-13
 Auri, JaakkoEC3-10
 Avery, RachaelEC3-03
 Axelsson, GuðniER1-02
 Ágústsdóttir, ThorbjörgGT2-04, GT1-04
 Ágústsdóttir, ÞorbjörgUV1-02
 Ágústsson, KristjánGT1-06, GT1-03
 Árnadóttir, SigurveigUV4-05
 Árnason, ÁrniER5-06
 Ásbjörnsdóttir, LovísaIS3-01

B

Baadshaug, UlfIS2-04
 Bäcklund, PiaGA1-12
 Bailo, DanieleIS2-05
 Baker, DonUV4-03
 Bakke, JosteinIS4-07
 Bali, Eniko ..GT1-03, IM1-18, IM1-11, IM1-14
 Bally, PhilippeRS2-06
 Balsamo, FabrizioGT6-09
 Balzer, DirkGA1-17
 Baqué, MickaelIS1-02
 Baranwal, Vikas ChandAG1-02
 Barbee, OliviaUV4-04
 Bark, GlennIS4-11
 Barker, AbigailUV4-06, GT1-01
 Barnes, JaimeIM1-18
 Barnie, TalfanUV1-03, UV4-01
 Barrett, RachelEC3-07
 Barry, Peter H.IM1-11
 Barsotti, SaraGA1-08, GT1-04, UV1-03, UV1-04
 Barsotti, SaraUV1-06
 Batchelor, ChristineEC3-07
 Bauer, E. TobiasIS2-01
 Bauer, Tobias E.ER5-04
 Bazargan, MohsenER1-07
 Beach, TimothyEC2-02
 Becher, MarinaEC1-03

NAME ABSTRACT NO

Beier, ChristophIM1-01, IM1-04, IM1-05
 Belart, Joaquin M. C. RS2-05, RS4-04, RS2-07
 Bellwald, Benjamin .ER6-07, EC3-07, EC3-09, EC3-06
 Ben-Asher, MatanEC4-03
 Benediktsson, Ívar ...EC3-04, EC3-12, EC2-04, EC2-03
 Bennedsen, LarsER3-05
 Ben-Yehoshua, DanielGA1-10, GA1-03, EC2-04, RS2-05
 Berastegui, Rosa MariaGA1-14
 Berg, Sylvia EUV2-04
 Bergh, SteffenGT6-05
 Bergh, SteffenRS2-02
 Bergur, SigfússonPL-5
 Bergvik Bredal, MarieRS2-02
 Bergþórsdóttir, IngibjörgIM1-09
 Bernd, EtmüllerGA1-15
 Berndt, ChristianER6-07, UV3-03, UV3-02
 Berthier, EtienneRS2-07
 Berthier, EtienneRS2-05
 Betlem, PeterUV3-03
 Bezerra, Francisco H.R.GT6-09
 Bhiry, NajatGA1-06, GA1-22, GA1-13
 Bindeman, IlyaUV2-03
 Bitetto, MarcelloIM1-14
 Bjerg, PoulER3-05
 Björdal-Olsen, StineER6-08, EC3-08
 Björklund, LennartIS4-12
 Björnsdóttir, SnædisIS1-01
 Björnsson, HalldórEC1-01
 Bjørnstad, AndersER2-05
 Blischke, AnettGT6-01, UV4-05
 Blomdin, RobinEC3-17
 Bock, JosuéEC4-03
 Boehme, MartinaGA1-17
 Boissier, EnguerranRS2-06
 Boldreel, Lars OleER2-02
 Bonali, Fabio LucaGT6-10
 Bording, ThueER1-06, ER3-05
 Braathen, AlvarER6-04, ER6-15, ER6-09, GT5-05, ER2-06, GT6-03
 Brandsdóttir, BryndísEC3-02, GT6-01
 Brattebø, Elena VictoriaIS4-03
 Braut, HildeER6-06
 Bredal, MarieER1-11, RS2-01
 Brekke, HaraldER4-03
 Brown, CatherineIS4-13
 Brown, Eric L.GT6-01
 Brunstad, Harald ..ER6-01
 Brynjarsson, BaldurER1-05
 Brynjólfsson, Skafti EC2-03, GA1-19, EC3-15, EC3-04
 Brynjólfsson, SveinnGA1-19, GA1-18
 Buchardt, BjørnER3-02
 Buenz, StefanUV3-02, ER6-07
 Buitter, SusanneGT6-02
 Bünz, StefanEC3-06
 Burchardt, SteffiUV4-06, ER1-07, GT1-01, UV2-04, GT1-02
 Burrige, GlenER1-01, IS3-03, IS4-08
 Butcher, AlanIM1-15, UV4-04, IS4-11
 Butcher, FrancesIS1-03
 Bøe, ReidulvRS3-01
 Bøgh, AnnaUV4-07

NAME ABSTRACT NO

C

Callegaro, SaraUV4-03, IM1-10, IM1-19
 Calner, MikaelER3-04
 Capobianco, VittoriaGA1-05, GA1-16, GA1-14
 Capriolo, ManfredoIM1-19, UV4-03
 Caracciolo, AlbertoIM1-14, IM1-18
 Carlson, Richard W.IM1-07, IM1-08
 Chamberlain, KatyUV4-04
 Chatterjee, SayantaniUV3-03
 Chiarella, DomenicoER6-05
 Christensen, Jon MagnusIS2-04
 Christensen, JørgenER3-05
 Christiansen, Flemming G.ER5-09
 Church, NathanAG1-06
 Ciraula, DanielER1-06
 Clark, DeirdreER2-08, PL-5
 Cloutier, DanielleGA1-13
 Coldwell, BeverleyUV4-04
 Cole, Rosie P.UV2-08
 Colin W., DeveyIM1-05
 Colleoni, FlorenceGT5-04
 Collier, RichardER6-13
 Conrad, Clinton P.GT6-01
 Conway, SusanIS1-03, EC4-04
 Cook, JeremyIS2-04
 Coratza, PaolaIS3-02
 Corfe, IanUV4-04
 Corti, NoemiGT6-10
 Costa, AntonioGA1-08
 Cowling, Owen C.EC3-15
 Coxall, Helen K.GT6-01
 Csuka, JoleenIS1-02
 Cumming, WilliamER1-04
 Czekirda, JustynaEC4-01

D

Dagestad, AtleAG1-02, ER1-11
 Dahm, TorstenGT1-03
 Dal Corso, JacopoUV4-03
 Dannberg, JulianeGT6-01
 David, ChristianER3-04
 Davidson, JonathanER1-07
 Davie-Martin, Cleo L.EC1-07
 Dawson, KyleER1-09
 De' Michieli Vitturi, MattiaUV1-06
 Decaulne, ArmelleGA1-13
 Decaulne, ArmelleGA1-06, GA1-22
 Deegan, FrancesUV2-03
 Deegan, Frances M.IM1-19
 Dehls, JohnER1-11, RS2-01, IS2-04
 Deline, PhilipEC4-04, EC4-03
 Deryabin, AlexeyER6-06
 Devey, ColinGT6-01
 Diomidis, NikitasER5-12
 Doin, Marie-PierreRS2-06
 Dr Evans, SianER2-04
 Dr Vallius, HenryRS3-02
 Dr. Ágústsdóttir, ÞorbjörgGT2-03
 Dr. Hjörleifsdóttir, ValaGT2-03
 Drouin, VincentGT1-05, RS2-03, GA1-20, GT1-06, RS2-07, GT1-03, GT1-04
 Ducrocq, CécileGT1-05
 Dunkel, KristinaIS1-01
 Dunkl, IstvanGT6-08
 Dunning, StuartEC4-04
 Dürig, TobiasRS2-05
 Dypvik, HenningIS1-01

NAME	ABSTRACT NO	NAME	ABSTRACT NO	NAME	ABSTRACT NO
E					
Eberli, Gregor P.	ER6-12	Gawthorpe, Rob	ER6-13	Hansen, Louise	AG1-02
Eddudóttir, Sigrún Dögg	UV2-09	Gawthorpe, Robert	ER6-14	Härmä, Paavo	IS3-05
Eide, Christian Haug	UV4-07, ER6-02, EC1-04	Geirsson, Halldór	GT1-05, RS3-04	Harstad, Andreas Olaus	IM1-10
Eidsvíg, Unni	GA1-14	Geirsson, Halldór	ER1-09, GT1-04, GT1-02, GT1-06	Hartley, Margaret	IM1-18
Eilertsen, Raymond	GA1-17	Georgiopolou, Aggeliki	UV3-04	Haugen, Ellen E. D.	RS2-04
Einarsson, Bergur	GA1-09	Geppert, Wolf	IS1-02	Haugen, Maria	ER6-09
Einarsson, Páll	UV2-01, RS2-05, GT6-10, UV1-01, GT1-04	Gernigon, Laurent	ER6-07	Hauksdóttir, Erla María	AG1-03
Eiríksson, Jón	UV2-09, EC3-12	Gestsson, Einar	ER1-07	Heap, Michael J.	ER1-07
Ellefmo, Steinar L.	PL-2	Ghione, Federica	GT2-01	Heikkilä, Pasi	UV4-04
Elvenes, Sigrid	RS3-01	Gies, Nils	RS2-05	Heimann, Ariel	UV4-09
Engelschön, Victoria Sjøholt	ER6-03	Gilbert, Graham	GA1-14	Heimann, Sebastian	GT1-03
EPOS ICS, Team	IS2-05	Gilbert, Graham L.	GA1-05	Heimdal, Thea Hatlen	IM1-10, IM1-19
Eriksen, Sissel	ER4-01	Gilmullina, Albina	ER6-02	Heinonen, Aku	IM1-01
Erlendsson, Egill	UV2-09	Gislason, Sigurdur R.	PL-5	Heinonen, Jussi S.	IM1-07, ER5-05
Erlendsson, Ögmundur	ER5-06, GT6-01	Gislefoss, Lina	EC3-18	Helgadóttir, Helga Margret	ER1-06, ER2-08
Erlingsson, Sigurður	GA1-03	Gíslason, Fannar	GT5-02	Helgason, Jón Kristinn	GA1-04, GA1-19, RS2-03, GA1-20
Eshelman, Evan	ER4-02	González-Maurel, Osvaldo	IM1-15	Hellebrand, Eric	IS1-02
Eskola, Kari Olavi	EC3-11	Goodfellow, Bradley W.	EC3-17, EC3-19	Hellevang, Helge	IS1-01
Etzelmüller, Bernd	GA1-15	Gradmann, Sofie	AG1-02	Hennig, Benjamin	IS2-06
Etzelmüller, Bernd	EC4-01	Greenwood, Sarah	EC3-03, EC3-17	Hermanns, Reginald	GA1-03, EC4-04, PL-4, GA1-17
Evans, David	IS2-07	Greiner, Sonja	GT1-01, UV4-06, GT1-02	Hermanowski, Piotr	EC2-08
Eyjólfsson, Vigfús	UV2-01	Grenier, Jérémy	GA1-22, GA1-13, GA1-06	Hersir, Gylfi Páll	GT1-03, UV1-02, GT1-06
F					
Fabregas, Natacha	ER6-13, ER6-14	Gresseth, Julie	GT5-05	HERVE, Garance	UV4-02
Faleide, Jan Inge	UV3-02, ER6-07	Gresseth, Julie Linnea S.	GT6-03	Hestnes, Åse	GT6-08
Farnsworth, Wesley R.	UV2-09, EC3-15, EC2-04, EC3-20, EC2-03	Grímsdóttir, Harpa	GA1-19, GA1-20	Hickey, James	UV4-04
Fiandaca, Gianluca	ER1-06, ER3-05	Grundvåg, Sten-Andreas	ER6-03	Hieronimus, Christoph	ER1-07
Filina, Irina	UV3-03	Grönholm, Pentti	IM1-12	Hietala, Satu	ER5-10
Filla, Sara	GA1-05	Grönvold, Karl	IM1-11	Hjaltadóttir, Sigurlaug	GT1-04
Fitton, Godfrey	UV4-08	Grøtan, Bjørn-Ove	IS2-04	Hjartardóttir, Ásta Rut	UV2-01, RS2-05, GT6-10
Flóvenz, Ólafur	GT1-03, UV1-02	Guðfinnsson, Guðmundur	IM1-14	Hjartarson, Árni	ER1-03, UV4-05
Foged, Niels	EC4-02	Guðmundsdóttir, Esther Ruth	UV2-09	Hjorth Dundas, Siv	ER4-04
Folch, Arnau	GA1-08	Guðmundsson, Magnús T.	RS2-07	Hjörleifsóttir, Vala	ER1-10
Fonnes, Gro	IS2-04	Guðmundsson, Magnús Tumi	IM1-03, UV1-04, RS2-05, UV1-01	Hjörleifsson, Einar	GA1-09
Ford, Mary	ER6-14, ER6-13	Guðnason, Egill Árni	GT2-03, GT2-04	Hlidar Jensen, Esther	GA1-20
Fortin, Jérôme	ER3-04	Guðfinnsson, Guðmundur	IM1-18, IM1-11	Hobé, Alex	ER1-07
Forwick, Matthias	EC3-05, EC3-08, RS3-03	Guðlaugardóttir, Hrefna	IS1-02	Hodgskiss, Malcolm	ER6-01
Fourel, Loic	GT6-02	Guðmundsdóttir, Esther Ruth	EC3-12	Hokka, Janne	ER5-07
Franzson, Hjalti	ER5-06, ER5-02	Guðmundsson, Ásgrímur	GT1-06	Holden, Nora	ER2-06
Friðleifsson, Guðmundur Ómar	ER5-02	Guðmundsson, Magnús Tumi	UV2-08	Holm, Paul Martin	UV2-06
Friðriksdóttir, Hildur María	GT1-05	Guðnason, Egill Árni	GT1-03, UV1-02	Hooper, Andrew	GT1-05, GT1-04
Friðriksson, Þráinn	ER1-10, ER1-03	Gunnarsdóttir, Sveinborg Hlíf	ER2-08, ER2-07	Hopper, John R.	UV3-04, GT6-01
Frieling, Joost	GT6-01	Gunnarsson Robin, Jóhann	ER2-07, IM1-11, IM1-14	Horálek, Josef	GT1-03
Frogner Borge, Amund	GA1-02	Gunnarsson, Andri	RS2-05	Horálek, Josef Horálek	GT1-04
Frumkin, Amos	UV4-09	Gunnarsson, Gunnar	ER1-08, ER1-10	Houghton, Bruce F.	UV2-08
Fuchs, Michael	GA1-17	Gunnarsson, Hjalti Steinn	GT2-03	Hólmgeirsdóttir, Þorbjörg	AG1-03
Funatsu, Beatriz	GA1-06	Gustafsson, Ludvik E.	UV2-04	Hreinsdóttir, Sigrún	GT1-06
Funck, Thomas	UV3-04	Gyllencreutz, Richard	ER2-09, RS3-04	Hreinsdóttir, Sigrún	GT1-05
Furze, Mark F. A.	EC3-20	Gyllencreutz, Richard	EC3-17	Hreinsdóttir, Sigrún	GT1-04
G					
Gaina, Carmen	GT6-01				
Galeczka, Iwona	ER2-07, ER2-08				
Gallagher, Catherine R.	UV2-08, UV2-05				
Galland, Olivier	GT1-02				
Galvez, Matthieu E.	ER5-05				
García, Aurora	EC3-09, EC3-07				
Gasser, Deta	GT6-08				
Gautason, Bjarni	GT6-01, UV4-05				
H					
Haaland, Linda	GT6-06				
Hag, Maria	ER3-05				
Haga, Torbjørn	GA1-11				
Håkansson, Lena	IS4-04, IS4-02				
Hall, Adrian	ER5-11, EC2-07				
Geirsson, Halldór	ER2-09				
Halldorsson, Saemundur Ari	IM1-14, IM1-18, IM1-04, IM1-11, IM1-17				
Halpaap, Felix	GT2-02				
Hamilton, Christopher W.	RS2-05				
Hammer, Erik	ER6-01				
Hanghøj, Karen	ER5-01				
Hannesdóttir, Krista	RS2-07				
Hansen, Harald	GT6-05				
Hansen, Lars Maersk	AG1-01, AG1-04				
I					
Iakubivysi, Iaroslav	IS1-02				
Ilyinskaya, Evgenia	IM1-14				
Ingeman-Nielsen, Thomas	EC4-02				
Ingimarsson, Heimir	ER1-03				
Ingólfsson, Halldór	ER1-06				

NAME ABSTRACT NO
 Ingólfsson, ÓlafurEC3-04, EC2-03, EC3-08,
 EC2-04
 IODP , EXP396 ScientistsUV3-03
 Isaksen, KetilEC4-01
 Isken, Marius PaulGT1-03

J

Jackson, Christopher A-LER6-05
 Jackson, MatthewIM1-14
 Jackson, Matthew G.IM1-11
 Jacobs, JoachimGT6-08
 Jamtveit, BjørnER2-01
 Jeffery, KeithIS2-05
 Jenner, FrancesIM1-17
 Jensen, Odd AreGA1-02
 Jeon, HeejinIM1-14, IM1-18
 Jerram, DougalER6-07, UV3-03, IM1-13
 Jerram, Dougal A.IM1-19
 Jiménez-Franco, AbigailER5-03
 Johannesen, Rakul MariaER2-02
 Johansson, MagnusIS4-08
 Johnson, Mark D.EC3-16
 Johnsson, AndreasIS4-12
 Jolis, EsterIM1-15, UV4-04
 Jolley, DavidUV3-03
 Jones, MorganUV3-03
 Jones, Morgan T.UV3-01
 Jones, Stephen M.UV3-04
 Jonsson, TraustiEC1-01
 Josnin, Jean-YvesEC4-03
 Jousset, PhilippeGT1-03
 Jóhannesson, TómasRS2-07, GA1-07
 Jónasdóttir, Sigurdís B.GA1-19
 Jónasson, HallgrímurER5-02
 Jóngeirsdóttir , Irma GnáUV2-05
 Jónsdóttir, Hafdis EyglóAG1-05, AG1-03
 Jónsdóttir, Ingibjörg SEC1-06
 Jónsdóttir, Ingibjörg SvalaEC1-06
 Jónsdóttir, KristínPL-1
 Jónsdóttir, KristínGT1-04
 Jónsson, Magni HreinnGA1-19, GA1-20,
 RS2-03
 Jónsson, SteingrímurEC1-02
 Junno, NiinaGA1-12
 Jæger, Maja LianIS4-03

K

Kahl, MarenIM1-18
 Kaikkonen, RiinaIM1-11
 Kalliokoski, MaaritIM1-14
 Kalliokoski, Maarit HUV2-09
 Kalsnes, BjørnGA1-14, GA1-16
 Karlsdóttir, RagnaUV1-02
 Karner, Garry D.GT6-01
 Karsten M., HaaseIM1-05
 Karvinen, SeppoIM1-01
 Katia, SvendbyGT6-06
 Keers, HenkIS4-01
 Kennedy, BenER1-07
 Kenyeres, AmbrusRS2-01
 Khadhraoui, MadihaGA1-13
 Kierulf, HalfdanIS2-04
 Kietäväinen, RiikkaER3-03
 Kim, Dong-EunGT6-07
 Kinnunen, JanneIS4-10

NAME ABSTRACT NO
 Kirchner, NinaEC3-20
 Kjartansdóttir, RikeyUV4-01
 Kjartansdóttir, RikeyIM1-14
 Kjellman, Sofia E.EC3-15, EC3-20
 Kjenes, MartinUV4-07
 Kjöll, Hans JørgenIM1-10, ER2-01
 Klarenberg, Ingeborg J.IS1-02
 Klausen, Tore GraneER6-02
 Kleine, BarbaraER1-06, IM1-14, ER2-07
 Kleine, Barbara I.IM1-03
 Kling, MelanieEC1-04
 Klug, MartinEC3-18
 Klüpfel, SimonER1-10
 Knight, HazelUV3-04
 Knutsen, Stig-MortenER6-08, ER2-03
 Kollsgård, Christine TømmervikEC3-05,
 EC3-08
 Kontula, AnneGT5-04
 Kopacz, NinaIS1-02
 Korja, AnnakaisaGA1-12
 Krawczyk, CharlotteGT1-03
 Kristensen, LeneRS2-04
 Kristian, SvennevigEC4-04
 Kristinnsson, SigurðurER1-03
 Kristjánsson, Bjarni ReyrrER1-10
 Krossøy, TheaIS4-07
 Ksienzyk, Anna K.GT6-08
 Kuhn, DirkGA1-17
 Kuikka, JaroER5-08
 Kultti, SeijaER5-11
 Kuosmanen, NiinaEC1-05
 Kurtti, JoonasIM1-12
 Kuva, JukkaIS4-11, UV4-04
 Kvam, Maria HuseEC3-18
 Köhler, AndreasGT2-01

L

Laberg, Jan Sverre ...ER6-08, EC3-08, RS3-03,
 EC3-05
 Lacroix, PascalRS2-06
 Lahaye , YannUV4-04
 Lahaye, YannIM1-12, ER5-12, IS4-10
 Lamb, OliverUV4-01
 Lambart, SarahUV3-03
 Lampe, Ove DaaeIS2-04
 Langeland, TorIS2-04
 Lanzi, ChiaraGT1-06
 Lars Eivind, AuglandGT6-04
 Larsen, Berg-Edland, RuneIM1-02
 Larsen, Bjørn EskilAG1-02
 Larsen, GuðrúnIM1-09, UV1-04, UV2-09,
 UV2-08
 Larsen, Hans ChristianGT6-01
 Larsen, YngvarRS2-01
 Larsson, Simon A.UV2-10
 Lasabuda, Amando P. E.EC3-05, ER6-08,
 EC3-08
 Lauknes, Tom RuneRS2-02, RS2-01
 Lång-Ritter, IlonaGA1-05
 Lepland, AivoER6-01, IS4-09
 Lerch, BenediktER6-03
 Leshar, Charles E.GT6-01
 Leväniemi, HannaER5-07
 Levillayer, NicolasUV2-02
 Lévy, LéaER1-06, ER3-05
 Li, TaoEC1-07
 Liakka, JohanGT5-04
 Liebscher, AxelER5-12

NAME ABSTRACT NO
 Lilja, ChristinaER5-12
 Lilleøren, KarianneEC4-05
 Line, Lina H.ER6-15
 Liu, Emma J.UV3-01
 Liu, XuanER5-12
 Logan, LeslieER5-04
 Loiseau, RaphaëlGA1-06
 Lorenzo, Alba MartínUV4-04
 Lucas, AntoineEC4-04, IS1-03
 Lukas, SvenEC2-06
 Lukkari, SariIM1-15, UV4-04, IM1-12
 Lund, BjörnGT5-04, GT5-03
 Lundmark, Anders Mattias ...IM1-13, GT6-04,
 ER6-10, IS4-05
 Lundqvist, JennieIS4-04
 Lunkka, Juha PekkaEC3-11
 Luoto, MiskaEC3-13
 Luttinen, Arto V.IM1-07, IM1-08
 Luzzadder-Beach, SherylEC2-02

M

Mabula Didas, MakoyeER1-04
 Macedonio, GiovanniGA1-08
 MacLennan, JohnIM1-14, IM1-17
 Macrander, AndreasEC1-02
 Madsen, Turid HátúnER2-02
 Magnin, FlorenceEC4-04, EC4-01, EC4-03
 Magnússon, EyjólfurRS2-07
 Magnússon, RögnvaldurIM1-03
 Magnússon, Rögnvaldur LindalGT2-03,
 GT2-04
 Maharjan, Dwarika .UV3-03, ER6-07, EC3-07
 Mair, KarenIS4-01
 Malet, Jean-PhilippeRS2-06
 Malm, RieIS4-02
 Mandon, CelineIM1-16
 Manseau, FrédéricGA1-13
 Manton, BenER6-07, UV3-03
 Marieni, ChiaraPL-5
 Marinkovic, PetarRS2-01
 Märki, LenaER5-05
 Marshall , EdwardIM1-14
 Marshall, EdwardIM1-18, IM1-04
 Marshall, Edward W.IM1-11
 Marteinsson, KjartanER2-08
 Martínez Montesinos, BeatrizGA1-08
 Marzoli, AndreaUV4-03
 Matthews, SimonIM1-14, IM1-17
 Mattsson, TobiasUV4-06, GT1-01
 Maupin, ValerieIS2-04
 Maurya, PradipER1-06
 Mayer-Ullmann, FerdinandGT6-08
 McCarthy, AndersGT6-01
 McClenaghan, Sean H.ER4-04
 McKenzie, MarionEC3-01
 Meakins, Max William JohnER2-01
 Menzies, AndrewUV4-04, IM1-15
 Mibe, GeoffreyIM1-14
 Michalek, JanIS2-05, IS2-04
 Michallik, RadoslawUV4-04
 Michallik, Radoslaw MarkusIM1-20
 Michea, DavidRS2-06
 Middleton, MaaritIS4-10
 Midtkandal, IvarER6-15, EC3-09, ER6-09,
 ER6-04, EC3-07
 Midtun, YngveGA1-02
 Mikkelsen, Odd-ArneGA1-02
 Mikko, HenrikEC3-17, EC3-19

NAME ABSTRACT NO

Milkereit, Claus GT1-03
Millett, John ER6-07, UV3-03
Millett, John M. ER2-01
Mingari, Leonardo GA1-08
Mohn, Geoffroy UV3-03
Molnár, Ferenc ER5-05
Molson , John GA1-13
Moreland, William UV2-03
Moreland, William M. UV2-08
Morén, Björn EC3-03
Morino, Costanza EC4-04, IS1-03, IS3-02
Mortensen, Anette ER1-09
Mortensen, Anette Kærgaard GT2-03
Motagh, Mahdi GT1-03
Mulrooney, Mark J. ER6-15
Mulrooney, Mark Joseph ER2-06
Mundl-Petermeier, Andrea IM1-07
Muravchik, Martin ER6-13, ER6-14
Murton, Bramley IM1-17
Myhren Stordahl, Elise IS4-01
Myklebust, Reidun .UV3-03, ER6-07, UV3-02,
EC3-09, EC3-07
Mørk, Atle ER6-01

N

Nadim, Farrokh GA1-16
Nagler, Thomas RS2-07
Nakken, Lise ER6-05
Näslund, Jens-Ove GT5-04
Natvik, Øyvind IS2-04
Naursgaard, Mads P. EC1-07
Neubeck, Anna IS1-02
Neumann, Else Ragnhild IM1-10
Newton, Robert UV4-03
Niiranen, Tero IS2-02, IS2-03
Noblet, Axel IS1-03, EC4-04
Nogueira, Francisco, C.C. GT6-09
Noormets, Riko EC3-20
Nordgulen, Øystein IS4-09
Norðdahl, Hreggviður EC2-01
Norris, Simon ER5-12
Nyberg, Björn IS4-01
Nyby, Vilhelm IS4-03
Nykänen, Vesa IS2-02, IM1-11, IS2-03
Nystad, Lisa Julianne IS4-06

O

O'Brien, Hugh UV4-04
O'Connell, Bailey EC3-02
Oberhardt, Nikolas AG1-06
O'Brien, Hugh IM1-11
Oddsson, Björn RS2-05
Oelkers, Eric ER2-07
Oen, Amy GA1-16
Olesen, Odleiv IS2-04
Olsen, Lars EC3-18
Olsen, Stine ER6-09
Oppenheimer, Clive UV4-01, IM1-14
O'Reilly, Brian UV3-04
Óskarsson, Birgir V. UV2-04
Osmond, Johnathon ER2-06
Osmundsen, Per Terje GT6-06, ER6-04,
GT5-05, GT6-03
Ottemöller, Lars GT2-02, IS2-04
Ovaskainen, Juha EC3-10

NAME ABSTRACT NO

Oye, Volker GT2-01
Ófeigsson, Benedikt G. RS2-07, GT1-05,
GT1-04
Óladóttir, Bergrún Arna UV2-09, UV1-06
Ólafsdóttir, Sólveig R. EC1-02
Ólafsdóttir, Kristín EC1-01
Ólavsdóttir, Jana ER2-02
Óskarsson, Birgir RS4-04
Óskarsson, Birgir V. UV2-08
Óskarsson, Birgir Vilhelm RS4-03, UV2-05
Óskarsson, Birgir Vilhelm RS2-05
Óskarsson, Finnbogi ER1-03

P

Pacini, Fabrizio RS2-06
Palau, Rosa M. GA1-05
Pankhurst, Matthew UV4-04
Parks, Michelle GT1-04, GT1-05
Parks, Michelle RS2-07
Parks, Michelle Maree GT1-06
Pasquarè Mariotto, Federico GT6-10
Patton, Henry GT5-03
Páll Hersir , Gylfi ER1-04
Pálsdóttir, Arna ER1-05
Pálsson, Finnur RS2-07, PL-3
Peate, David GT6-01
Pechlivanidou, Sofia ER6-13
Pedersen, Asger Ken RS4-01
Pedersen, Gro B. M. RS2-05, UV1-06
Pedersen, Gro B.M. UV1-04
Pedersen, Jon Halvard ER6-03
Pedersen, Leif-Erik Rydland ER6-02
Pedersen, Rolf B. ER4-04
Peignaux, Coralie IS1-03
Peltonen, Veikko ER5-11
Penna, Ivanna AG1-02, RS2-02
Peron-Pinvidic, Gwenn GT6-02
Perrels, Adriaan GA1-05
Petersen, Guðrún Nína UV1-03
Petersen, Thomas Guldborg EC4-02
Peterson Becher, Gustaf EC3-17, EC3-19
Péron-Pinvidic, Gwenn GT6-03
Pétursson, Halldór G EC2-01
Pétursson, Fridgeir GT2-03
Pétursson, Friðgeir GT2-04
Pétursson, Friðgeir ER1-06
Pfeffer, Melissa IM1-14, UV4-01
Pfeffer, Melissa A. UV1-06
Pfeffer, Melissa Anne UV1-03
Phd. Skurtveit, Elin ER2-05
Philippe, Meven IS1-03
Piciullo, Luca GA1-14
Piispa, Elisa UV2-07
Pinel, Virginie RS2-05
Piotrowski, Jan A. EC2-08, EC2-05
Planke, Sverre EC3-07, EC3-06,
UV3-03, GT6-01, IM1-02, UV3-02, EC3-09,
ER6-07, ER2-01
Planke, Sverre IM1-19
Plaza-Faverola, Andreia GT5-03
Pointal, Elisabeth RS2-06
Polozov, Alexander G. IM1-19
Popova, Inna IS2-01
Pospiech, Solveig IS4-10
Poyatos-Moré, Miquel ER6-15
Prause, Simon IM1-03
Principato, Sarah EC3-01
Prof. Jacobs, Joachim ER2-05

NAME ABSTRACT NO

Professor Braathen, Alvar ER2-04
Provost, Floriane RS2-06
Proy, Catherine RS2-06
Putkinen, Niko ER5-11

Q

Quintela, Orlando GT1-01

R

Ragnarsdóttir, Kolbrún Ragna ER1-10
Ragnarsson, Sigurður ER1-08
Ransed, Gunnel EC3-19, EC3-17
Ranta, Eemu IM1-14, IM1-17, IM1-11
Räsänen, Matti E. EC3-10
Rasmussen , Maja IM1-14
Rasmussen, Maja Bar IM1-11
Ratouis, Thomas ER1-06
Ravel, Ludovic EC4-03
Redfield, Tim GT5-05, GT6-06
Redfield, Tim F. GA1-17
Regnet, Jean-Baptiste ER3-04
Regnéll, Carl EC3-17
Regnéll, Joachim EC3-17, IS3-04
Reijonen, Heini ER5-12
Renne, Paul UV4-03
Repczynska, Maria IM1-14
Reynolds, Hannah Iona RS2-05
Rhodes, Emma GT1-01, GT1-02, UV4-06
Rian, Maiken IM1-13
Riber, Lars GT5-05
Richo, Sylvain ER3-04
Riis, Fridtjof ER6-06
Riishuus, Morten S. UV2-04
Rinnan, Riikka EC1-07
Rinterknecht, Vincent ER5-11
Rivalta, Eleonora GT1-03
Rizzello , Daniele ER1-04
Roberti, Gioachino IS1-03
Roberts , Matthew GA1-09
Roberts, Matthew J. RS2-07
Robion, Philippe ER3-04
Rodriguez Blanco, Leticia ER6-12
Rodríguez, Fátima UV4-04
Rollinson, Gavyn UV4-04
Romer, Rolf IM1-06
Ronchin, Erika UV4-06, GT1-01, ER1-07
Roque-Rosell, Josep ER5-03
Rosenqvist, Marija Plahter ER2-01
Rouyet, Line RS2-02
Rudge, John F. IM1-17
Rügge, Kirsten ER3-05
Ruskeeniemi, Timo ER5-12
Russo, Elena GT6-10
Rúnarsdóttir, Rebekka IM1-14
Ryde, Ingvild EC1-07
Rydningen, Tom Arne EC3-08, EC3-05,
ER6-08, RS3-03
Ryen, Sofie Hildegard GT6-04
Rønnevik, Christian IS2-04
Rønning, Jan Steinar AG1-02

NAME	ABSTRACT NO
S	
Sahlström, Fredrik	ER4-04
Salehi, Sara	RS4-02
Salminen, Johanna	IS2-07
Salonen, J. Sakari	EC3-14, EC3-13
Sandri, Laura	GA1-08
Sarala, Pertti	EC3-11
Saubin, Elodie	ER1-07
Sayyadi, Sara	UV1-01
Scarow, Jane	UV4-04
Scheiber, Thomas	GT6-08
Schiellerup, Henrik	IS4-09
Schläpfer, Daniel	RS4-02
Schmidt, Peter	GT5-04, GT5-03, GT1-01, UV4-06
Schmitt, Axel	IM1-06
Schnurer, Anna	IS1-02
Schofield, Nicolas	UV4-07
Schomacker, Anders	EC3-20, EC3-15
Schüßler, Nick	GA1-17
Scott, Samuel	UV4-01, IM1-14, RS3-04, ER2-09
Sebastian, Hainzl	GT1-03
Sellin, Carolina	GA1-05
Selonen, Olavi	IS3-05
Sendula, Eszter	ER4-04
Senger, Kim	GT6-06
Seong, Yeong Bae	GT6-07
Seppa, Heikki	EC1-05
Shevchenko, Alina	UV2-03
Shorttle, Oliver	IM1-17
Sigfússon, Bergur	ER2-07
Sigmarsson, Olgeir	IM1-09, UV4-02, IM1-14, UV2-09, UV2-02
Sigmundsson, Freysteinn	GT1-04, GT1-05, GT1-06, GT1-02
Sigurdarson, Sigurdur	GT5-02
Sigurðsson, Gunnar	RS2-07
Sigurðsson, Gylfi	IM1-14
Sigurðsson, Ingvar Atli	IS3-01
Siira, Jenniina	ER5-08
Silva, Amanda, C.E.	GT6-09
Silvennoinen, Joel	ER3-03
Simkins, Lauren	EC3-01
Simon, Kirby	ER4-02
Singh, Abhijeet	IS1-02
Sirevaag, Hallgeir	ER6-02, EC1-04
Sjöqvist, Axel	IS4-12
Skrede, Ingrid	RS2-02, RS2-04
Skurtveit, Elin	ER2-06
Slagstad, Trond	GT6-05
Slåtten Sagen, Martine	GA1-02
Slawson, Jacob	EC3-01
Smail, Nathan	GA1-10
Smith, Colby	EC3-17, EC3-19
Snæbjörnsdóttir, Sandra Ósk	PL-5, ER2-07, ER2-08
Sobron, Pablo	ER4-02
Sohlenius, Gustav	EC1-03
Solberg, Inger-Lise	AG1-02
Soldal, Magnus	ER2-05
Soldati, Mauro	IS3-02
Solheim, Anders	GA1-14, GA1-16, GA1-05
Sorjonen-Ward, Peter	IM1-15
Souza, Jorge, A.B.	GT6-09
Sparrenbom, Charlotte	EC2-06
Stefánsson, Andri	IM1-11, ER2-07, IM1-16, IM1-14, UV4-01
Stefánsson, Árni B.	IS1-02
Steinberger, Bernhard	GT6-01

NAME	ABSTRACT NO
S	
Steingrímsson, Jón Haukur	GA1-21, GA1-19
Sternai, Pietro	EC3-09
Stéfansson, Andri	IM1-03
Stivrins, Normunds	EC3-14
Stockmann, Gabrielle	ER2-09, ER3-02
Stockmann, Gabrielle J.	RS3-04
Stockwell, Brent R.	IS1-02
Stokke, Ella Wulfsberg	UV3-01
Stokke, Henrik Henriksen	EC3-06
Storm, Malte	UV4-03
Stracke, Andreas	IM1-06
Strmic Palinkas, Sabina	ER4-04
Strom, Alexander	EC4-04
Strout, James	GA1-16, GA1-14
Stumpf, André	RS2-06
Sturkell, Erik	ER2-09, EC2-03, RS3-04, IS4-12
Stødle, Daniel	RS2-01
Sundal, Anja	ER2-06
Sundblad, Krister Leon	ER5-03
Sunde, Pia	AG1-02
Svebo, Joachim R.	ER6-10
Sveinbjörnsdóttir, Árný	ER3-02, ER3-01
Svensden, John Inge	GT5-01
Svennevig, Kristian	IS1-03, GA1-01
Svensen, Henrik H.	IM1-19
Svensen, Henrik H.	UV3-02
Svensen, Henrik Hovland	IM1-10
Swart, Peter K.	ER6-12
Sæmundsson, Þorsteinn	GA1-03, GA1-04, GA1-10, GA1-19, EC2-02
Sørensen, E, Bjørn	IM1-02
Sørensen, Erik Vest	RS4-01, UV2-06
Sørensen, Mathilde B.	GA1-11
T	
Taivalkoski, Anne	IS4-10
Tappe, Sebastian	IM1-06
Tarquini, Simone	UV1-06
Tassis, Georgios	AG1-02
Taurisano, Andrea	GA1-02
Tegner, Christian	IM1-02
Ten Kate, Inge Loes	IS1-02
Thalund-Hansen, Rasmus	ER3-05
The Shipboard, Scientific Party	UV3-02
Thiagarajan, Nivedita	ER6-01
Thießen, Olaf	ER6-03
Thomas, Elizabeth K.	EC3-15
Thomas, Ratouis	PL-5
Thordarson, Thor	UV2-03
Thordarson, Thorvaldur	UV2-05, UV4-08, UV2-08
Thorhallsson, Eythor	ER5-06
Thölix, Laura	GT5-04
Tibaldi, Alessandro	GT6-10
Titos, Manuel	GA1-08
Tomaškovičová, Soňa	EC4-02
Torabi, Anita	GT6-09
Torizin, Jewgenij	GA1-17
Trasune, Liva	EC3-14
Troll, Valentin	UV2-08, UV2-03
Tudisko, Erika	EC2-06
Tuffen, Hugh	ER1-07
Tuomaala, Emilia	EC3-14
Tuomisaari, Johanna	GA1-12
Turunen, Sanni T.	IM1-07
Tuxen, Nina	ER3-05
Tvingsholm, Søren B	IS4-05
Törmänen, Tuomo	IS2-03

NAME	ABSTRACT NO
U	
Udal Hansen, Lena	EC2-06
V	
Vachon, Rémi	GT5-03
Väliranta, Minna	EC3-14
Valsson, Guðmundur	RS4-04
Valsson, Guðmundur	RS2-05
van Boeckel, Mikis	EC3-18, EC2-07
van Boeckel, Tayo	EC2-07
Van der Meer, Quinten	IM1-14
Van Hoesen, Daniel	ER4-02
Van Rooij, David	UV3-04
Vasconcelos, David L.	GT6-09
Vassileva, Magdalena Stefanova	GT1-03
Veress, Cs. Ervin	IS2-01
Vest Christiansen, Anders	ER3-05
Vest Sørensen, Erik	RS4-02
Vick, Louise	RS2-02
Vilhelmsson, Oddur	IS1-02
Virtanen, Ville J.	ER5-05
Vogfjörð, Kristín S.	GT1-04
Voigt, Martin	PL-5
Voje, Thilde Justine	IS4-03
W	
Walter, Thomas	UV2-03, GT1-03
Wang, Rongjiang	GT1-03
Wang, Shujie	EC3-01
Wanhainen, Christina	IS4-11
Warlo, Mathis	IS4-11
Wasrud, Jaran	GA1-02
Wastegård, Stefan	UV2-10
Watt, Warwick	ER5-12
Weckwerth, Piotr	EC2-05
Weger, Ralf J.	ER6-12
Weisenberger, Tobias Björn	IM1-03
Weisenberger, Tobias Björn	ER2-07
Wells, Greta	EC2-02, GA1-10
Wenrich, William C.	UV2-05
Wesenlund, Fredrik	ER6-03
Westermann, Sebastian	EC4-01
Whipp, David	ER5-11
Whitehouse, Martin	IM1-14
Whitehouse, Martin	IM1-18
Wiberg, Daniel Hesjedal	RS3-03
Wicker, Vincent	ER6-14
Winsborrow, Monica	EC3-08
Witcher, Taylor	GT1-01, UV4-06
Wold, Marie	ER4-04
Wuite, Jan	RS2-07
Würtzen, Camilla	ER6-15
Wysota, Wojciech	EC2-05
X	
Xuan, Liu	UV4-04

NAME	ABSTRACT NO	NAME	ABSTRACT NO	NAME	ABSTRACT NO
------	-------------	------	-------------	------	-------------

Y

Yanchilina, AnastasiaER4-02

Z

Zastrozhnov, DmitryER6-07

Zábori, JuliaEC1-03

Zetterlind, AlexandraIS1-02

Zhang, ShihongIS2-07

Zheng, TingtingER1-02

Zorn, EdgarUV2-03

Þ

Þorbergsson, AlbertER1-03

Þorbjörg, ÁgústsdóttirGT1-03

Þorgilsson, GunnarER2-08

Þórarinsdóttir, TinnaGA1-09

Þórðarson, ÞorvaldurUV4-05

Þrastarson, Ragnar HeiðarUV1-06

Ö

Öhrling, ChristianEC1-03, EC3-19, EC3-16,
EC3-17,

AUTHOR
INDEX



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Group of scientist at one of the cauldrons connected to Bárðarbunga volcano making gas measurements in the geothermal area, which was revealed after the eruption in 2015.



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Cover photo: The eruption in Geldingadalir, Fagaradalsfjall in the Reykjaneskagi peninsula. Photo taken the 6th of May 2021
Photo: Þorsteinn Sæmundsson