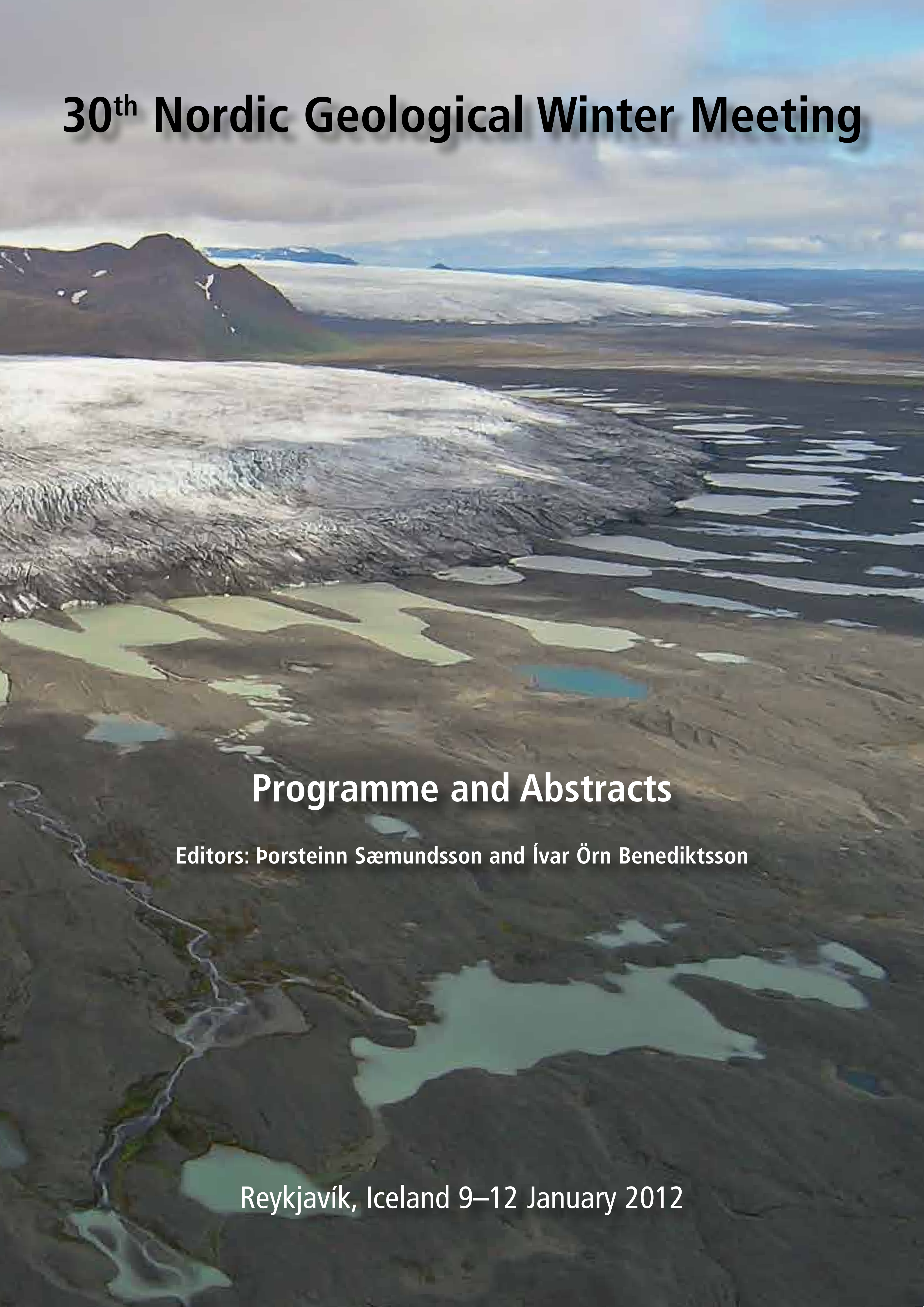

30th Nordic Geological Winter Meeting

Programme and Abstracts

Editors: Þorsteinn Sæmundsson and Ívar Örn Benediktsson

Reykjavík, Iceland 9–12 January 2012

30th Nordic Geological Winter Meeting

Harpa concert hall and conference centre

Reykjavík, Iceland 9-12 January 2012

Editors

Þorsteinn Sæmundsson and Ívar Örn Benediktsson

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Programme and Abstracts
Editors: Þorsteinn Sæmundsson and Ívar Örn Benediktsson

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Welcome

Þorsteinn Sæmundsson

Ívar Örn Benediktsson

Dear Colleagues,

It is our great pleasure to welcome you to Reykjavík for the 30th Nordic Geological Winter Meeting. The Nordic Geological Winter Meetings have proofed 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.

This is the 30th Nordic Geological Winter Meeting and the 4th meeting held here in Iceland. To celebrate this anniversary, we proudly hold the meeting in the newly built Harpa concert hall and conference centre, at the harbor in downtown Reykjavík. Apart from this, we add one day to the conference with excursions to unique geological locations in south and south-west Iceland.

On the 8th of January 2012, we commemorate the centenary of the birth of the late Professor Sigurður Þórarinsson. Sigurður was a pioneer among Icelandic geoscientists, the founder of tephrochronology, and the first professor in geology at the University of Iceland. To honor his memory and his great contribution to geosciences, we dedicate one theme to him at this meeting. In addition, a special volume of Jökull, the Icelandic Journal of Earth Sciences, will be published in 2012 with focus on Þórarinsson´s main research areas, glaciology and volcanology. As all of you know, the last couple of years have been rather eventful regarding volcanic activity in Iceland. Eyjafjallajökull woke up in 2010 after almost two hundred years of quiescence, Grímsvötn followed in 2011 with an unusually powerful eruption, and our sleeping giant, Katla, occasionally reminds us of its power with frequent earthquakes, or even jökulhlaups, like last summer after a small subglacial eruption. These volcanic eruptions, even though they were not large in historical respect, have shown how sensitive our infrastructure is to the great forces of nature. This clearly highlights the importance of our work to understand Earth's behavior and history, and not least the importance of disseminating that knowledge to the society.

At this meeting the Nordic Geoscientist Award will be presented for the first time. The award will be 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 in geosciences. The prize for this award consists of a framed diploma and an engraved plate of columnar basalt from Iceland. The Swan, the symbol of Nordic cooperation, is also engraved on the plate. The winner is invited to hold a plenary lecture at the meeting in connection with the presentation of the Award.

The organization of a meeting like this requires more than a year of preparation, a task that many people are involved in. We would like to thank the Scientific Programme Committee (SPC) 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 "Congress Reykjavík" for professional assistance, and not least the many sponsors who have made this event possible.

We hope that the 30th Nordic Geological Winter Meeting will be fruitful and lead to 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

Þorsteinn Sæmundsson

Chairman of the Geoscience Society of Iceland
and the 2012 NGWM SPC

Ívar Örn Ben.

Ívar Örn Benediktsson

Secretary General, Geoscience Society of Iceland
and vice chairman of the 2012 NGWM SPC

Kristján Breki tók þátt í því ásamt foreldrum sínum að prýða umhverfi leikskólans Kærabæjar á Fáskrúðsfirði.

Starfsmenn Alcoa um allan heim leggja samfélagsmálum lið á hverju ári. Í fyrra tóku yfir 29.000 manns þátt í margvíslegum verkefnum víðs vegar um heim og hér á landi tóku rúmlega 300 sjálfboðaliðar úr röðum starfsmanna Alcoa Fjarðaáls og fjölskyldna þeirra þátt í ýmsum verkefnum á Austurlandi.

Auk þess að hvetja starfsfólk sitt til sjálfboðastarfa leggur Alcoa verkefnunum til peninga með hverjum starfsmanni sem tekur þátt. Alls greiddi Samfélagssjóður Alcoa rúmlega 2 milljónir króna til verkefnanna sem unnin voru á síðasta ári á Austurlandi.

Fyrir samfélagið, umhverfið og komandi kynslóðir.

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Table of Contents

Programme Overview

MONDAY 9 January

	Silfurberg	Kaldalón	Ríma A	Ríma B	Vísa	Stemma	
08:00	Registration						
09:00	Welcome - Dr. Þorsteinn Sæmundsson, Geoscience Society of Iceland						
09:10	Opening - Mr. Ólafur Ragnar Grímsson president of Iceland						
09:20	Plenary 1: Magnús Tumi Guðmundsson (30 min)						
09:40							
10:00	SÞ-3 [x6]	ER-2 [x5]	GA-1 [x6]	GD [x6]	IS-3 [x5]	EC-3 [x6]	6 talks
10:20							
10:40							
11:00							
11:20							
11:40							
12:00	Lunch (60 min)						
13:00	Plenary 2: Helgi Björnsson (30 min)						
13:40	SÞ-3 [x2]	ER-2 [x6]	GA-1 [x6]	GD [x3]	IS-2 [x4]	EP-1 [x6]	6 talks
14:00							
14:20							
14:40	SÞ-2 [x4]						
15:00							
15:20							
15:40	Poster session w/ refreshments						
16:00							
16:20							
16:40							
17:00	IceBreaker - Reykjavík City Hall						
18:30							

WEDNESDAY 11 January

CONFERENCE EXCURSIONS

08:00	Conference excursions. Departures from Harpa. Further information in abstract volume.
08:20	
08:50	
09:00	
09:20	
09:40	
10:00	
10:20	
10:40	
11:00	
11:20	
11:40	
12:00	
13:00	
13:40	
14:00	
14:20	
14:40	
15:00	
15:20	
15:40	
16:00	
16:20	
16:40	
17:00	

TUESDAY 10 January

	Silfurberg	Kaldalón	Ríma A	Ríma B	Vísa	Stemma	
08:00							
08:20	Plenary 3: Jan Mangerud (30 min)						
08:50							
09:00	EC-1 [x4]	UV-1 [x4]	EC-4 [x4]	EP-3 [x4]	IS-4 [x4]	ER-1 [x4]	4 talks
09:20							
09:40							
10:00							
10:20	Refreshments (20 min)						
10:40	EC-1 [x4]	UV-1 [x1]	EC-4 [x4])	EP-2 [x4]	IS-4 [x4]	ER-1 [x4]	4 talks
11:00		UV-3 [x3]					
11:20							
11:40							
12:00	Lunch (60 min)						
13:00	Plenary 4: Stefan Rahmstorf (30 min)						
13:40	EC-1 [x4]	UV-3 [x4]	EC-4 [x4]	EP-4 [x4]	IS-1 [x4]	SÞ-1 [x4]	4 talks
14:00							
14:20							
14:40							
15:00	Refreshments (20 min)						
15:20	EC-1 [x3]	UV-3 [x5]		EP-4 [x3]	IS-1 [x5]	SÞ-1 [x2]	5 talks
15:40							
16:00							
16:20							
16:40							
17:00	Conference dinner, Blue Lagoon with bath - Bus departure from Harpa						
18:00	Conference dinner, Blue Lagoon without bath - Bus departure from Harpa						
19:00	Conference dinner, Blue Lagoon Address - Mrs. Svandís Svavarsdóttir, minister for the environment Blue Lagoon, departure to Reykjavík						
23:00							

THURSDAY 12 January

	Silfurberg	Kaldalón	Ríma A	Ríma B	
08:00	Plenary-5: Nordic Geoscientist Award (40 min)				
08:20					
08:50					
09:00	EC-2 [x4]	GA-2 [x4]	UV-4 [x4]	ER-6 [x3]	4 talks
09:20					
09:40					
10:00					
10:20	Refreshments (20 min)				
10:40	EC-2 [x4]	GA-2 [x3]	UV-4 [x4]	ER-4 [x4]	4 talks
11:00					
11:20					
11:40		GA-3 [x1]			
12:00	Lunch (60 min)				
13:00	Plenary-6: Þóra Árnadóttir (30 min)				
13:40	EC-2 [x5]	GA-3 [x3]	UV-4 [x5]	ER-4 [x2]	5 talks
14:00					
14:20				ER-5 [x3]	
14:40		SÞ-4 [x2]			
15:00					
15:20	Poster session w/refreshments				
15:40					
16:00	EC-2 [x4]	SÞ-4 [x4]		ER-3 [x5]	5 talks
16:20					
16:40					
17:00					
17:20					

Theme 1
Theme 2
Theme 3
Theme 4
Theme 5
Theme 6
Theme 7
Theme 8
Posters
Excurs.

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Social Programme

Monday, 9 January

17:00–18:30	**Icebreaker – Reception in Reykjavik City Hall**
	The City of Reykjavík cordially invites all delegates and registered accompanying persons to the Reception. Light refreshment will be served and the music group Brother Grass will perform during the reception. The Reykjavík City Hall is located in the city centre, by the lake Tjörnin.

Tuesday, 10 January

19:30	**Conference dinner in Blue Lagoon**
17:00	**Bus departure from Harpa for those taking bath in the Blue Lagoon before dinner**
18:30	**Bus departure from Harpa for dinner guests** The Conference dinner is at the Blue Lagoon restaurant, where a three course dinner with wine will be served after a welcome drink. The Icelandic artists, Ragnar Ólafsson, Margrét Kristín Sigurðardóttir and Unnur Birna Björnsdóttir will perform during the dinner. Address by Mrs. Svandís Svavarsdóttir, minister for the environment.
23:00	**Bus departure to Reykjavík** *Price: ISK 16.000,- per person with bath entrance* *Price: ISK 12.000,- per person without bath entrance* *Ticket can be obtained at the Congress Hospitality Desk*

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WHEN?

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WHERE?

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Photos: UKK

QUESTIONS?

Contact Erika Ingvald, project manager, erika.ingvald@sgu.se, tel. +46 18 17 93 50.

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Programme

Monday, January 9

08:00	**Registration opens**	
09:00–09:10	**Welcome – Dr. Þorsteinn Sæmundsson, Geoscience Society of Iceland**	SILFURBERG B
09:10–09:20	**Opening – Mr. Ólafur Ragnar Grímsson president of Iceland**	SILFURBERG B
09:20–09:50	**Plenary 1**	SILFURBERG B

PL-1 Hazards from explosive eruptions in Iceland, near and far

Magnús Tumi Guðmundsson
Institute of Earth Sciences, University of Iceland, REYKJAVÍK, Iceland

10:00–12:00 **EC 3 – Permafrost and periglacial processes** **STEMMA**

Conveners: Ivar Berthling and Bernd Etzelmüller

10:00–10:20 **EC3-1 Permafrost in Iceland and Norway**

Bernd Etzelmüller[1], Àgùst Guðmundsson[2], Karianne Lilleøren[1], Herman Farbrot[1]
[1]University of Oslo, OSLO, Norge
[2]Jardfrædistofan Geological Services, REYKJAVIK, Iceland

10:20–10:40 **EC3-2 A new assessment of distribution and activity of permafrost landforms in the Tröllaskagi peninsula, northern Iceland**

Karianne Lilleøren[1], Isabelle Gärtner-Roer[2], Bernd Etzelmüller[3]
[1]University of Oslo, OSLO, Norge
[2]University of Zürich, Department of Geography, ZÜRICH, Switzerland
[3]University of Oslo, Department of Geosciences, OSLO, Norge

10:40–11:00 **EC3-3 Typology of sorted patterned ground sites in Skagafjörður (Northern Iceland) by using a factor analysis of mixed data**

Thierry Feuillet[1], Denis Mercier[2], Armelle Decaulne[3], Etienne Cossart[4]
[1]University of Nantes, NANTES, France
[2]Université de Nantes, CNRS Laboratoire Géolittomer-UMR 6554 LETG, NANTES, France
[3]CNRS Laboratoire Geolab-UMR6042, CLERMONT-FERRAND, France
[4]Université Paris 1, Laboratoire PRODIG-UMR 8586, PARIS, France

11:00–11:20 **EC3-4 Permafrost degradation in West Greenland**

Niels Foged, Thomas Ingeman-Nielsen
Technical University of Denmark, KGS.LYNGBY, Denmark

11:20–11:40 **EC3-5 Temperature measurements providing evidence for permafrost thickness and talik occurrences in Kangerlussuaq, West Greenland**

Jon Engström[1], Ilmo Kukkonen[1], Timo Ruskeeniemi[1], Lillemor Claesson Liljedahl[2], Anne Lehtinen[3]
[1]Geological Survey of Finland, ESPOO, Finland
[2]Svensk Kärnbränslehantering AB, STOCKHOLM, Sverige
[3]Posiva Oy, EURAJOKI, Finland

11:40–12:00 **EC3-6 Geophysical investigations of a pebbly rock glacier, Kapp Linné, Svalbard**

Ivar Berthling[1], Håvard Juliussen[2]
[1]Norwegian University of Science and Technology, TRONDHEIM, Norway
[2]University of Bergen, Department of Geography, BERGEN, Norway

10:00–12:00	**ER 2 – CO_2 sequestration**	KALDALÓN

Conveners: Sigurður R. Gíslason and Per Ågård

10:00–10:40 **ER2-01 Mapping and Estimating the Potential for Geological Storage of CO_2 in the Nordic countries – a new project in NORDICCS**

Karen Lyng Anthonsen
GEUS, COPENHAGEN, Denmark

10:40–11:00 **ER2-02 CO_2 Storage Atlas, Norwegian part of the North Sea**

Eva Halland
Norwegian Petroleum Directorate, STAVANGER, Norway

11:00–11:20 **ER2-03 CO_2 storage options in the Norwegian part of the North Sea**

Wenche T. Johansen
Norwegian Petroleum Directorate, STAVANGER, Norway

11:20–11:40 **ER2-04 Methods and experience in qualification of geological CO_2 storage sites.**

Karl Erik Karlsen, Hallvard Høydalsvik, Espen Erichsen
Gassnova, PORSGRUNN, Norway

11:40–12:00 **ER2-05 Challenges with qualification of storage sites for CCS in deep aquifers**

Lise Horntvedt, Kari-Lise Rørvik
Gassnova, SANDEFJORD, Norway

10:00– 12:00	**GA 1 – Geohazards in the Nordic and Arctic regions**	RÍMA A

Conveners: Þorsteinn Sæmundsson and Hermanns Reginald

10:00–10:20 **GA1-01 Landslide mapping activities and landslide products of the Norwegian Geological Survey**

Reginald Hermanns, Louise Hansen, Kari Sletten, Martina Böhme, Halvor Bunkholt, John Dehls, Raymond Eilertsen, Luzia Fischer, Jean-Sebastian L´Heureux, Frederik Høgaas, Thierry Oppikofer, Lena Rubensdotter, Inger-Lise Solberg, Knut Stalsberg, Freddy Yugsi Molina
Geological Survey of Norway, TRONDHEIM, Norway

10:20–10:40 **GA1-02 Impacts of extreme weather events on infrastructure in Norway – the InfraRisk project.**

Anders Solheim[1], Regula Frauenfelder[2], Nele Kristin Meyer[3], Anita Verpe Dyrrdal[4], Ketil Isaksen[4], Bård Romstad[5]
[1]Norwegian Geotechnical Institute, OSLO, Norway
[2]NGI, OSLO, Norway
[3]NGI/ICG, OSLO, Norway
[4]Norwegian Meteorological Institute, OSLO, Norway
[5]CICERO, OSLO, Norway

10:40–11:00 **GA1-03 Changes in snow-avalanche activity on selected paths in Northern Iceland and Western Norway highlighted by dendrogeomorphologic analyses**

Armelle Decaulne[1], Ólafur Eggertsson[2], Katja Laute[3], Þorsteinn Sæmundsson[4], Achim Beylich[3]
[1]CNRS, CLERMONT-FERRAND, France
[2]Iceland Forest Service, Research Branch, REYKJAVÍK, Iceland
[3]Geological Survey of Norway, Quaternary Geology and Climate group, TRONDHEIM, Norway
[4]Natural Research Centre of Northwestern Iceland, SAUÐÁRKRÓKUR, Iceland

11:00–11:20 **GA1-04 Recent rock slide and rock avalanche activity in Iceland and its connection to climate change**

Halldór G. Pétursson[1], Þorsteinn Sæmundsson[2]
[1]Icelandic Institute of Natural History, AKUREYRI, Iceland
[2]Natural Research Centre of Northwestern Iceland, SAUÐÁRKRÓKUR, Iceland

11:20–11:40 **GA1-05 The rock avalanche on the Morsárjökull outlet glacier, 20th of March 2007 and its effects on the glacier**

Þorsteinn Sæmundsson[1], Halldór Pétursson[2], Ingvar Sigurðsson[3], Armelle Decaulne[4], Helgi Jónsson[1]
[1]Natural Research Centre of NW Iceland, SAUÐÁRKRÓKUR, Iceland
[2]Icelandic Institute of Natural History, AKUREYRI, Iceland
[3]South Iceland Nature Centre, VESTMANNAEYJAR, Iceland
[4]University Blaise Pascal Clermont 2, CNRS Geolab UMR6042, CLERMONT-FERRAND, France


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11:40–12:00 **GA1-06 Use of cosmogenic nuclide dating in rockslide hazard assessment in Norway**

Reginald Hermanns[1], Thomas Redfield[1], Cassandra Fenton[2], John Gosse[3], Samuel Niedermann[2], Oddvar Longva[1], Martina Böhme[1]

[1]Geological Survey of Norway, TRONDHEIM, Norway
[2]Helmholz-Zentrum Potsdam, Deutsches GeoForschungsZentrum, POTSDAM, Germany
[3]Cosmogenic Nuclide Exposure Dating Facility, Dalhousie University, HALIFAX, Canada

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10:00–12:00 **GD – Geodynamics** RÍMA B

Conveners: Steinunn S. Jakobsdóttir, Sigurlaug Hjaltadóttir and Þóra Árnadóttir

10:00–10:20 **GD-01 The 2011 Grímsvötn Eruption Observed with High Rate Geodesy**

Sigrún Hreinsdóttir[1], Ronni Grapenthin[2], Freysteinn Sigmundsson[3], Matthew J. Roberts[4], Josef Holmjarn[4], Halldór Geirsson[5], Thora Arnadottir[3], Rick Bennett[6], Thierry Villemin[7], Benedikt Gunnar Ofeigsson[1], Erik Sturkell[8]

[1]University of Iceland, REYKJAVÍK, Iceland
[2]University of Alaska, FAIRBANKS, USA
[3]Nordic Volcanological Center, REYKJAVIK, Iceland
[4]Icelandic Meteorological Office, Reykjavik, Iceland
[5]Pennsylvania State University, STATE COLLEGE, United States of America
[6]University of Arizona, TUCSON, AZ, USA
[7]University of Savoie, SAVOIE, France
[8]University of Gothenburg, GOTHENBURG, Sweden

10:20–10:40 **GD-02 Plate spreading in the North Volcanic Zone, Iceland, constrained by geodetic GPS observations and finite element numerical modeling**

Md. Tariqul Islam[1], Erik Sturkell[1], Freysteinn Sigmundsson[2], Benedikt Ófeigsson[3]

[1]University of Gothenburg, GOTHENBURG, Sweden
[2]Nordic Volcanological Center, Institute of Earth Science, University of Iceland, REYKJAVIK, Iceland
[3]Institute of Earth Science, University of Iceland, REYKJAVIK, Iceland

10:40–11:00 **GD-03 Long-term monitoring of coupling between seismic activity and groundwater chemistry at Husavik, northern Iceland**

Alasdair Skelton

Stockholm University, STOCKHOLM, Sweden

11:00–11:20 **GD-04 Rheology in east Iceland, revealed by InSAR and finite element modeling of the GIA around Vatnajökull ice cap**

Amandine Auriac[1], Freysteinn Sigmundsson[2], Karsten Spaans[2], Andrew Hooper[3], Peter Schmidt[4], Bjorn Lund[4]

[1]University of Iceland, REYKJAVIK, Iceland
[2]University of Iceland, Institute of Earth Sciences, REYKJAVIK, Iceland
[3]Delft University of Technology, DEOS, DELFT, Netherlands
[4]Uppsala University, Department of Earth Sciences/Geophysics, UPPSALA, Sweden

11:20–11:40 **GD-05 Preliminary results from GPS measurements of the Värmland Network (Southern Sweden) between 1997-2011**

Faramarz Nilfouroushan[1], Christopher Talbot[1], Peter Hodacs[1], Hemin Koyi[1], Lars Sjöberg[2]

[1]Uppsala University, UPPSALA, Sweden
[2]Royal Institute of Technology (KTH), STOCKHOLM, Sweden

11:40–12:00 **GD-06 The Hydrorift Experiment**

Sigridur Kristjansdottir[1], Kristjan Agustsson[1], Mathilde Adelinet[2], Cécile Doubre[3], Ólafur G. Flóvenz[1], Jérome Fortin[4], Aurore Franco[2], Laurent Geoffroy[2], Gylfi Páll Hersir[1], Ragna Karlsdóttir[1], Alexandre Schubnel[4], Arnar M. Vilhjálmsson[1]

[1]Iceland GeoSurvey, REYKJAVIK, Iceland
[2]Université du Maine, UMR 6112, France
[3]EOST, Université de Strasbourg, STRASBOURG, France
[4]Laboratoire de Géologie, ENS, PARIS, France

10:00–11:40	**IS 3 – Earth history – stratigraphy and palaeontology**	VÍSA

Convener: Friðgeir Grímsson

10:00–10:20 **IS3-1 Palaeoarchean to upper Ediacaran provenance of the Neoproterozoic Mora Formation in northern Spain**

Thanusha Naidoo[1], Udo Zimmermann[1], S.R.A. Bertolino[2], Jeff Vervoort[3], M Moczydlowska-Vidal[4], M Madland[1], Jenny Tait[5]
[1]Universitetet i Stavanger, STAVANGER, Norway
[2]IFEG-FAMAF, CONICET, CORDOBA, Argentina
[3]Washington State University, PULLMAN, United States of America
[4]Uppsala University, UPPSALA, Sweden
[5]University of Edinburgh, EDINBURGH, United Kingdom

10:20–10:40 **IS3-2 What can detrital zircon really tell us about the depositional age and provenance of clastic sediments? The strange case of the Precambrian Eriksfjord Formation sandstones, southern Greenland**

Tom Andersen
University of Oslo, OSLO, Norge

10:40–11:00 **IS3-3 Early Triassic palynostratigraphy of the Barents Sea area, a reflection of environmental instability in the aftermath of the end Permian mass extinction**

Gunn Mangerud[1], Jorunn Os Vigran[2], Atle Mørk[2], Peter A. Hochuli[3]
[1]University of Bergen, N-5020 BERGEN, Norway
[2]Sintef Petroleum Research, NO-7465 TRONDHEIM, Norway
[3]Palaeontological Institute and Museum, University Zürich, CH-8006 ZÜRICH, Switzerland

11:00–11:20 **IS3-4 CO_2 and stomatal responses at the Triassic-Jurassic Boundary**

Margret Steinthorsdottir[1], Jennifer McElwain[2]
[1]Stockholm University, STOCKHOLM, Sweden
[2]University College Dublin, DUBLIN, Ireland

11:20–11:40 **IS3-5 Tracing the phytogeographic history of Northern Hemispheric angiosperms using fossils, tectonic evidence, and palaeoclimate**

Friðgeir Grímsson[1], Thomas Denk[2], Reinhard Zetter[1]
[1]University of Vienna, VIENNA, Austria
[2]Swedish Museum of Natural History, STOCKHOLM, Sweden

10:00–12:00	**SÞ 3 – Tephrochronology – on land, in ice, lakes and sea**	SILFURBERG B

Conveners: Esther R. Guðmundsdóttir and Stefan Wastegård

10:00–10:20 **SÞ3-1 Framework for the tephra stratigraphy and chronology in western Iceland for the last 12ka**

Þorvaldur Þórðarson[1], Áslaug Geirsdóttir[2], Christopher Hayward[1], Gifford Miller[3]
[1]University of Edinburgh, EDINBURGH, United Kingdom
[2]Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, IS-101, REYKJAVIK, Iceland
[3]Department of Geological Sciences, Institute of Arctic and Alpine Research, Uni, BOULDER, CO 80309, United States of America

10:20–10:40 **SÞ3-2 Late glacial and Holocene tephra stratigraphy on the North Icelandic shelf**

Esther Ruth Guðmundsdóttir, Jón Eiríksson, Guðrún Larsen
Institute of Earth Sciences, University of Iceland, REYKJAVÍK, Iceland

10:40–11:00 **SÞ3-3 Mid- and Late Holocene tephrastratigraphy in a high resolution marine archive from the Eastern Norwegian Sea (Ormen Lange)**

Haflidi Haflidason
University of Bergen, BERGEN, Norway

11:00–11:20 **SÞ3-4 How much of the 'European' tephrochronological framework is North American?**

Sean PYNE-O'DONNELL
University of Bergen, BERGEN, Norway

11:20–11:40 **SÞ3-5 The Hoftorfa tephra: a 6th Century tephra layer from Eyjafjallajökull**

Kate Smith[1], Andrew Dugmore[1], Kerry-Anne Mairs[1], Thorvaldur Thordarson[1], Guðrún Larsen[2], Anthony Newton[1], Costanza Bonadonna[3]
[1]*University of Edinburgh, EDINBURGH, United Kingdom*
[2]*Institute of Earth Sciences, University of Iceland, REYKJAVÍK, Iceland*
[3]*Earth and Environmental Sciences Section, University of Geneva, GENEVA, Switzerland*

11:40–12:00 **SÞ3-6 The Classical Surtarbrandsgil Locality, Brjánslækur, W. Iceland – A Mineralogical and Chemical Study**

Elen Roaldset[1], Hrefna Kristmannsdóttir[2]
[1]*University of Oslo, OSLO, Norway*
[2]*University of Akureyri, AKUREYRI, Iceland*

12.00–13.00 **Lunch**

13:00–13:30 **Plenary 2** SILFURBERG B

PL-2 Glaciological research in Iceland: reflections and outlook in the beginning of the 21st century

Helgi Björnsson
Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

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13:40–15:40 **EP 1 – Tectonic evolution of the North Atlantic area** STEMMA

Conveners: Maryam Khodayar

13:40–14:00 **EP1-1 The Transscandinavian Igneous Belt – a large magmatic arc formed along a rotating Proto-Baltica**

Joakim Mansfeld
Stockholm University, STOCKHOLM, Sweden

14:00–14:20 **EP1-2 Structure and evolution of NE Atlantic conjugate margins**

Jan Inge Faleide[1], Filippos Tsikalas[1], Olav A. Blaich[1], Roy Helge Gabrielsen[1], Asbjørn Johan Breivik[1], Rolf Mjelde[2]
[1]*University of Oslo, OSLO, Norway*
[2]*University of Bergen, BERGEN, Norway*

14:20–14:40 **EP1-3 Opening of the North Atlantic & Norwegian – Greenland Sea – Lessons From the South and Central Atlantic Ocean**

Chris Parry
Conocophillips, STAVANGER, Norway

14:40–15:00 **EP1-4 Submarine fieldwork on the Jan Mayen Ridge; integrated seismic and ROV -sampling**

Nils Sandstå[1], Rolf Birger Pedersen[2], Robert Williams[1], Dag Bering[1], Christian Magnus[1], Morten Sand[1], Harald Brekke[1]
[1]*Norwegian Pteroleum Directorate, STAVANGER, Norway*
[2]*University of Bergen, BERGEN, Norway*

15:00–15:20 **EP1-5 The significance of new aeromagnetic surveys for a better understanding of the crustal and basin structures in the Barents Sea**

Laurent Gernigon, Marco Brönner, Odleiv Olesen
Geological Survey of Norway, TRONDHEIM, Norway

15:20–15:40 **EP1-6 Puzzle of Icelandic rift-jumps/migrating transform zones in North Atlantic**

Maryam Khodayar[1], Sveinbjörn Björnsson[2]
[1]*Iceland GeoSurvey, REYKJAVIK, Iceland*
[2]*National Energy Authority (Orkustofnun), REYKJAVIK, Iceland*

13:40–15:40 **ER 2 – CO_2 sequestration** KALDALÓN

Conveners: Sigurður R. Gíslason and Per Ågård

13:40–14:00 **ER2-06 Time-lapse analysis of pseudo-3D seismic data from the CO_2 storage pilot site at Ketzin, Germany**

Monika Ivandic[1], Can Yang[2], Stefan Stefan[3], Calin Calin Cosma[4], Christopher Juhlin[2]
[1]Uppsala Universitet, UPPSALA, Sweden
[2]Department of Earth Sciences, Uppsala University, UPPSALA, Sweden
[3]Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ), POTSDAM, Germany
[4]Vibrometric Oy, PERTTULA, Finland

14:00–14:20 **ER2-07 On uncertainties in estimating the long-term potential for CO_2 mineral storage**

Helge Hellevang, Per Aagaard
University of Oslo, OSLO, Norway

14:20–14:40 **ER2-08 Flux rates for water and carbon during greenschist facies metamorphism estimated from natural examples of carbon sequestration**

Alasdair Skelton
Stockholm University, STOCKHOLM, Sweden

14:40–15:00 **ER2-09 The CarbFix project – Mineral seqestration of CO_2 in basalt**

Sigurdur Gislason[1], Domenik Wolff-Boenisch[1], Andri Stefansson[1], Helgi Alfredsson[1], Kiflom Mesfin[1], Eric Oelkers[2], Einar Gunnlaugsson[3], Holmfridur Sigurdardottir[3], Bergur Sigfusson[3], Edda Aradottir[3], Wally Broecker[4], Juerg Matter[4], Martin Stute[4], Gudni Axelsson[5]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]LMTG-Université de Toulouse-CNRS-IRD-OMP, TOULOUSE, France
[3]Reykjavik Energy, REYKJAVÍK, Iceland
[4]Lamont-Doherty Earth Observatory, NEW YORK, United States of America
[5]ISOR, Iceland GeoSurvey, REYKJAVÍK, Iceland

15:00–15:20 **ER2-10 Dissolution rates of plagioclase feldspars as a function of mineral and solution composition at 25°C**

Snorri Gudbrandsson[1], Domenik Wolff-Boenisch[2], Sigurdur Reynir Gislason[2], Eric H Oelkers[1]
[1]CNRS, TOULOUSE, France
[2]University of Iceland/Institute of Earth Sciences, REYKJAVÍK, Iceland

15:20–15:40 **ER2-11 Reactive transport models of CO_2-water-basalt interaction and applications to CO_2 mineral sequestration**

Edda þind Aradottir[1], Eric Sonnenthal[2], Grímur Björnsson[3], Hannes Jónsson[4]
[1]Reykjavík Energy, REYKJAVÍK, Iceland
[2]Lawrence Berkeley National Laboratory, BERKELEY, United States of America
[3]Reykjavík Geothermal, REYKJAVÍK, Iceland
[4]Science Institute of the University of Iceland, REYKJAVÍK, Iceland

13:40–15:40 **GA 1 – Geohazards in the Nordic and Arctic regions** RÍMA A

Conveners: Þorsteinn Sæmundsson and Hermanns Reginald

13:40–14:00 **GA1-07 Slope-channel coupling and fluvial sediment transfer in a steep mountain river, Oppdal, Norway**

Wenche Larsen
NTNU (Norwegian Univeristy of Technology and Science, TRONDHEIM, Norway

14:00–14:20 **GA1-08 Dynamics of observed extreme winds in Iceland**

Birta Líf Kristinsdóttir[1], Haraldur Ólafsson[2]
[1]Univ. Iceland & Icelandic Meteorol. Office, REYKJAVÍK, Iceland
[2]Univ. Iceland & Bergen, Icel. Meteorol. Office, REYKJAVÍK, Iceland

14:20–14:40 **GA1-09 The marine limit as a basis for mapping of landslide susceptibility in fine-grained, fjord deposits, onshore Norway**

Louise Hansen[1], Harald Sveian[1], Lars Olsen[1], Fredrik Høgaas[1], Bjørn Ivar Rindstad[1], Toril Wiig[2], Einar Lyche[2]
[1]Geological Survey of Norway, TRONDHEIM, Norway
[2]Norwegian Water Resources and Energy Directorate, OSLO, Norway

14:40–15:00 **GA1-10 Dynamics of extreme winds over Iceland in a numerical downscaling of current climate**

Haraldur Ólafsson[1], Hálfdán Ágústsson[2], Ólafur Rögnvaldsson[3], Kristján Jónasson[4]

[1]Univ. Iceland & Bergen, Icel. Meteorol. Office, REYKJAVÍK, Iceland
[2]Inst. Meteorol. Res., Icel. Meteorol. Office & Univ. Iceland, REYKJAVÍK, Iceland
[3]Inst. Meteorol. Res., Univ. Bergen, REYKJAVÍK, Iceland
[4]Univ. Iceland, REYKJAVÍK, Iceland

15:00–15:20 **GA1-11 Climate Change and Natural Hazards in Svalbard**

Jan Otto Larsen

The University Centre in Svalbard, LONGYEARBYEN, Norway

15:20–15:40 **GA1-12 Westman Islands and the South Coast Transportation and Natural Hazards**

Birgir Jónsson

University of Iceland, REYKJAVIK, Iceland

13:40–14:40 **GD – Geodynamics** RÍMA B

Conveners: Steinunn S. Jakobsdóttir , Sigurlaug Hjaltadóttir and Þóra Árnadóttir

13:40–14:00 **GD-07 The inflation and deflation episodes in the Krísuvík geothermal area**

Karolina Michalczewska[1], Sigrún Hreinsdóttir[1], Þóra Árnadóttir[2], Amandine Auriac[1], Thorbjorg Agustsdottir[1], Halldór Geirsson[3], Andrew Hooper[4], Gunnar Gudmundsson[5], Páll Einarsson[1], Freysteinn Sigmundsson[2], Kurt Feigl[6], Rick Bennett[7]

[1]University of Iceland, REYKJAVIK, Iceland
[2]Nordic Volcanological Center, IES, REYKJAVIK, Iceland
[3]The Pennsylvania State University, DUNMORE, PA, USA
[4]Delft University of Technology, DELFT, The Netherlands
[5]Icelandic Meteorological Office, REYKJAVIK, Iceland
[6]University of Wisconsin-Madison, MADISON, WI, USA
[7]University of Arizona, TUCSON, AZ, USA

14:00–14:20 **GD-08 Eyjafjallajökull's plumbing system and magma movements during 2009-2010 through relocated earthquakes and GPS measurements**

Sigurlaug Hjaltadóttir[1], Sigrún Hreinsdóttir[1], Kristín S. Vogfjörð[2], Freysteinn Sigmundsson[1], Ragnar Slunga[3]

[1]Institute of Earth Sciences, REYKJAVIK, Iceland
[2]Icelandic Meteorological Office, REYKJAVIK, Iceland
[3]QuakeLook Stockholm AB, STOCKHOLM, Sweden

14:20–14:40 **GD-09 The May 2008 earthquake sequence: Crustal deformation, stress and strain.**

Thóra Árnadóttir[1], Martin Hensch[1], Björn Lund[2], Sigrún Hreinsdóttir[3], Judicael Decriem[1]

[1]Nordic Volcanological Center, REYKJAVIK, Iceland
[2]Dept. of Earth Sci., Uppsala University, UPPSALA, Sweden
[3]Dept. of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

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13:40–15:00 **IS 2 – Developments in data aquisition, modelling and visualization** VÍSA

Conveners: Ola Fredin and Anders Romundset

13:40–14:00 **IS2-1 Evaluation of geological specimen composition and structure using X-ray µCT. Part 2: qualitative and quantitative analyses**

Mark Tarplee[1], Emrys Phillips[2], Jaap Van der Meer[1], Graham Davis[1], Anders Schomacker[3], Ólafur Ingólfsson[4], John Groves[5], Bryn Hubbard[5]

[1]Queen Mary, University of London, LONDON, United Kingdom
[2]British Geological Survey, EDINBURGH, Scotland
[3]Norwegian University of Science and Technology, Department of Geology, TRONDHEIM, Norway
[4]University of Iceland, Department of Geology and Geography, REYKJAVÍK, Iceland
[5]Institute of Geography & Earth Sciences, Aberystwyth University, ABERYSTWYTH, United Kingdom

14:00–14:20 **IS2-2 Mapping of Quaternary deposits at the Geological Survey of Norway: Digital workflow from field observation to database and hard-copy map**

Ola Fredin, Renata Lapinska-Viola, Lena Rubensdotter, Bjørn Andre Follestad, Bjørn-Ivar Rindstad, Jochen Knies, Anders Romundset

Geological Survey of Norway, TRONDHEIM, Norway

14:20–14:40	**IS2-3 Generating digital surfaces – mapping the sub-Cambrian peneplain in southern Norway** Erlend Morisbak Jarsve[1], Roy Helge Gabrielsen[1], Svein Olav Krøgli[2] *[1]University of Oslo, OSLO, Norge* *[2]The Norwegian Forest and Landscape Institute, ÅS, Norge*	
14:40–15:00	**IS2-4 Application of SketchUp, ArcScene and GSI3D for 2.5D visualisation and analysis of geophysical data from valley-fill deposits** Louise Hansen *Geological Survey of Norway, TRONDHEIM, Norway*	

13:40–14:20	**SÞ 3 – Tephrochronology – on land, in ice, lakes and sea**	SILFURBERG B
	Conveners: Esther R. Guðmundsdóttir and Stefan Wastegård	
13:40–14:00	**SÞ3-7 Deposition in the UK of Tephra from Recent Icelandic Eruptions.** John Stevenson[1], Susan Loughlin[2], Colin Rae[3], Alison MacLeod[4], Thor Thordarson[1] *[1]University of Edinburgh, EDINBURGH, United Kingdom* *[2]British Geological Survey, EDINBURGH, United Kingdom* *[3]A.E.A., GLENGARNOCK, United Kingdom* *[4]Plymouth University, PLYMOUTH, United Kingdom*	
14:00–14:20	**SÞ3-8 Towards a complete Holocene tephrochronology for the Faroe Islands** Stefan Wastegård[1], Esther Gudmundsdóttir.[2], Ewa Lind[1], Jesper Olsen[3] *[1]Stockholm University, STOCKHOLM, Sweden* *[2]University of Iceland, REYKJAVÍK, Iceland* *[3]Queen's University, BELFAST, United Kingdom*	

14:20–15:40	**SÞ 2 – Eruption types and styles in Iceland and long distnace plume transport**	SILFURBERG B
	Conveners: Ármann Höskuldsson and Fred Prata	
14:20–14:40	**SÞ2-1 What caused the Grímsvötn 2011 eruption to penetrate into the stratosphere?** Olgeir Sigmarsson[1], Ármann Höskuldsson[1], Þorvaldur Þórðarson[2], Guðrún Larsen[1] *[1]Sciences Institute, REYKJAVIK, Iceland* *[2]University of Edinburgh, School of Geoscience, EDINBURGH, Scotland*	
14:40–15:00	**SÞ2-2 Assessing simple models of volcanic plumes using observations from the summit eruption of Eyjafjallajökull in 2010** Halldór Björnsson *Icelandic Meteorology Office, REYKJAVIK, Iceland*	
15:00–15:20	**SÞ2-3 Energy fluxes in volcanic eruptions** Magnús Gudmundsson[1], Bernd Zimanowski[2], Ralf Buettner[2], Piero Dellino[3], Tanya Jude-Eton[4], Thorvaldur Thordarson[4], Björn Oddsson[1], Guðrún Larsen[5] *[1]Nordvulk, Institute of Earth Sciences, REYKJAVÍK, Iceland* *[2]Physicalisch Vulkanologisches Labor, Universität Würzburg, WÜRZBURG, Germany* *[3]Dipartimento Geomieralogico, Universitá di Bari, BARI, Italy* *[4]Department of Earth Sciences, University of Edinburgh, EDINBURGH, United Kingdom* *[5]Institute of Earth Sciences, University of Iceland, REYKJAVÍK, Iceland*	
15:20–15:40	**SÞ2-4 Resuspension of ash from the Grímsvötn volcanic eruption** Hálfdán Ágústsson[1], Haraldur Ólafsson[2] *[1]Inst. Meteorol. Res., Icel. Meteorol. Office & Univ. Iceland, REYKJAVÍK, Iceland* *[2]Univ. Icel. & Bergen, Icel. Meteorol. Inst., REYKJAVÍK, Iceland*	
15:40–17:00	**Poster session with refreshment**	FOYER OF KALDALÓN
17:00–18:30	**Icebreaker – Reykjavik City Hall**	

Tuesday, January 10

08:20–08:50	**Plenary 3**	SILFURBERG B

PL-3 When did Humans first cross the Arctic Circle – and were they Neandertals or Modern Humans?

Jan Mangerud
Department of Earth Science and Bjerknes Centre for Climate Research, University of Bergen, BERGEN, Norway

09:00–10:20	**EC 1 – Glaciers and glacial processes**	SILFURBERG B

Conveners: Ívar Örn Benediktsson and Tómas Jóhannesson

09:00–09:20 **EC1-01 Reconstructing chronology of post-glacial mass movements in the Skagafjörður, (Northern Iceland) from radiocarbon, tephrochronological and geomorphological results**

Denis Mercier[1], Armelle Decaulne[2], Etienne Cossart[3], Thierry Feuillet[1], Þorsteinn Sæmundsson[4], Helgi Jonsson[4]
[1]University of Nantes – CNRS Laboratoire Geolittomer, NANTES CEDEX 3, France
[2]CNRS-Geolab UMR 6042, CLERMONT-FERRAND, France
[3]University Paris1-Labo. Prodig, PARIS, France
[4]Natural Research Centre of NW Iceland, SAUÐÁRKRÓKUR, Iceland

09:20–09:40 **EC1-02 Formation of the Hellemobotn (Vuodnabahta) Canyon in Tysfjord, Northern Norway**

Håvard Dretvik
University of Bergen, BERGEN, Norway

09:40–10:00 **EC1-03 Speleogenesis in the marble karst of north Norway during the last interglacial- glacial cycle**

Stein-Erik Lauritzen[1], Rannveig, Ø. Skoglund[2]
[1]Department of Earth Science, BERGEN, Norway
[2]Department of Geography, BERGEN, Norway

10:00–10:20 **EC1-04 Lateral debris accumulations above the glacial equilibrium altitude line: lateral moraines or talus landforms?**

Ivar Berthling[1], Geir Vatne[1], Ola Fredin[2]
[1]Norwegian University of Science and Technology, TRONDHEIM, Norway
[2]Geological Survey of Norway/Department of Geography, NTNU, TRONDHEIM, Norway

09:00–10:20	**EC 4 – Climate change impacts in the Nordic region during the 21st century**	RÍMA A

Conveners: Þorsteinn Þorsteinsson and Halldór Björnsson

09:00–09:20 **EC4-01 Climate scenarios for the Nordic Region until 2050: results from the CES project**

Erik Kjellström[1], Räisänen Jouni[2], Drews Martin[3], Haugen Jan Erik[4]
[1]SMHI, NORRKÖPING, Sweden
[2]University of Helsinki, HELSINKI, Finland
[3]DMI, COPENHAGEN, Denmark
[4]Met.No, OSLO, Norway

09:20–09:40 **EC4-02 Climate change scenarios for Iceland**

Halldór Björnsson, Nikolai Nawri
Icelandic Meteorology Office, REYKJAVIK, Iceland

09:40–10:00 **EC4-03 Downscaling precipitation in Scandinavia in a future climate scenario**

Ólafur Rögnvaldsson[1], Hálfdán Ágústsson[2], Haraldur Ólafsson[3]
[1]Inst. Meteorol. Res. & Univ. Bergen, REYKJAVÍK, Iceland
[2]Inst. Meteorol. Res., Icel. Meteorol. Office & Univ. Iceland, REYKJAVÍK, Iceland
[3]Univ. Iceland & Bergen and Icel. Meteorol. Office, REYKJAVÍK, Iceland

10:00–10:20 **EC4-04 Precipitation over Iceland simulated in a future climate scenario at various horizontal resolutions**

Hálfdán Ágústsson[1], Ólafur Rögnvaldsson[2], Haraldur Ólafsson[3]
[1]Inst. Meteorol. Res., Icel. Meteorol. Office & Univ. Iceland, REYKJAVÍK, Iceland
[2]Inst. Meteorol. Res., & Univ. Bergen, REYKJAVÍK, Iceland
[3]Univ. Icel. & Bergen, Icel. Meteorol. Inst., REYKJAVÍK, Iceland

09:00–10:20	**EP 3 – Structure and stability of minerals**	RÍMA B

Conveners: Kristján Jónasson and Alasdair Skelton

09:00–09:20 **EP3-1 Non-carbonate subglacial minerals, preliminary study**

Martin Gasser, Christian Schlüchter

University of Bern, Bern, Switzerland

09:20–09:40 **EP3-2 Reycrystallization of submicrometer calcite**

Logan Schultz, Knud Dideriksen, Dirk Mueter, Denis Okhrimenko, Susan Stipp

Copenhagen University, COPENHAGEN, Denmark

09:40–10:00 **EP3-3 Encrustations from the 2010 Fimmvörðuháls eruption**

Kristján Jónasson, Sveinn P. Jakobsson

Icelandic Institute of Natural History, GARÐABÆR, Iceland

10:00–10:20 **EP3-4 Rich mineralogy of the fumaroles on Eldfell volcano, Heimaey, Iceland**

Tonci Balic-Zunic[1], Morten Jacobsen[1], Donatela Mitolo[2], Anna Katerinopoulou[1], Anna Garavelli[2], Sveinn Jakobsson[3], Pasquale Acquafredda[2], Filippo Vurro[2]

[1]University of Copenhagen, COPENHAGEN, Denmark
[2]University of Bari, BARI, Italy
[3]Icelandic Institute of Natural History, REYKJAVIK, Iceland

09:00–10:20	**ER 1 – Geothermal Research and exploitation**	STEMMA

Conveners: Anette K. Mortensen and Björn S. Harðarson

09:00–09:20 **ER1-1 Key Issue in Climate Mitigation: Capacity Building in Renewable Energy Technologies in Developing Countries**

Ingvar Birgir Fridleifsson

United Nations University, REYKJAVIK, Iceland

09:20–09:40 **ER1-2 Iceland Deep Drilling Project (IDDP) – Status in 2012**

Guðmundur Friðleifsson

HS Orka hf, REYKJANESBÆR, Iceland

09:40–10:00 **ER1-3 Induced and triggered seismicity in Icelandic geothermal systems**

Kristján Ágústsson, Ólafur Flóvenz

Iceland GeoSurvey, REYKJAVÍK, Iceland

10:00–10:20 **ER1-4 Evolution of the Hengill Volcanic Center, SW-Iceland**

Steinthor Nielsson

Iceland GeoSurvey, REYKJAVIK, Iceland

09:00–10:20	**IS 4 – General contributions to geosicence – Open for session proposals**	VÍSA

Conveners: Árni Hjartarson

09:00–09:20 **IS4-1 GeoTreat – the geotourism app for Fennoscandia**

Erika Ingvald

Geological Survey of Sweden, UPPSALA, Sweden

09:20–09:40 **IS4-2 The Norwegian millstone landscape: new insight from multidisciplinary research**

Gurli Birgitte Meyer[1], Tor Grenne[1], Irene Baug[2], Torbjørn Løland[3], Øystein James Jansen[2], Tom Heldal[1]

[1]The Geological Survey of Norway, TRONDHEIM, Norway
[2]University of Bergen, BERGEN, Norway
[3]The Municipality of Hyllestad, HYLLESTAD, Norway

09:40–10:00 **IS4-3 Paleogeopraphy and depositional environment of Grumantbyen Formation (Paleocene), Svalbard**

Espen Simonstad[1], William Helland-Hansen[2], John Gjelberg[3]

[1]Norwegian Petroleum Directorate, STAVANGER, Norge
[2]University of Bergen, BERGEN, Norge
[3]North Energy ASA, ALTA, Norge

10:00–10:20 **IS4-4 Relay evolution in carbonate rocks: implications for localizing point sourced conduits for vertical and lateral fluid flow**

Atle Rotevatn[1], Eivind Bastesen[2]
[1]University of Bergen, BERGEN, Norway
[2]Uni CIPR, BERGEN, Norway

09:00–10:20 **UV 1 – Volcanoes in Iceland** KALDALÓN

Conveners: Ármann Höskuldsson and Hannes Mattson

09:00–09:20 **UV1-1 Post glacial activity and magma output rates on the Askja volcanic system**

Þorvaldur Þórðarson, Margaret Hartley
University of Edinburgh, EDINBURGH, United Kingdom

09:20–09:40 **UV1-2 The Hekla 2000 tephra deposit: Grain-size characteristics and eruptive parameters**

Kate Smith[1], Costanza Bonadonna[2], Thorvaldur Thordarson[1], Ármann Höskuldsson[3], Guðrún Larsen[3], Stefán Árnason[3], Freysteinn Sigmundsson[3]
[1]University of Edinburgh, EDINBURGH, United Kingdom
[2]Earth and Environmental Sciences Section, University of Geneva, GENEVA, Switzerland
[3]Institute of Earth Sciences, University of Iceland, REYKJAVÍK, Iceland

09:40–10:00 **UV1-3 Real-time procsessing of harmonic tremor from digital seismograps in the SILsystem – five volcanic eruptions in 15 years.**

Einar Kjartansson
Icelandic Meteorological Office, REYKJAVIK, Iceland

10:00–10:20 **UV1-4 Sulphur release from Subglacial Basalt Eruptions in Iceland**

Þorvaldur Þórðarson
University of Edinburgh, EDINBURGH, United Kingdom

10:20–10:40 **Refreshments**

10:40–12:00 **EC 1 – Glaciers and glacial processes** SILFURBERG B

Conveners: Ívar Örn Benediktsson and Tómas Jóhannesson

10:40–11:00 **EC1-05 Reconstruction of the deglaciation in Grødalen, northwestern Norway**

Even Vie
University of Bergen, BERGEN, Norway

11:00–11:20 **EC1-06 Changed character of marine varves west of Billingen after Baltic Ice Lake drainage**

Mark Johnson[1], Lovise Casserstedt[2], Rodney Stevens[3]
[1]University of Gothenburg, GÖTEBORG, Sweden
[2]Geovetarcenturm, GÖTEBORG, Sweden
[3]Geovetarcentrum, GÖTEBORG, Sweden

11:20–11:40 **EC1-07 The Genesis of the Kivijärvi-Lohtaja Interlobate Esker and its Implications for Geomorphology and Deglacial Palaeo-Ice stream Dynamics in the Trunk of the Finnish Lake District Lobe**

Elina Marita Ahokangas, Joni Kalevi Mäkinen
University of Turku, TURKU, Finland

11:40–12:00 **EC1-08 Why did ice move so fast? Water under the land-based, southern Scandinavian palaeo-ice streams**

Jan Piotrowski[1], Jerome-Etienne Lesemann[1], Ian Alsop[2], Wojciech Wysota[3]
[1]Aarhus University, AARHUS C, Denmark
[2]University of Aberdeen, ABERDEEN, United Kingdom
[3]N. Copernicus University, TORUN, Poland

10:40–12:00	**EC 4 – Climate change impacts in the Nordic region during the 21st century**	RÍMA A

Conveners: Þorsteinn Þorsteinsson and Halldór Björnsson

10:40–11:00 **EC4-05 The effect of climate change on runoff from two watersheds in Iceland**

Bergur Einarsson, Sveinbjörn Jónsson
Icelandic Meteorological Office, REYKJAVIK, Iceland

11:00–11:20 **EC4-06 Some hydrological consequences of glacier variations**

Oddur Sigurðsson
Icelandic Meteorological Office, 150-REYKJAVÍK, Iceland

11:20–11:40 **EC4-07 The Impact of Climate Change on Glaciers and Glacial Runoff in the Nordic Countries**

Tomas Johannesson[1], Guðfinna Aðalgeirsdottir[2], Anders Ahlstrøm[3], Liss Andreassen[4], Stein Beldring[4], Helgi Björnsson[5], Philippe Crochet[6], Bergur Einarsson[6], Hallgeir Elvehøy[4], Sverrir Guðmundsson[5], Regine Hock[7], Horst Machguth[3], Kjetil Melvold[4], Finnur Pálsson[5], Valentina Radic[8], Oddur Sigurdsson[6], Thorsteinn Thorsteinsson[6]
[1]Icelandic Meteorological Office, REYKJAVÍK, Iceland
[2]Danish Climate Centre, DMI, COPENHAGEN, Denmark
[3]GEUS, COPENHAGEN, Denmark
[4]NVE, OSLO, Norway
[5]University of Iceland, REYKJAVÍK, Iceland
[6]IMO, REYKJAVÍK, Iceland
[7]Uppsala University, UPPSALA, Sweden
[8]University of British Columbia, VANCOUVER, Canada

11:40–12:00 **EC4-08 Climate change impacts on renewable energy sources in the Nordic and Baltic region until 2050**

Thorsteinn Thorsteinsson[1], Árni Snorrason[1], Sten Bergström[2], Halldór Björnsson[1], Niels-Erik Clausen[3], Jórunn Harðardóttir[1], Tómas Jóhannesson[1], Erik Kjellström[2], Tanya Kolcova[4], Jurate Kriauciuniene[5], Seppo Kellomaki[6], Deborah Lawrence[7], Birger Mo[8], Alvina Reihan[9], Jari Schabel[10]
[1]Icelandic Meteorological Office, REYKJAVÍK, Iceland
[2]SMHI, NORRKÖPING, Sweden
[3]Risö National Laboratory, ROSKILDE, Denmark
[4]LVGMA, RIGA, Latvia
[5]Lithuanian Energy Institute, VILNIUS, Lithuania
[6]University of Joensuu, JOENSUU, Finland
[7]NVE, OSLO, Norway
[8]SINTEF, TRONDHEIM, Norway
[9]Tallinn University of Technology, TALLINN, Estonia
[10]VTT, ESPOO, Finland

10:40–12:00	**EP 2 – Structure and processes of the Earth's crust**	RÍMA B

Conveners: Ólafur Guðmundsson and Bryndís Brandsdóttir

10:40–11:00 **EP2-1 Structural and K/Ar illite geochronological constraints on the brittle deformation history of the Olkiluoto region, SW Finland**

Jussi Mattila[1], Giulio Viola[2], Horst Zwingmann[3]
[1]Geological Survey of Finland, ESPOO, Finland
[2]Geological Survey of Norway, 7491 TRONDHEIM, Norway
[3]CSIRO Earth Science and Resource Engineering, BENTLEY W.A. 6102, Australia

11:00–11:20 **EP2-2 S-wave velocity structure of southern Norway from P receiver functions and surface wave dispersion**

Marianne Kolstrup, Valerie Maupin
University of Oslo, OSLO, Norway

11:20–11:40 **EP2-3 Meso- to Neoarchaean evolution of mid- to lower crustal rocks from the North Atlantic Craton of South-East Greenland**

Jochen Kolb[1], Kristine Thrane[1], Leon Bagas[2], Bo Stensgaard[1]
[1]Geological Survey of Denmark and Greenland, COPENHAGEN, Denmark
[2]Centre for Exploration Targeting, University of Western Australia, CRAWLEY, Australia

11:40–12:00 **EP2-4 Complex structuring and sedimentation of the southern Pyrenean foreland basins.**

Roy Gabrielsen[1], Johan Nystuen[1], Cai Puigdefabrigas[2], Ivar Midtkandal[1], Erlend Jarsve[1], Magnus Kjemperud[1]

[1]University of Oslo, OSLO, Norway
[2]University of Barcelona, BARCELONA, Spain

10:40–12:00 **ER 1 – Geothermal Research and exploitation** STEMMA

Conveners: Anette K. Mortensen and Björn S. Harðarson

10:40–11:00 **ER1-5 Hydrothermal dissolution of olivine and pyroxene in the Hellisheiði geothermal field, SW-Iceland**

Helga Margrét Helgadóttir

ISOR – Iceland Geosurvey, REYKJAVÍK, Iceland

11:00–11:20 **ER1-6 Structure and composition of clay minerals in the Hellisheiði Geothermal Field, SW-Iceland**

Sandra Snaebjornsdottir, Bjorn Hardarson, Hjalti Franzson

ISOR/Iceland Geosurvey, REYKJAVIK, Iceland

11:20–11:40 **ER1-7 Opaque minerals in geothermal well HE-42, Hellisheiði, SW Iceland.**

Sveinborg Hlíf Gunnarsdóttir

ISOR, REYKJAVÍK, Iceland

11:40–12:00 **ER1-8 Resistivity from 73 Boreholes in the S-Hengill Geothermal Field, SW-Iceland, compared with Surface Resistivity Data and Alteration Minerals**

Svanbjörg Helga Haraldsdóttir, Hjalti Franzson, Knútur Árnason

ÍSOR (Iceland GeoSurvey), REYKJAVÍK, Iceland

10:40–12:00 **IS 4 – General contributions to geosicence – Open for session proposals** VÍSA

Conveners: Árni Hjartarson

10:40–11:00 **IS4-5 A revised Michel Levy interference color chart based on first principles calculations**

Bjørn Eske Sørensen

NTNU, TRONDHEIM, Norway

11:00–11:20 **IS4-6 The fault architecture and damage zone characteristics of normal, inverted faults of the Northumberland Basin, northeast England**

Magnus Kjemperud[1], Marie Valdresbråten[2], Roy Gabrielsen[3], Roald Færseth[4], Jan Tveranger[4], Simon Buckley[4], Anders Lundmark[3]

[1]University of Oslo, OSLO, Norway
[2]TOTAL Norge, STAVANGER, Norway
[3]Department of Geosciences, University of Oslo, OSLO, Norway
[4]Centre for Integrated Petroleum Research, University of Bergen, BERGEN, Norway

11:20–11:40 **IS4-7 EMODNET GEOLOGY – Data on seafloor geology and substrates for pan-European marine assessments**

Anu Kaskela[1], Ulla Alanen[1], Aarno Kotilainen[1], Stevenson Alan[2]

[1]Geological Survey of Finland, ESPOO, Finland
[2]British Geological Survey (BGS), EDINBURGH, United Kingdom

11:40–12:00 **IS4-8 Holocene saline water inflow changes into the Baltic Sea, ecosystem responses and future scenarios – BONUS+ INFLOW project**

Aarno Kotilainen[1], Laura Arppe[2], Slawomir Dobosz[3], Eystein Jansen[4], Karoline Kabel[5], Juha Karhu[2], Mia Kotilainen[2], Antoon Kuijpers[6], Bryan Lougheed[7], Markus Meier[8], Matthias Moros[5], Thomas Neumann[5], Christian Porsche[5], Niels Poulsen[6], Sofia Ribeiro[6], Bjørg Risebrobakken[4], Daria Ryabchuk[9], Ian Snowball[7], Mikhail Spiridonov[9], Joonas Virtasalo[1], Andrzej Witkowski[3], Vladimir Zhamoida[9]

[1]Geological Survey of Finland, ESPOO, Finland
[2]University of Helsinki, HELSINKI, Finland
[3]University of Szczecin, SZCZECIN, Poland
[4]Bjerknes Centre for Climate Research, BERGEN, Norway
[5]Leibniz-Institute for Baltic Sea Research, WARNEMÜNDE, Germany
[6]Geological Survey of Denmark and Greenland, COPENHAGEN, Denmark

[7]Lund University, LUND, Sweden
[8]Swedish Meteorological and Hydrological Institute, NORRKÖPING, Sweden
[9]A.P.Karpinsky Russian Geological Research Institute (VSEGEI), ST. PETERSBURG, Russian Federation

10:40–11:00 **UV 1 – Volcanoes in Iceland** KALDALÓN

Conveners: Ármann Höskuldsson and Hannes Mattson

10:40–11:00 **UV1-5 Simulation of the eruption of a volatile-rich magma column**

Galen Gisler
University of Oslo, OSLO, Norway

11:00–12:00 **UV 3 – Volcanism in the North Atlantic** KALDALÓN

Conveners: Rolf B. Pedersen and Romain Meyer

11:00–11:20 **UV3-01 Ongoing Challenges on North Atlantic Rift-, Ridge- and Continental Margin-Volcanism**

Romain Meyer, Rolf B. Pedersen
Centre for Geobiology; University of Bergen, BERGEN, Norway

11:20–11:40 **UV3-02 The temporal transition between mantle sources at the end of flood volcanism in the Faroes: the elemental and isotopic development in the Enni Formation at Sandoy**

Paul Martin Holm
University of Copenhagen, COPENHAGEN, Denmark

11:40–12:00 **UV3-03 The evolution of the Icelandic hotspot subsequent to the CFB volcanism in East Greenland and the Faroes: a geochemical and petrological investigation of the tuffs in the Eocene Fur Formation, Denmark**

Majken Djurhuus Poulsen, Paul Martin Holm
University of Copenhagen, COPENHAGEN, Denmark

12:00–13:00 **Lunch**

13:00–13:30 **Plenary 4** SILFURBERG B

PL-4 Modern climate change and sea-level rise

Stefan Rahmstorf
Potsdam Institute, POTSDAM, Germany

13:40–15:00 **EC 1 – Glaciers and glacial processes** SILFURBERG B

Conveners: Ívar Örn Benediktsson and Tómas Jóhannesson

13:40–14:00 **EC1-09 The active drumlin field at the Múlajökull surge-type glacier, Iceland – geomorphology and sedimentology**

Anders Schomacker[1], M. D. Johnson[2], Í. Ö. Benediktsson[3], Ó. Ingólfsson[3], S. A. Jónsson[3]
[1]*Norwegian University of Science & Technology, TRONDHEIM, Norway*
[2]*University of Gothenburg, GÖTEBORG, Sweden*
[3]*University of Iceland, REYKJAVÍK, Iceland*

14:00–14:20 **EC1-10 Strain patterns through a drumlin revealed by till-fabric analysis and GPR profiling**

Simon Carr[1], Niall Lehane[2], Ricky Stevens[1], Jonathan Wheatland[1], Christopher Coleman[3]
[1]*Queen Mary University of London, LONDON, United Kingdom*
[2]*University College Cork, Department of Geography, CORK, Ireland*
[3]*Fugro Environmental Sciences, WALLINGFORD, United Kingdom*

14:20–14:40 **EC1-11 Blast it – fracture propagation, sedimentation and deformation during the evolution of hydrofracture systems**

Emrys Phillips[1], Jaap Van der Meer[2], Mark Tarplee[2]
[1]*British Geological Survey, EDINBURGH, United Kingdom*
2Queen Mary University of London, LONDON, United Kingdom

14:40–15:00 **EC1-12 The landscape architecture of the forefield of Eyjabakkajökull, a surge-type glacier in Iceland**

Ívar Örn Benediktsson[1], Anders Schomacker[2]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]Norwegian University of Science and Technology, TRONDHEIM, Norway

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13:40–15:00 **EC 4 – Climate change impacts in the Nordic region during the 21st century** RÍMA A

Conveners: Þorsteinn Þorsteinsson and Halldór Björnsson

13:40–14:00 **EC4-09 Is the oceanic heat transport towards the Arctic changing ?**

Bogi Hansen[1], Svein Østerhus[2], Steffen Olsen[3], Steingrímur Jónsson[4], Héðinn Valdimarsson[4]
[1]Faroe Marine Research Institute, TÓRSHAVN, Färöerne
[2]Bjerknes Center, BERGEN, Norway
[3]Danish Meteorological Institute, COPENHAGEN, Denmark
[4]Marine Research Institute, REYKJAVIK, Iceland

14:00–14:20 **EC4-10 Modelling the Arctic hydrological cycle – the Devil is in the details**

Jens Christensen, Martin Stendel, Gudfinna Adalgeirsdottir, Ruth Mottram
Danish Meteorological Institute, COPENHAGEN, Denmark

14:20–14:40 **EC4-11 The recently discovered North Icelandic Jet and its role in the Atlantic Meridional Overturning Circulation.**

Steingrimur Jonsson[1], Hedinn Valdimarsson[2], Robert S Pickart[3], Kjetil Våge[4], Daniel J Torres[3], Micheal A Spall[3], Svein Österhus[5], Tor Eldevik[4]
[1]University of Akureyri and Marine Research Institute, AKUREYRI, Iceland
[2]Marine Research Institute, REYKJAVÍK, Iceland
[3]Woods Hole Oceanographic Institution, WOODS HOLE, USA
[4]Geophysical Institute, University of Bergen, BERGEN, Norway
[5]UNI Bjerknes, Bjerknes Center for Climate Research, BERGEN, Norway

14:40–15:00 **EC4-12 The Global Cryosphere Watch**

Árni Snorrason[1], Thorsteinn Thorsteinsson[1], Barry Goodison[2], Jeff Key[3], Tómas Jóhannesson[1]
[1]Icelandic Meteorological Office, REYKJAVÍK, Iceland
[2]WMO, GENEVA, Switzerland
[3]University of Wisconsin, MADISON, USA

13:40–15:00 **EP 4 – Igneous and metamorphic processes** RÍMA B

Conveners: Olgeir Sigmarsson

13:40–14:00 **EP4-1 Metamorphic Map of Sweden**

Alasdair Skelton
Stockholm University, STOCKHOLM, Sweden

14:00–14:20 **EP4-2 Geothermobarometric investigation of St Persholmen, Utö as part of the Metamorphic Map of Sweden**

Adam Engström
Stockholm University, STOCKHOLM, Sweden

14:20–14:40 **EP4-3 Small scale metasomatism of mafic gneiss in the Norwegian Caledonides associated with brine infiltration – Fluid inclusions, SEM-CL and mineralogical record of the fluid infiltration**

Kristian Drivenes
NTNU, TRONDHEIM, Norway

14:40–15:00 **EP4-4 Intra-orogenic magmatism in southwestern Finland: heat source for the late Svecofennian metamorphism?**

Markku Väisänen[1], Jenni Nevalainen[1], Olav Eklund[2], Hugh O'Brien[3]
[1]University of Turku, TURKU, Finland
[2]Åbo Akademi University, TURKU, Finland
[3]Geological Survey of Finland, ESPOO, Finland

13:40–15:00	**IS 1 – Planetary geoscience (including e.g. Impact craters, Mars etc.)**	VÍSA

Conveners: Henning Dypvik and Elin Kalleson

13:40–14:00 **IS1-1 Post impact sedimentation in the Ritland impact structure, Western Norway**

Abdus Samad Azad[1], Henning Dypvik[1], Elin Kalleson[1], Fridtjof Riis[2]
[1]University of Oslo, OSLO, Norway
[2]Norwegian Petroleum Directorate, STAVANGER, Norway

14:00–14:20 **IS1-2 Ejecta distribution and stratigraphy – field evidence from the Ritland impact structure**

Elin Kalleson[1], Ronny Setså[1], Fridtjof Riis[2], Henning Dypvik[1]
[1]University of Oslo, OSLO, Norway
[2]Norwegian Petroleum Directorate, STAVANGER, Norway

14:20–14:40 **IS1-3 Geophysical survey of the proposed målingen Marine-Target Crater, Sweden**

Erik Sturkell[1], Irene Melero Asensio[2], Jens Ormö[2]
[1]University of Gothenburg, GOTHENBURG, Sweden
[2]Centro de Astrobiología (INTA-CSIC), MADRID, Spain

14:40–15:00 **IS1-4 Middle Ordovician L-chondritic meteorite shower and clastic sedimentary facies in Baltoscandian carbonate shelf: are these related?**

Kairi Põldsaar, Leho Ainsaar
University of Tartu, Inst. of Ecology and Earth Sciences, TARTU, Estonia

13:40–15:00	**SÞ 1 – Volcanic eruptions in historical records**	STEMMA

Conveners: Bergrún A. Óladóttir and Jan Mangerud

13:40–14:00 **SÞ1-1 Volcanic eruptions in prehistory – the Laacher See case study**

Felix Riede
Århus University, HØJBJERG, Denmark

14:00–14:20 **SÞ1-2 Short accounts of large events**

Gudrun Larsen[1], Thorvaldur Thordarson[2]
[1]Institute of Earth Sciences, REYKJAVÍK, Iceland
[2]School of GeoSciences, University of Edinburgh, EDINBURGH, Scotland

14:20–14:40 **SÞ1-3 Perception of volcanic eruptions in Iceland**

Þorvaldur Þórðarson
University of Edinburgh, EDINBURGH, United Kingdom

14:40–15:00 **SÞ1-4 Late Holocene terrestrial ecosystem change in West Iceland**

Guðrún Gísladóttir[1], Egill Erlendsson[1], Rattan Prof. Lal[2]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]School of Environment and Natural Resources, the Ohio State University, COLUMBUS, OH, United States of America

13:40–15:00	**UV 3 – Volcanism in the North Atlantic**	KALDALÓN

Conveners: Rolf B. Pedersen and Romain Meyer

13:40–14:00 **UV3-03 Seismic Volcanostratigraphy and Sub-Basalt Structure on the Mid-Norway Margin**

Sverre Planke[1], Mikal Trulsvik[1], Reidun Myklebust[2], Jan Inge Faleide[3], Henrik Svensen[3]
[1]Volcanic Basin Petroleum Research, OSLO, Norway
[2]TGS-NOPEC, ASKER, Norway
[3]University of Oslo, OSLO, Norway

14:00–14:20 **UV3-05 Early Oligocene alkaline volcanism related to the formation of the Jan Mayen Microcontinent**

Rolf Birger Pedersen[1], Jiri Slama[1], Romain Meyer[1], Jan Kosler[1], Bart Hendriks[2]
[1]University of Bergen, BERGEN, Norway
[2]NGU, TRONDHEIM, Norway

14:20–14:40 **UV3-06 Lead Isotope and Trace Element Results for Basaltic Rocks Dredged from the Extinct Aegir Ridge and the Jan Mayen Fracture Zone**

Barry Hanan[1], Kaan Sayit[1], Garrett Ito[2], Samuel Howell[2], Peter Vogt[3], Asbjorn Breivik[4]

[1]San Diego State University, SAN DIEGO, USA
[2]University of Hawaii, HONOLULU, HAWAII, United States of America
[3]University of California, Santa Barbara, SANTA BARBARA, CALIFORNIA, United States of America
[4]University of Oslo, OSLO, Norway

14:40–15:00 **UV3-07 The Tertiary Rum Volcanic Centre, NW-Scotland: origin, evolution and death of a large central volcano**

Valentin Troll[1], Graeme Nicoll[1], Henry Emeleus[2], Colin Donaldson[3], Rob Ellam[4]

[1]Uppsala University, UPPSALA, Sweden
[2]Durham University, DURHAM, United Kingdom
[3]University of St Andrews, ST ANDREWS, United Kingdom
[4]SUERC, EAST KILBRIDE, GLASGOW, United Kingdom

15:00–15:20 **Refreshments**

15:20–16:20 **EC 1 – Glaciers and glacial processes** SILFURBERG B

Conveners: Ívar Örn Benediktsson and Tómas Jóhannesson

15:20–15:40 **EC1-13 Mapping the Surface and Surface Changes of Icelandic Ice Caps with LiDAR**

Tómas Jóhannesson[1], Helgi Björnsson[2], Finnur Pálsson[2], Oddur Sigurðsson[1], Þorsteinn Þorsteinsson[1]

[1]Icelandic Meteorological Office, REYKJAVIK, Iceland
[2]Institute of Earth Science, University of Iceland, REYKJAVIK, Iceland

15:40–16:00 **EC1-14 Hofsjökull ice cap: 25 years of mass-balance measurements and related research**

Thorsteinn Thorsteinsson, O. Sigurdsson, B. Einarsson, T. Jóhannesson, V.S. Kjartansson

Icelandic Meteorological Office, REYKJAVÍK, Iceland

16:00–16:20 **EC1-15 High resolution glacier catchment monitoring: the Virkisjökull Observatory, southeast Iceland**

Jeremy Everest[1], Tom Bradwell[1], Heiko Buxel[1], Andrew Finlayson[1], Lee Jones[1], Michael Raines[1], Thomas Shanahan[1], Óðinn Þórarinnsson[2], Bergur Bergsson[2]

[1]British Geological Survey, EDINBURGH, United Kingdom
[2]Veðurstofa Íslands, REYKJAVIK, Iceland

15:20–16:40 **EP 4 – Igneous and metamorphic processes** RÍMA B

Conveners: Olgeir Sigmarsson

15:20–15:40 **EP4-5 Crystallization-induced melt migration in columnar basalts**

Hannes Mattsson[1], Sonja Bosshard[1], Bjarne Almqvist[2], Luca Caricchi[3], Mark Caddick[1], György Hetenyi[1], Ann Hirt[4]

[1]Institute for Geochemistry and Petrology, ZURICH, Switzerland
[2]Geological Institute, ETH Zurich, ZURICH, Switzerland
[3]Department of Earth Sciences, University of Bristol, BRISTOL, United Kingdom
[4]Institute of Geophysics, ETH Zürich, ZURICH, Switzerland

15:40–16:00 **EP4-6 Is formation segregation melts in basaltic lava flows a viable analogue to melt generation in basaltic systems?**

Þorvaldur Þórðarson[1], Olgeir Sigmarsson[2], Margaret Hartley[1], Jay Miller[3]

[1]University of Edinburgh, EDINBURGH, United Kingdom
[2]Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, IS-101, REYKJAVIK, Iceland
[3]IODP, Texas A&M University, 1000 Discovery Drive,, COLLEGE STATION, TEXAS 77845-9547, United States of America

16:00–16:20 **EP4-7 Stability of götzenite in peralkaline nephelinite at Nyiragongo, D.R. Congo**

Tom Andersen[1], Marlina Elburg[2], Muriel Erambert[1]

[1]University of Oslo, OSLO, Norge
[2]University of KwaZulu-Natal, DURBAN, South Africa

15:20–17:00	**IS 1 – Planetary geoscience (including e.g. Impact craters, Mars etc.)**	VÍSA

Conveners: Henning Dypvik and Elin Kalleson

15:20–15:40 **IS1-5 The origin of alteration fluids at the Ries crater, Germany: boron isotopic composition of secondary smectite in suevites**

Nele Muttik[1], Kalle Kirsimäe[1], Horton Newsom[2], Lynda Williams[3]
[1]University of Tartu, TARTU, Estonia
[2]University of New Mexico, ALBUQUERQUE, United States of America
3Arizona State University, TEMPE, United States of America

15:40–16:00 **IS1-6 Water-Related Geological events of the Eastern Hellas Rim, Mars**

Jouko Raitala[1], Petri Kostama[1], Soile Kukkonen[1], Mikhail Ivanov[2], Jarmo Korteniemi[1]
[1]University of Oulu, OULU, Finland
2Vernadsky Institute, MOSCOW, Russian Federation

16:00–16:20 **IS1-7 Alteration of impact melt – implications for our understanding of Noachian of Mars?**

Henning Dypvik[1], Helge Hellevang[2], Elin Kalleson[1]
[1]University of Oslo, OSLO, Norway
[2]University of Oslo, OSLO, Norway

16:20–16:40 **IS1-8 Bicarbonate, olivine, hydrogen and methane**

Anna Neubeck[1], Thanh Duc Nguyen[1], Helge Hellevang[2], Josefin Plathan[1], David Bastviken[3], Nils Holm[1]
[1]Stockholm University, STOCKHOLM, Sweden
[2]University of Oslo, OSLO, Norway
[3]Linköping University, LINKÖPING, Sweden

16:40–17:00 **IS1-9 Biosignatures in secondary minerals in tertiary basalts, Breiðdalur, Eastern Iceland**

Christa Maria Feucht
Iceland Geosurvey ISOR, REYKJAVIK, Iceland

15:20–16:00	**SÞ 1 – Volcanic eruptions in historical records**	STEMMA

Conveners: Bergrún A. Óladóttir and Jan Mangerud

15:20–15:40 **SÞ1-5 The Askja 1875 eruption: World’s first map of an ash plume and properties of the ash from samples collected in Norway in 1875**

Jan Mangerud[1], Thorvaldur Thordarson[2], John Stevenson[2]
[1]University of Bergen, BERGEN, Norway
[2]Earth And Planetary Sciences, School of Geosciences, University of Edinburgh, EDINBURGH, United Kingdom

15:40–16:00 **SÞ1-6 The Grímsvötn 2011 eruption – scientific and social views**

Bergrún Óladóttir[1], G. Larsen[2], A. Höskuldsson[1], M.T. Gudmundsson[2]
[1]Nordic Volcanological Center, REYKJAVIK, Iceland
[2]Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

15:20–17:00	**UV 3 – Volcanism in the North Atlantic**	KALDALÓN

Conveners: Rolf B. Pedersen and Romain Meyer

15:20–15:40 **UV3-08 Atypical depleted mantle components at Mohns Ridge and along the Mid-Atlantic Ridge near the Azores**

Cedric Hamelin[1], Laure Dosso[2], Antoine Bezos[3], Javier Escartin[4], Mathilde Cannat[4], Catherine Mevel[4]
[1]IPGP, PARIS, France
[2]CNRS, BREST, France
[3]Nantes University, NANTES, France
[4]CNRS, IPGP, PARIS, France

15:40–16:00 **UV3-09 Eocene volcanism in Virginia: The North American ‚passive‘ rifted margin being not so passive**

Lauren Schultz[1], Romain Meyer[2], David Harbor[1], Chris Connors[1], Bart W.H. Hendricks[3]
[1]Washington and Lee University, LEXINGTON, VA, United States of America
[2]University of Bergen, BERGEN, Norway
[3]Norges geologiske undersøkelse, TRONDHEIM, Norway

16:00–16:20 **UV3-10 A late Devonian to late Jurassic volcanic triplet in the Embla oil field, the North Sea: constraints from geochemical signatures in altered volcanic rocks**

Anders Mattias Lundmark[1], Roy H. Gabrielsen[1], Tor Strand[2], Sverre E. Ohm[2]
[1]Oslo University, OSLO, Norway
[2]ConocoPhillips Norge, STAVANGER, Norway

16:20–16:40 **UV3-11 The mantle source of Eyjafjallajökull volcano**

Olgeir Sigmarsson[1], Séverine Moune[2], Pierre Schiano[2]
[1]Sciences Institute, REYKJAVIK, Iceland
[2]Laboratoire Magmas et Volcans, CNRS – Université Blaise Pascal – IRD, CLERMONT-FERRAND, France

16:40–17:00 **UV3-12 Volcanological studies of the Neogene Hólmar and Grjótá olivine basalt lava groups in eastern Iceland**

Birgir Oskarsson, Morten Riishuus
Nordic Volcanological Center, REYKJAVÍK, Iceland

17:00	**Conference dinner with bath – Bus departure from Harpa to Blue Lagoon**
18:15	**Conference dinner without bath – Bus departure from Harpa to Blue Lagoon**
19:00	**Conference dinner**

Wednesday, January 11

Conference Excursions

Thursday, January 12

08:00–08:50 **Plenary 5 – Nordic Geoscientist Award** SILFURBERG B

09:00–10:20 **EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments** SILFURBERG B

Conveners: Ólafur Ingólfsson

09:00–09:20 **EC2-01 Mid and Late Holocene glacier changes in Greenland**

Ole Bennike[1], Jason Briner[2], Lena Håkansson[1], Thomas Lowell[3]
[1]GEUS, COPENHAGEN, Danmark
[2]University at Buffalo, BUFFALO, United States of America
[3]University of Cincinnati, CINCINNATI, USA

09:20–09:40 **EC2-02 The climatic signal in the stable isotope record of the NEEM SS0802 shallow firn/ice core from the NEEM deep drilling site in NW Greenland**

Hera Gudlaugsdottir, Árny Erla Sveinbjörnsdóttir, Sigfús J. Johnsen
Institude of Earth Sciences, REYKJAVIK, Iceland

09:40–10:00 **EC2-03 Climate and volcanic reconstructions from the Greenland ice core records**

Sune Olander Rasmussen, Sigfús J. Johnsen, Anders Svensson, Bo Vinther, Henrik B. Clausen, Inger Seierstad
Niels Bohr Institute, University of Copenhagen, COPENHAGEN, Denmark

10:00–10:20 **EC2-04 Middle to Late Pleistocene stratigraphy and Kara Sea Ice Sheet margins on the Taymyr Peninsula, Arctic Siberia: current status and future plans**

Per Möller[1], Ívar Örn Benediktsson[2]
[1]Lund university, LUND, Sweden
[2]Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

09:20–10:20 **ER 6 – Environmental Impact and Challenges** RÍMA B

Conveners: Magnús Ólafsson and Halldór Ármannsson

09:20–09:40 **ER6-1 Challenges managing environmental impact assessment of geothermal projects**

Auður Andrésdóttir
Mannvit, REYKJAVÍK, Iceland

09:40–10:00 **ER6-2 Using benthic foraminifera as bioindicators of pollution in the SW Barents Sea**

Noortje Dijkstra[1], Juho Junttila[1], JoLynn Carroll[2], Katrine Husum[1], Morten Hald[1]
[1]University of Tromsø, TROMSØ, Norge
[2]Akvaplan Niva, TROMSØ, Norway

10:00–10:20 **ER6-3 Anthropogenic pollutants in surface sediments of SW Barents Sea**

Juho Junttila[1], Noortje Dijkstra[1], JoLynn Carroll[2], Morten Hald[1]
[1]University of Tromsø, TROMSØ, Norge
[2]Akvaplan-niva, TROMSØ, Norway

09:00–10:20 **GA 2 – Risk assessment and management of geohazards** KALDALÓN

Conveners: Anders Solheim and Harpa Grímsdóttir

09:00–09:20 **GA2-1 The SafeLand project; Impacts of global change on landslide hazard and risk in Europe in 21st century**

Christian Jaedicke[1], Farrokh Nadim[1], Bjørn Kalsnes[1], Kjetil Sverdrup-Thygeson[1], Christine Radermacher[2], Guenther Fischer[3], Javier Hervas[4], Miet Van den Eeckhaut[4], Anders Solheim[5]
[1]NGI/ICG, OSLO, Norway
[2]MPG, HAMBURG, Germany
[3]IIASA, LAXENBURG, Austria
[4]JRC, ISPRA, Italy
[5]NGI, OSLO, Norway

09:20–09:40 **GA2-2 Landslide hazard mapping in Bergen, Norway**

Espen Eidsvåg
University of Bergen, BERGEN, Norway

09:40–10:00 **GA2-3 Assessing and managing the risk from landslides in a loess plateau, Heifangtai, Gansu Province, NW China**

Anders Solheim[1], Øyvind Armand Høydahl[2], Trond Vernang[2], Zhang Maosheng[3]
[1]Norwegian Geotechnical Institute, OSLO, Norway
[2]NGI, OSLO, Norway
[3]China Geological Survey, X'IAN, China

10:00–10:20 **GA2-4 Avalanche hazard mapping and risk assessment in Iceland**

Harpa Grimsdottir, Eirikur Gislason, Tomas Johannesson
Icelandic Meteorological Office, ISAFJORDUR, Iceland

09:00–10:20 **UV 4 – Magma plumbing system** RÍMA A

Conveners: Paul Martin Holm and Christian Tegner

09:00–09:20 **UV4-01 Volcanic plumbing systems in Iceland; inferences from geodetic observations**

Rikke Pedersen[1], Freysteinn Sigmundsson[1], Sigrun Hreinsdóttir[2], Elske De Zeeuw-van Dalfsen[3], Andrew Hooper[4], Erik Sturkell[5], Timothy Masterlark[6]
[1]Nordic Volcanological Center, REYKJAVIK, Iceland
[2]Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland
[3]IPGP, Equipe de Dynamique des Fluides Geologiques, PARIS, France
[4]Delft University of Technology, DELFT, Netherlands
[5]Göteborg University, GÖTEBORG, Sweden
[6]University of Alabama, TUSCALOOSA, USA

09:20–09:40 **UV4-02 Deformation cycle of the Grímsvötn sub-glacial volcano, Iceland, measured by GPS**

Erik Sturkell[1], Freysteinn Sigmundsson[2], Páll Einarsson[3], Sigrún Hreinsdóttir[3], Thierry Villemin[4], Halldór Geirsson[5], Benedikt Ófeigsson[6], Francois Jouanne[4], Helgi Björnsson[3], Gunnar Gudmundsson[6], Finnur Pálsson[3]
[1]University of Gothenburg, GOTHENBURG, Sweden
[2]Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland
[3]Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland
[4]Laboratoire de Géodynamique des Chaînes Alpines UMR 5025, Université de Savoie, LE BOURGET DU LAC, France
[5]The Pennsylvania State University, STATE COLLEGE, USA
[6]The Icelandic Meteorological Office, REYKJAVIK, Iceland

09:40–10:00 **UV4-03 Grímsvötn 2011 Explosive Eruption, Iceland: Relation between Magma Chamber Pressure Drop inferred from High Rate Geodesy and Plume Strength from Radar Observations**

Freysteinn Sigmundsson[1], Sigrun Hreinsdottir[1], Halldór Björnsson[2], Þórður Arason[2], Ronni Grapenthin[3], Matthew Roberts[2], Jósef Hólmjárn[2], Halldór Geirsson[4], Þóra Árnadóttir[1], Rick Benett[5], Björn Oddsson[1], Magnús Tumi Guðmundsson[1], Benedikt G. Ófeigsson[2], Thierry Villemin[6], Erik Sturkell[7]
[1]University of Iceland, REYKJAVIK, Iceland
[2]Icelandic Meteorological Office, REYKJAVIK, Iceland
[3]University of Alaska, FAIRBANKS, USA
[4]Pennsylvania State University, STATE COLLEGE, United States of America
[5]University of Arizona, TUCSON, USA
[6]University of Savoie, SAVOIE, France
[7]University of Gothenburg, GOTHENBURG, Sweden

10:00–10:20 **UV4-04 Resonating eruptive flow rate during the Grímsvötn 2011 volcanic eruption**

Þórður Arason[1], Halldór Björnsson[1], Guðrún Nína Petersen[1], Matthew J. Roberts[1], Melanie Collins[2]
[1]Icelandic Meteorological Office – Veðurstofa Íslands, REYKJAVÍK, Iceland
[2]Met Office, EXETER, United Kingdom

10:20–10:40 **Refreshment**

10:40–12:00	**EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments**	SILFURBERG B

Conveners: Ólafur Ingólfsson

10:40–11:00 **EC2-05 Lake Lögurinn, Eastern Iceland – recording the Holocene meltwater and surge history of Eyjabakkajökull**

Ólafur Ingólfsson[1], Svante Björck[2], Johan Striberger[2]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]Lund University, Sweden, LUND, Sweden

11:00–11:20 **EC2-06 History of glacier variations of Vatnajökull´s southeast outlet glaciers during the last 300 years -a key to modelling their response to climate change**

Hrafnhildur Hannesdóttir
University of Iceland, REYKJAVÍK, Iceland

11:20–11:40 **EC2-07 A new Svalbard land-ocean deglaciation chronology of the northern Barents Sea ice sheet**

Anne Hormes[1], Endre Gjermundsen[1], Tine Rasmussen[2]
[1]University Centre in Svalbard, LONGYEARBYEN, Norway
[2]University of Tromsø, TROMSØ, Norway

11:40–12:00 **EC2-08 New data on Late Weichselian ice stream configuration in Kongsfjorden, NW Svalbard**

Mona Henriksen[1], Jon Y. Landvik[1], Gustaf Peterson[2], Helena Alexanderson[3]
[1]Norwegian University of Life Sciences, ÅS, Norway
[2]Geological Survey of Sweden, UPPSALA, Sweden
[3]Lund University, LUND, Sweden

10:40–12:00	**ER 4 – Ore deposits and fossil fuel**	RÍMA B

Convener: Hjalti Franzson

10:40–11:00 **ER4-1 Archaean orogens in the North Atlantic craton and related orogenic gold mineralisation in southern West and South-West Greenland**

Jochen Kolb[1], Denis Schlatter[2], Annika Dziggel[3]
[1]Geological Survey of Denmark and Greenland, COPENHAGEN, Denmark
[2]Helvetica Exploration Services GmbH, ZÜRICH, Switzerland
[3]Institute of Mineralogy and Economic Geology, RWTH Aachen University, AACHEN, Germany

11:00–11:20 **ER4-2 Rock magnetic investigations constraining internal structures and relative timing for gold deposits in southern Finland**

Fredrik Karell[1], Satu Mertanen[2]
[1]Geological Survey of Finland/Åbo Akademi University, ESPOO, Finland
[2]Geological Survey of Finland, ESPOO, Finland

11:20–11:40 **ER4-3 Au-mineralization in the St. Jonsfjorden area, the West Spitsbergen Fold Belt, Svalbard**

Juhani Ojala
Store Norske Gull AS, ROVANIEMI, Finland

11:40–12:00 **ER4-4 Gold and silver deposition in Reykjanes geothermal system, southwest Iceland**

Vigdís Hardardóttir[1], Jeffrey Hedenquist[2], Mark Hannington[2]
[1]ÍSOR, REYKJAVÍK, Iceland
[2]Department of Earth Sciences, University of Ottawa, OTTAWA, Canada

10:40–11:40	**GA 2 – Risk assessment and management of geohazards**	KALDALÓN

Conveners: Anders Solheim and Harpa Grímsdóttir

10:40–11:00 **GA2-5 Risk assessment of natural hazards at the Icelandic Meteorological Office – an overview**

Sigrún Karlsdóttir, Eiríkur Gíslason, Trausti Jónsson, Evgenia Ilinskya
Icelandic Meteorological Office, REYKJAVÍK, Iceland

11:00–11:20 **GA2-6 Natural hazard and disaster risk reduction in Iceland regarding volcanic ash, vegetation and soil conservation**

Anna María Ágústsdóttir
Soil Conservation Service of Iceland, HELLA, Iceland

11:20–11:40 **GA2-7 Development of guidelines for the sustainable exploitation of aggregate resources in arsenic rich areas in Finland**

Kirsti Loukola-Ruskeeniemi[1], Jussi Mattila[1], Paavo Härmä[1], Timo Tarvainen[1], Jaana Sorvari[2], Outi Pyy[2], Pirjo Kuula-Väisänen[3]
[1]Geological Survey of Finland, ESPOO, Finland
[2]Finnish Environment Institute, HELSINKI, Finland
[3]Tampere University of Technology, P.O. BOX 527, FI-33101 TAMPERE, Finland

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11:40–12:00 **GA 3 – Offshore, near-shore and coastal geohazards** KALDALÓN

Convener: Bjarni Richter and Sebastian L´Heureux

11:40–12:00 **GA3-1 A multiproxy analysis of the 2004 tsunami deposits of west coast Thailand: comparison with paleo-tsunami sediments**

Vivi Vajda, Jane Wigforss-Lange
Lund University, LUND, Sweden

10:40–12:00 **UV 4 – Magma plumbing system** RÍMA A

Conveners: Paul Martin Holm and Christian Tegner

10:40–11:00 **UV4-05 Inferring volcanic plumbing systems from ground deformation: what we learn from laboratory experiments**

Olivier Galland
Physics of Geological Processes – University of Oslo, OSLO, Norway

11:00–11:20 **UV4-06 Early Cretaceous magmatism on Svalbard – a review of geochemistry, generation, geometry and implications for CO_2 sequestration**

Kim Senger[1], Kei Ogata[2], Jan Tveranger[1], Alvar Braathen[2]
[1]Uni CIPR, BERGEN, Norway
[2]University Centre on Svalbard, LONGYEARBYEN, Norway

11:20–11:40 **UV4-07 Constraints from short-lived U-series nuclides on the magma dynamics leading to the 2010 Eyjafjallajökull eruption**

Olgeir Sigmarsson[1], Pierre-Jean Gauthier[2], Michel Condomines[3]
[1]Sciences Institute, REYKJAVIK, Iceland
[2]Laboratoire Magmas et Volcans, CNRS – Université Blaise Pascal – IRD, CLERMONT-FERRAND, France
[3]Géosciences Montpellier, Université Montpellier 2 et CNRS, MONTPELLIER, France

11:40–12:00 **UV4-08 New U-series isotope data from the Andean backarc stress the OIB-character of the Payún Matrú volcanic complex**

Charlotte Dyhr[1], Paul Martin Holm[1], Thomas Kokfelt[2]
[1]University of Copenhagen, COPENHAGEN, Danmark
[2]The National Geological Survey of Denmark and Greenland, COPENHAGEN, Danmark

12:00–13:00 **Lunch**

13:00–13:30 **Plenary 6** SILFURBERG B

PL-6 Crustal Deformation in Iceland – fast and slow

Þóra Árnadóttir
Nordic Volcanological Center, Institute of Earth Sciences, REYKJAVIK, Iceland

13:40–15:20	**EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments**	SILFURBERG B

Conveners: Ólafur Ingólfsson

13:40–14:00 **EC2-09 Last deglaciation of Kveithola, NW Barents Sea as revealed by seafloor geomorphology and seismic stratigraphy**

Lilja Bjarnadóttir, Denise Rüther, Karin Andreassen, Monica Winsborrow
University of Tromsø, TROMSØ, Norway

14:00–14:20 **EC2-10 Re-examining the stratigraphy of the Poolepynten coastal cliffs, Svalbard – implications for the natural history of the polar bear (Ursus maritimus)**

Ólafur Ingólfsson[1], Helena Alexanderson[2]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]Lund University, Sweden, LUND, Sweden

14:20–14:40 **EC2-11 Postglacial uplift and relative sea level changes in Finnmark, northern Norway**

Anders Romundset[1], Stein Bondevik[2], Ole Bennike[3]
[1]Geological Survey of Norway, TRONDHEIM, Norway
[2]Sogn og Fjordane University College, SOGNDAL, Norge
[3]Geological Survey of Denmark and Greenland, KØBENHAVN, Danmark

14:40–15:00 **EC2-12 Once upon a time under the ice divide: provenance, transport and exposure history of glacial erratics at Rendalssølen (1755 m a.s.l.), southeastern Norway**

Åshild Danielsen Kvamme[1], Henriette Linge[1], Håvard Juliussen[1], Johan Petter Nystuen[2]
[1]University of Bergen, BERGEN, Norway
[2]University of Oslo, OSLO, Norway

15:00–15:20 **EC2-13 The late Plio-Pleistocene outbuilding of the mid-Norwegian continental shelf: seismic sequence stratigraphy reflecting ~ 30 glaciations**

Jan Inge Faleide, Johan Petter Nystuen, Amer Hafeez
University of Oslo, OSLO, Norway

13:40–14:20	**ER 4 – Ore deposits and fossil fuel**	RÍMA B

Convener: Hjalti Franzson

13:40–14:00 **ER4-5 Oxygen isotope and geochemical constraints on the genesis of the Grängesberg apatite-iron oxide deposits, Bergslagen, Sweden**

Erik Jonsson[1], Karin Högdahl[2], Franz Weis[2], Katarina Nilsson[1], Chris Harris[3], Valentin Troll[2]
[1]Geological Survey of Sweden, UPPSALA, Sweden
[2]CEMPEG, Department of Earth Sciences, Uppsala University, UPPSALA, Sweden
[3]Dept. Geological Sciences, University of Cape Town, RONDEBOSCH, South Africa

14:00–14:20 **ER4-6 The role of D2 for the structural architecture of the apatite-iron oxide deposit at Grängesberg, Bergslagen, Sweden**

Katarina P. Nilsson[1], Karin Högdahl[2], Erik Jonsson[1], Valentin R. Troll[2]
[1]Geological Survey of Sweden, UPPSALA, Sweden
[2]CEMPEG, Department of Earth Sciences, Uppsala University, UPPSALA, Sweden

14:20–15:20	**ER 5 – Petroleum provinces of the NE Atlantic region**	RÍMA B

Convener: Thorarinn S. Arnarson and Bjarni Richter

14:20–14:40 **ER5-1 Spatial occurrences of selected sandstone bodies in the De Geerdalen Formation, Svalbard, and their relation to depositional facies**

Rita Sande Rød
NPD, HARSTAD, Norge

14:40–15:00 **ER5-2 History of geology and research of the Jan Mayen Micro-Continent and associated exploration risks**

Anett Blischke[1], Thorarinn Arnarson[2], Karl Gunnarsson[1]
[1]Iceland GeoSurvey, AKUREYRI, Iceland
[2]National Energy Authority, REYKJAVIK, Iceland

15:00–15:20 **ER5-3 Potential petroleum systems offshore northeast Greenland and outer Vøring margin from conjugate margin studies**

Mikal Trulsvik[1], Sverre Planke[1], Stephane Polteau[1], Reidun Myklebust[2], Carmen Gaina[3], Jan Inge Faleide[4]
[1]VBPR AS, OSLO, Norway
[2]TGS-NOPEC, ASKER, Norway
[3]Universitet i Oslo, TRONDHEIM, Norway
[4]Universitetet i Oslo, OSLO, Norway

13:40–14:40 **GA 3 – Offshore, near-shore and coastal geohazards** KALDALÓN

Convener: Bjarni Richter and Sebastian L´Heureux

13:40–14:00 **GA3-2 Offshore geo-hazards to be kept in mind during exploration and production activities in the Jan Mayen Micro-Continent area.**

Anett Blischke[1], Thorarinn Arnarson[2], Bjarni Richter[1]
[1]Iceland GeoSurvey, AKUREYRI, Iceland
[2]National Energy Authority, REYKJAVIK, Iceland

14:00–14:20 **GA3-3 The 1978 quick clay landslide at Rissa: subaqueous morphology and slide dynamics**

Jean-Sebastien L'Heureux[1], Raymond Eilertsen[1], Sylfest Glimsdal[2]
[1]NGU, TRONDHEIM, Norway
[2]NGI, OSLO, Norway

14:20–14:40 **GA3-4 Offshore Geohazards in the Atlantic Ocean Mapped by High-Resolution P-Cable 3D Seismic Data**

Ola Kaas Eriksen[1], Gareth Crutchley[2], Jens Karstens[2], Christian Berndt[2], Stefan Bünz[3], Frode Normann Eriksen[1], Sverre Planke[1]
[1]P-Cable 3D Seismic, OSLO, Norway
[2]IFM-GEOMAR, KIEL, Germany
[3]University of Tromsø, TROMSØ, Norway

14:40–15:20 **SÞ 4 – Volcanic pollution: its environmental and atmospheric effects** KALDALÓN

Convener: Sigfús Johnsen and Evgenia Ilyinskaya

14:40–15:00 **SÞ4-1 The rapid release of condensed volcanic salts and nutrients and the subsequent effect on aqueous environments**

Morgan Jones[1], Sigurður Gislason[1], Chris Smith[2], Debora Iglesias-Rodriguez[2]
[1]University of Iceland, REYKJAVIK, Iceland
[2]University of Southampton, SOUTHAMPTON, United Kingdom

15:00–15:20 **SÞ4-2 The Ash that Closed Europe's Airspace in 2010**

Sigurdur Gislason[1], Eydis Eiriksdottir[1], Helgi Alfredsson[1], Niels Oskarsson[1], Bergur Sigfusson[2], Gudrun Larsen[1], Tue Hassenkam[3], Sorin Nedel[3], Nicolas Bovet[3], Caroline Hem[3], Zoltan Balogh[3], Knud Dideriksen[3], Susan Stipp[3]
[1]University of Iceland, REYKJAVÍK, Iceland
[2]Reykjavik Energy, REYKJAVÍK, Iceland
[3]University of Copenhagen, COPENHAGEN, Denmark

13:40–15:20 **UV 4 – Magma plumbing system** RÍMA A

Conveners: Paul Martin Holm and Christian Tegner

13:40–14:00 **UV4-09 The magmatic evolution of lavas from Maipo, SVZ, Andes: on the relative roles of AFC and source contribution from continental crust to the magmas**

Paul Martin Holm, Nina Søager, Charlotte Thorup Dyhr
University of Copenhagen, COPENHAGEN, Denmark

14:00–14:20 **UV4-10 Zircon records mafic recharge-induced reheating and remobilization of crystal mush at the Austurhorn Intrusive Complex**

Abraham Padilla[1], Calvin Miller[1], Joe Wooden[2]
[1]Vanderbilt University, NASHVILLE, TN, USA
[2]Stanford-USGS MAC SHRIMP-RG Lab, STANFORD, CA, USA

14:20–14:40	**UV4-11 Efficiency of differentiation in the Skaergaard magma chamber**	

Christian Tegner[1], C.E. Lesher[2], M.B. Holness[3], J.K Jakobsen[4], L.P. Salmonsen[1], M.C.S. Humphreys[3], P. Thy[2]
[1]Aarhus University, AARHUS, Denmark
[2]Department of Geology, University of California, USA
[3]Department of Earth Sciences, University of Cambridge, United Kingdom
[4]GeoForschungsZentrum Potsdam, Germany

14:40–15:00 **UV4-12 The influence of crustal composition on magmatic differentiation across five major crustal terranes: the British-Irish Palaeocene Igneous Province revisited**

Valentin Troll[1], F.C. Meade[1], G.R. Nicoll[2], C.H. Emeleus[2], C.H. Donaldson[3], R.M. Ellam[4]
[1]Uppsala University, UPPSALA, Sweden
[2]University of Durham, Dept. of Earth Sciences, DURHAM, United Kingdom
[3]University of St Andrews, School of Geosciences, FIFE, Scotland
[4]S.U.E.R.C., EAST KILBRIDE, United Kingdom

15:00–15:20 **UV4-13 Igneous and ore-forming events at the roots of a giant magmatic plumbing system: the Seiland Igneous Province (SIP)**

Rune Larsen Berg[1], Markku Iljina[2], Mona Schanke[2]
[1]NTNU, TRONDHEIM, Norway
[2]Nordic Mining, OSLO, Norway

15:20–16:00 **Poster session with refreshments** FOYER OF KALDALÓN

16:00–17:20 **EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments** SILFURBERG B

Conveners: Ólafur Ingólfsson

16:00–16:20 **EC2-14 Cold-based palaeoglaciers and 10Be surface exposure dating**

Henriette Linge[1], Svein Olaf Dahl[2], Derek Fabel[3]
[1]BERGEN, Norway
[2]Department of Geography, University of Bergen, BERGEN, Norway
[3]School of Geographical and Earth Sciences, University of Glasgow, GLASGOW, United Kingdom

16:20–16:40 **EC2-15 Sub-till glaciofluvial and glaciolacustrine sediments on the Småland peneplain – their age and implication for glacial history within the south-western distribution area of Fennoscandian Ice Sheets**

Per Möller
Lund university, LUND, Sweden

16:40–17:00 **EC2-16 How long the glaciations do lasted during Weichselian in Finland?**

Pertti Sarala
Geological Survey of Finland, ROVANIEMI, Finland

17:00–17:20 **EC2-17 Weichselian stratigraphy and glacial history of Kriegers Flak in the southwestern Baltic Sea**

Johanna Anjar[1], Nicolaj Larsen[2], Lena Adrielsson[1]
[1]Lund University, LUND, Sweden
[2]Aarhus university, AARHUS, Denmark

16:00–17:40 **ER 3 – Hydrology and hydrogeology** RÍMA B

Convener: Daði Þorbjörnson and Þráinn Friðriksson

16:00–16:20 **ER3-1 Groundwater in Öxarfjördur: origin and composition**

Hrefna Kristmannsdóttir
University of Akureyri, AKUREYRI, Iceland

16:20–16:40 **ER3-2 Groundwater and Geothermal Utilization**

Þórólfur Hafstað, Daði Þorbjörnsson
Iceland Geosurvey, REYKJAVÍK, Iceland

16:40–17:00 **ER3-3 In-situ stresses and fluid flow in fractures of crystalline bedrock – a case study at the site of a potential nuclear waste repository, Finland**

Jussi Mattila[1], Eveliina Tammisto[2]
[1]Geological Survey of Finland, ESPOO, Finland
[2]Pöyry Finland Oy, VANTAA, Finland

17:00–17:20 **ER3-4 The relative influence of temperature versus runoff on chemical denudation rate.**

Eydís Salome Eiriksdóttir[1], Sigurdur Reynir Gislason[1], Erik H Oelkers[2]
[1]University of Iceland, REYKJAVIK, Iceland
[2]GET, CNRS/URM 5563-Université Paul Sabatier, TOULOUSE, France

17:20–17:40 **ER3-5 Dissolution of volcanic riverine particulate material in seawater: Consequences for global element cycling**

Morgan Jones[1], Christopher Pearce[2], Catherine Jeandel[3], Sigurður Gislason[1], Eric Oelkers[4]
[1]University of Iceland, REYKJAVIK, Iceland
[2]Open University, MILTON KEYNES, United Kingdom
[3]LEGOS, TOULOUSE, France
[4]GET – Université de Toulouse, TOULOUSE, France

16:00–17:20 **SÞ 4 – Volcanic pollution: its environmental and atmospheric effects** KALDALÓN

Convener: Sigfús Johnsen and Evgenia Ilyinskaya

16:00–16:20 **SÞ4-3 Surface properties of the Grímsvötn 2011 volcanic ash**

Jonas Olsson[1], Susan Stipp[2], Kim Dalby[2], Sigurður Gíslason[3]
[1]COPENHAGEN, Denmark
[2]Nano-Science Center, Chemistry Department, University of Copenhagen, COPENHAGEN, Denmark
[3]Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

16:20–16:40 **SÞ4-4 Gas release from Grímsvötn eruption in May 2011**

Evgenia Ilyinskaya[1], Georgina Sawyer[2], Alessadro Aiuppa[3]
[1]Icelandic Meteorological Office, REYKJAVÍK, Iceland
[2]University of Cambridge, CAMBRIDGE, United Kingdom
[3]University of Palermo, PALERMO, Italy

16:40–17:00 **SÞ4-5 Excess mortality in Europe following a future Laki-style Icelandic eruption**

Anja Schmidt[1], Bart Ostro[2], Kenneth Carslaw[1], Marjorie Wilson[1], Thorvaldur Thordarson[3], Graham Mann[4], Adrian Simmons[5]
[1]University of Leeds, LEEDS, United Kingdom
[2]Centre for Research in Environmental Epidemiology (CREAL), BARCELONA, Spain
[3]University of Edinburgh, EDINBURGH, United Kingdom
[4]University of Leeds, NCAS, LEEDS, United Kingdom
[5]European Centre for Medium-Range Weather Forecasts, READING, United Kingdom

17:00–17:20 **SÞ4-6 Impacts of the 2010 Eyjafjallajökull eruptions on the local communities**

Guðrún Gísladóttir[1], Deanne K. Bird[2]
[1]University of Iceland, REYKJAVIK, Iceland
[2]Risk Frontiers, Macquire University, SIDNEY, Australia

Conference Excursions

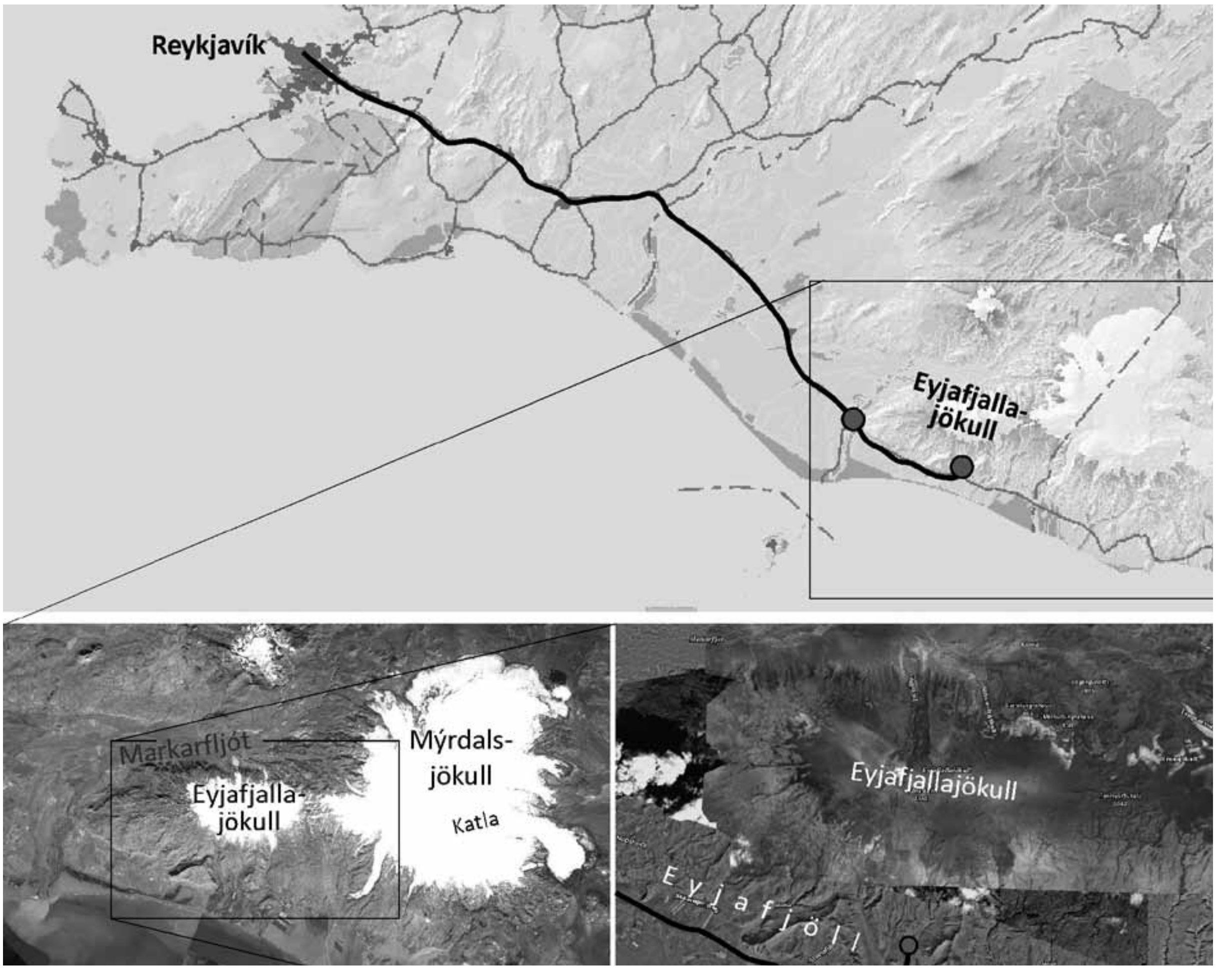
Eyjafjallajökull

Departure from Harpa: January 11th, 9:00
Expected arrival at Harpa: January 11th, 18:00

Guide: Prof. Magnús Tumi Guðmundsson, Institute of Earth Sciences, University of Iceland

Note: The weather in Iceland in January can be unpredictable so be prepared for any weather – warm or cold days (+10 to -10°C), strong winds or calm conditions, rain or snow. Heavy precipitation and/or thick cloud cover may prevent full daylight.

The eruption of Eyjafjallajökull in April–May 2010 brought air travel to a standstill in Europe for some days and disrupted trans-Atlantic aviation for weeks. However, during the first days of the eruption other things were on people's minds in Iceland, since in the vicinity of the volcano the threat of floods, lahars and ash fallout disrupted people's lives leading to repeated evacuation in some areas. This was in most respects an eruption of moderate size (about 0.27 km^3 of ash), but the deposit is split into two about equally sized parts: the ash that fell on land, and the part that fell into the sea to the southeast of Iceland. A very tiny part was transported all the way to mainland Europe. In this fieldtrip we will visit the Eyjafjöll district to the south of volcano where the effects of the eruption were most severe. The trachyandsite ash will be inspected as well as paths of floods and lahars where the rivers still carry ash from the slopes down to the lowlands and cause problems by filling the traditional river channels. A newly opened privately owned museum at the farm Þorvaldseyri, dedicated to the eruption, will be visited before returning to Reykjavík in the afternoon.



The Golden Circle – Þingvellir, Gullfoss and Geysir

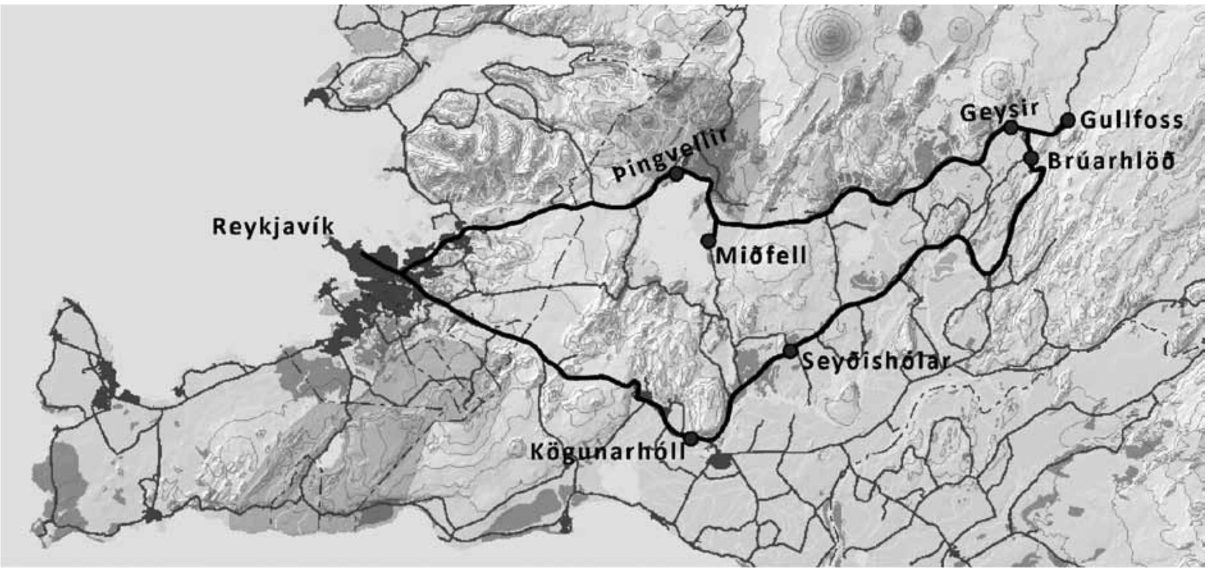
Departure from Harpa: January 11th, 9:30
Expected arrival at Harpa: January 11th, 18:00

Guides: Dr. Hreggviður Norðdahl and Dr. Esther Ruth Guðmundsdóttir
Institute of Earth Sciences, University of Iceland

Note: The weather in Iceland in January can be unpredictable so be prepared for any weather – warm or cold days (+10 to -10°C), strong winds or calm conditions, rain or snow. Heavy precipitation and/or thick cloud cover may prevent full daylight.

Three remarkable geological sites constitute the Golden Circle; Þingvellir, Gullfoss, and Geysir. Þingvellir is a part of the North Atlantic Rift system within the Reykjanes – Langjökull rift zone. Several rifting episodes and volcanic events have occurred in post-glacial times. Gullfoss is situated in an area with faulted bedrock composed of lava flows intercalated by sediment beds. The faults have controlled the formation of the Gullfoss canyon and the waterfall. In between Þingvellir and Gullfoss is the Geysir area with spouting hot springs. The trip goes from Reykjavík to Þingvellir and onwards to Geysir and Gullfoss. On the way back and forth, some or all of the following sites may be visited (depending on time and weather):

Miðfell	Pillow lava and pikrite
Brúarhlöð	A pillow – breccia, the lowermost part of the Gullfoss bedrock
Seyðishólar	The Grímsnes volcanic field with explosive volcanic activity at the boundary of the Hreppar micro-plate about 7000 years BP
Kögunarhóll	Cracks formed during the 2008 earthquake



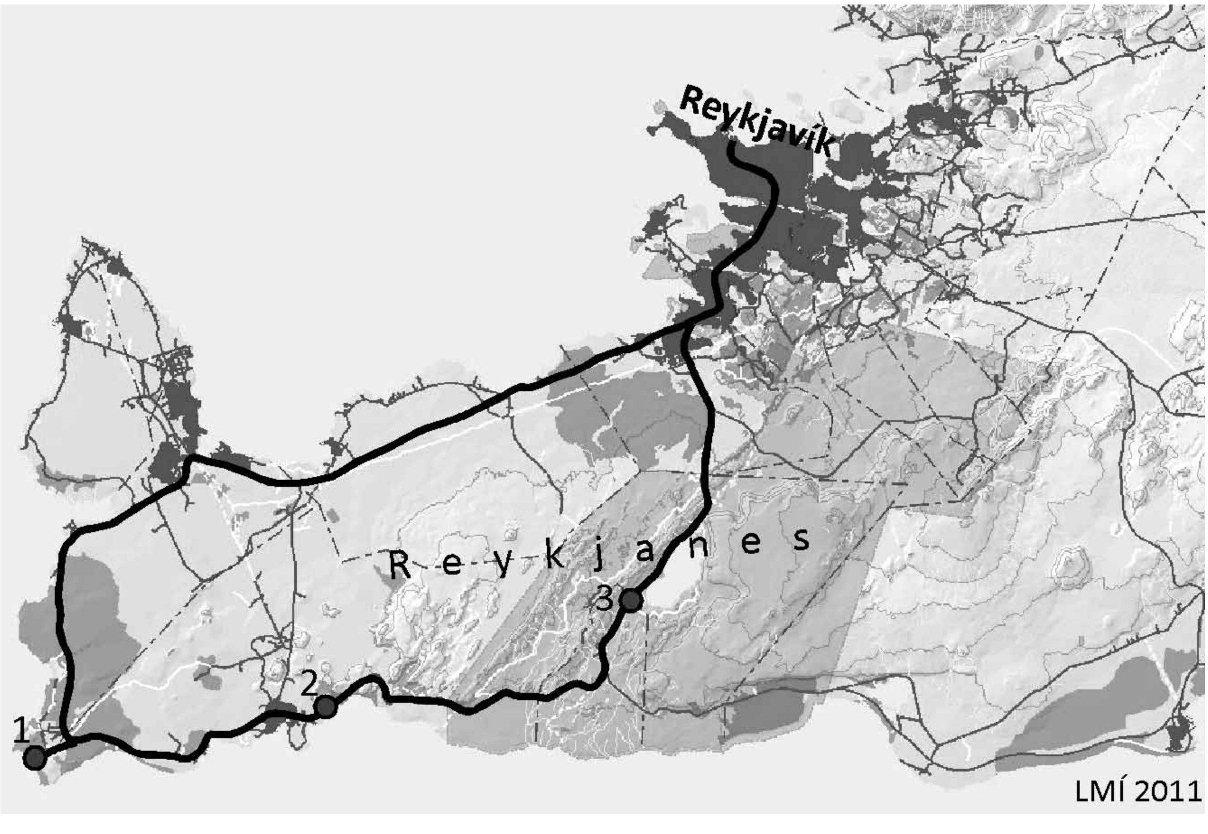
The Reykjanes volcanic belt

Departure from Harpa: January 11th, 9:30
Expected arrival at Harpa: January 11th, 18:00

Guide: Dr. Ármann Höskuldsson, Institute of Earth Sciences, University of Iceland

Note: The weather in Iceland in January can be unpredictable so be prepared for any weather – warm or cold days (+10 to -10°C), strong winds or calm conditions, rain or snow. Heavy precipitation and/or thick cloud cover may prevent full daylight.

The Reykjanes Volcanic Belt consists of four northeast trending volcanic systems that are arranged in a step-wise fashion across the peninsula. The mountain range along the centre of the peninsula, consisting of subglacial and submarine móberg ridges and table mountains, roughly delineates the axis of the belt. These are flanked, and in parts overlain, by subaerial lavas formed during the Holocene and to lesser extent in historic time. The northwestern part of the Reykjanes Peninsula consists mainly of three abutting Holocene lava shield volcanoes; Hrútagjá, Þráinsskjöldur, and Sandfellshæð. On the southeast side of the peninsula, 6 lava shields (i.e., Geitahlíð, Herdísarvík, Selvogsheiði, Heiðin há, Leitin, and Tröllahlíð) occupy similar positions. Hrútagjá and Þráinskjöldur, are abutting half shields with their summits at 200–240 m a.s.l. and tugged onto northwest slopes of the móberg mountain range. They produced pahoehoe lavas that spread radially northwards. The Hrútagjá shield lavas formed some of the largest tumuli found in Icelandic lavas, whereas Þráinsskjöldur is heavily dissected by fissures and faults formed by rifting on the Reykjanes volcanic system. These faults are easily seen from the road in form of northeast trending linear scarps on the lower slopes of the shield. Further up slope is the pyramid-shaped móberg cone Keilir – an island midst in an ocean of lava. The third lava shield, Sandfellshæð, has a more regular shape and covers large proportion of the southwest corner of the peninsula. Sandfellshæð has a well-formed summit crater, 450-m-wide and 20-m-deep, located about 4–5 km east of the road. All three shields were formed at the beginning of the Holocene about 9–10,000 years ago and their cumulative volume is ~15km^3, accounting for >75% of the volume of magma erupted. The Quaternary basement that outcrops from Vogastapi across Miðnes to Garðskagi is the oldest rock formations west of Reykjavík, about 640 ka. The eastern most part (i.e. Vogastapi) is heavily dissected by young fissures and faults formed in association with activity on the Reykjanes volcanic system. Straight south of Vogastapi are the remains of Stapafell and Þórðarfell, two submarine volcanoes composed of strongly olivine phyric pillow lava and hydroclastic tephra formed at the end of the Weichselian glaciation. During this trip we stop at three locations: (1) the western extremity of the peninsula where the Mid Atlantic Ridge takes land; (2) Hrólfsvík locality where xenoliths from the lower crust can be observed, and (3) Krísuvík area to observe active solfataras.



Plenary Abstracts

PLENUM ABSTRACTS

PL-1

Hazards from explosive eruptions in Iceland, near and far

Magnús T. Gudmundsson[1], Guðrún Larsen[1], Ármann Höskuldsson[1], Thorvaldur Thordarson[2], Þórdís Högnadóttir[1], Björn Oddsson[1]

[1]*Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland*

[2]*Department of Earth Sciences, University of Edinburgh, UK*

About three quarters of all volcanic eruptions in Iceland are explosive. The majority of these occur in glaciers where interaction with water leads to magma fragmentation, rapid ice melting and volcanic plume generation, once the eruption has broken through the ice cover. The largest explosive events are (a) basaltic fissure eruptions through the porous uppermost crust in areas of high groundwater table, and (b) major intermediate or silicic eruptions in large central volcanoes. Examples of the first type include the Vatnaöldur 871 AD and Veiðivötn 1477 AD eruptions and of the second type the rhyolitic eruptions of Öræfajökull 1362 AD and Askja 1875 AD. Other important explosive eruptions are the subplinian eruptions of Hekla (intermediate composition), and the basaltic, initially subglacial eruptions of Katla. The most frequent explosive eruptions are the ones in Grímsvötn in the center of Vatnajökull ice cap, which are mostly moderate-sized and phreatomagmatic in character. The largest explosive eruptions (Volcanic Explosivity Index VEI 6, bulk volume ~10 km^3) occur once or twice per millennium, while VEI 3 eruptions have a recurrence time of 10–20 years. Jökulhlaups caused by volcanic or geothermal activity under glaciers are the most frequent volcanically related hazard in Iceland. This is a direct consequence of the location of some of the most active volcanoes within glaciers. Fallout of tephra with resulting crop failures and fluorine poisoning caused famine in some instances before 1800 AD. This threat is remote today. However, the introduction of commercial passenger jets in the 1960s has brought a new type of hazard into play, the vulnerability of jet engines to volcanic ash. This has created the potential for regional disruption from moderate-sized explosive eruptions that would not have been noticed outside Iceland in earlier times. The threat to aircraft has been well known since the 1980s and has increased greatly the importance of monitoring volcanic ash in the atmosphere. At least 20 explosive eruptions are to be expected every century, but only three to four out the 20 can be expected to cause disruption in Europe. The recent example of Eyjafjallajökull in 2010 is a telling example, while the more powerful Grímsvötn eruption a year later (2011) caused relatively little airspace closures. The dissimilarity in impact can be explained by the difference in prevailing wind fields during these eruptions. Locally, the hazard from volcanic eruptions in Iceland is in some respects increasing. This is due to the fact that tourism is on the increase. Areas vulnerable to pyroclastic flows, ballistics and heavy tephra fallout include the slopes of Hekla, which has become a popular tourist destination in summer. Moreover, popular hiking routes lie in the vicinity of Katla increasing the risk of tourists being exposed to floods or heavy tephra fallout in the event of an eruption.

PL-2

Glaciological research in Iceland: reflections and outlook in the beginning of the 21st century

Helgi Björnsson

Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland

Over the last three decades the surface and bedrock topography of the main ice caps in Iceland has been mapped for describing their area and volume distribution, and exploring subglacial landforms and geological structures, active volcanoes and subglacial lakes. The glacier dynamics have been observed, including sporadic surges, the regular drainage of meltwater and occasional jökulhlaups investigated. Due to a unique combination of natural circumstances these studies have allowed us to assess current theories about water flow beneath glaciers and glacier-volcano interactions. Glacier mass balance has been monitored, its relation to meteorological conditions evaluated, the response of the present glaciers to climate change predicted and former glacier extent reconstructed by numerical modeling. Given plausible scenarios of future climate, the main ice caps in Iceland might vanish in 150 to 200 years. These studies are of international interest for evaluation of sea level rise, fresh water input to the ocean, and Holocene glacier variations. They are also of importance for the Icelandic community due to the glacier's impact on human activities.

PL-3

When did Humans first cross the Arctic Circle - and were they Neandertals or Modern Humans?

Jan Mangerud, John Inge Svendsen

Department of Earth Science and Bjerknes Centre for Climate Research, University, BERGEN, Norway

Moving northwards into the frozen landscapes at high latitudes was a challenge for ancient humans who originated and developed in a warm climate. We also have to keep in mind that the early emigrants were dark-skinned when they moved out of Africa. In particular it must have been tough to cross the Arctic Circle and meet the long and dark winters on the tundra-steppe. Difficulties with the adaptation to the Arctic environment have been used as an explanation for the late arrival of humans in North America.

We have studied 6 Palaeolithic sites along the western flank of the northern Ural Mountains (Svendsen et al., 2010). It was almost a sensation when we first showed that "Russians" had crossed the Arctic Circle as early as 40,000 calendar years ago (Pavlov et al., 2001) - in the middle of the Last Ice Age (Weichselian). It became a real sensation when we recently claimed that the unearthed artefacts at the Byzovaya site represent a Mousterian culture and were struck by Neanderthals (Slimak et al., 2011). A "protest paper" is already underway in Science. Up to now, the northernmost known Neanderthal remains are from the Netherlands, more than 1000 km farther south. We here present the documentation of the site that according to our dating results were occupied by humans about 32,000 years ago. More than 300 artefacts and several thousand animal remains, mostly of mammoth, have been un-earthed from coarse-grained debris-flow deposits, and sealed by eolian sand.

References

Pavlov, P., Svendsen, J. I. & Indrelid, S. 2001: Human presence in the European Arctic nearly 40,000 years ago. Nature 413, 64-67.

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Svendsen, J. I., Heggen, H., Hufthammer, A. K., Mangerud, J., Pavlov, P. & Roebroeks, W. 2010: Geo-archaeological investigations of Palaeolithic sites along the Ural Mountains - On the northern presence of humans during the last Ice Age. Quaternary Science Reviews 29, 3138-3156.

PL-4

Modern climate change and sea-level rise

Stefan Rahmstorf

Potsdam Institute, POTSDAM, Germany

We are in the midst of a major global warming, as witnessed not just by temperature measurements, but also for example by the record loss of Arctic sea ice in the past years and shrinking mountain glaciers around the world. In the last years, both the Northwest Passage and the Northeast Passage in the Arctic were open for ships to pass through for the first time in living memory. Ice loss and sea level rise are proceeding much faster than expected. Other consequences of warming, like increased drought in many regions, heat waves, wild fires and flooding, are already affecting millions of people. The talk will briefly review the latest data and analyses, and then discuss in more detail the latest studies on sea-level rise.

Sea-level rise is amongst the potentially most serious impacts of climate change. But sea-level changes cannot yet be predicted with confidence using models based on physical processes, since the dynamics of ice sheets and glaciers and to a lesser extent also that of oceanic heat uptake is not sufficiently understood.

This has caused considerable recent interest in semi-empirical approaches to projecting sea level rise. These are based on the observed past correlation of global temperature and the rate of sea-level rise.

We also discuss new paleoclimatic data for the past two millennia, which show that 20th Century sea level rise is unprecedented during this period. These proxy data can be used to further constrain the parameters of the semi-empirical approach and hence improve sea level projections for the future.

At least seven papers giving global sea level projections have been published since the AR4. Invariably they obtain much higher projections than those of the AR4: typically two to three times as high. Looking beyond the year 2100, sea level is likely to rise by several meters in the coming centuries in a delayed response to 21st Century anthropogenic warming.

PL-6

Crustal Deformation in Iceland - fast and slow

Thóra Árnadóttir

Nordic Volcanological Center, REYKJAVIK, Iceland

Iceland straddles the plate boundary of the North American and Eurasian plates. Several volcanic rift zones and two main fault zones accommodate the plate spreading across the island. Monitoring the high level of activity and understanding the complex tectonics requires a dense network of geodetic stations. Since the first Global Positioning System (GPS) experiment in 1986, numerous surveys have been conducted mostly focusing on limited parts of the plate boundary or individual volcanoes. Two countrywide GPS campaigns were conducted in 1993 and 2004, providing the first 3D velocity map of the whole country.

The continuous GPS (CGPS) network in Iceland was initiated in 1995 when an IGS station was installed in Reykjavík. From 1999 to 2005 the network grew from two IGS stations (REYK and HOFN) to about 20 stations, operated by the Icelandic Meteorological Office (IMO). In 2006 an international collaborative project was initiated, allowing us to triple the number of CGPS stations in Iceland. Most of the new stations are sampling data at a high rate (1-20 samples per second). The CGPS network has now approximately 70 stations, and is densest in the seismically active areas in the South Iceland Seismic Zone (SISZ), the Reykjanes Peninsula and across the Tjörnes Fracture Zone (TFZ) in North Iceland. The number of stations around active volcanoes has been steadily increasing, and high-rate CGPS stations are now operating on Hekla, Grímsfjall, Krafla, Katla and Eyjafjallajökull.

Expanding the CGPS network has significantly improved the temporal and spatial resolution of deformation measurements in Iceland, and enabled studies of both dynamic as well as lower-rate processes related to earthquakes and volcanic activity. In this talk I will summarize the different crustal deformation signals captured by GPS, ranging from large-scale long-term plate spreading signals and slow transients caused by post-seismic relaxation, magma movements and glacial rebound, to more rapid deformation due to earthquakes and eruptions.

Oral Abstracts

Themes:

Environment and climate (EC)

Endogenic processes (EP)

Earth resources (ER)

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

Geodynamics (GD)

Interdisciplinary sessions (IS)

A tribute to Sigurður Þórarinsson (SÞ)

Understanding volcanoes (UV)

THEME: ENVIRONMENT AND CLIMATE (EC)

EC 1 – Glaciers and glacial processes

ORAL EC 1

EC1-01

Reconstructing chronology of post-glacial mass movements in the Skagafjörður, (Northern Iceland) from radiocarbon, tephrochronological and geomorphological results

Denis Mercier[1], Armelle Decaulne[2], Etienne Cossart[3], Thierry Feuillet[1], Þorsteinn Sæmundsson[4], Helgi Jonsson[4]

[1]University of Nantes - CNRS Laboratoire Geolittomer, NANTES CEDEX 3, France
[2]CNRS-Geolab UMR 6042, CLERMONT-FERRAND, France
[3]University Paris1-Labo. Prodig, PARIS, France
[4]Natural Research Centre of NW Iceland, SAUÐÁRKRÓKUR, Iceland

Since the last major deglaciation, about 12-10,000 years ago, paraglacial landforms widely occurred in fjord and mountain areas; mass movements such as rock-slope failure, rock avalanches, rockslides, sackungs, etc., are common (Dikau et al., 1996; Ballantyne, 2008). In north Iceland, numerous mass movements' landforms occurred, mostly in areas within Tertiary basalt formation, in a landscape characterized by steep slopes and overdeepened glacial valleys. Many of those landforms can be observed in the Vestfirðir peninsula, in central North Iceland, and in Eastern Iceland. Jónsson (1957) made some early descriptions of such landforms. He concluded that most of those landforms were formed during or shortly after the last deglaciation, in Early Holocene; at the time of these first observations, results on absolute dating were lacking. Recently, several landslides have been studied in the Skagafjörður area (Decaulne et al., 2010, Mercier et al., 2011). The aim of this study is to date several landslides in the Skagafjörður area, by combining several proxies, e.g. radiocarbon dating, teprhochronology, raised beaches. We present here the result on one of those, the Höfðahólar case-study.

– The material originating from the Höfðahólar rock avalanche partly buried a succession of raised beaches. Raised beaches out in the Skagi peninsula, just west of the study area, exceeding 65 m a.s.l., have been dated older than 12,000 yr B.P. (Rundgren et al., 1997). Beaches between 43 and 50 m a.s.l. have been dated to 11,300-9,900 yr B.P. and beaches at 22-31 m a.s.l. between 9900 and 9600 yr B.P. Regression below the present sea level occurred at 9,000 yr BP. As the rock avalanche deposit does not display visible evidence of being impacted by the glacio-isostatic rebound, it is believed to be younger than 9,000 yr B.P.
– Tephra layers, occurring in a peat bog on top of the rock avalanche material date the avalanche older than 4,500 yr B.P., as the H4 tephra layer is found at 140 cm depth.
– 14C dating of birches (Betula sp.) trunk, branch and root pieces found 80 cm deeper than the H4 layer provide 6,070 yr B.C. calibrated age. This period, around 8,000 yr B.P. is known as the "early birch periode"in Iceland, known to have been warm and favouring tree development (Einarsson 1991, Óladóttir et al. 2001, Langdon et al., 2010).

Thus, the Höfðahólar rock avalanche event occurred between 9,000 B.P. (youngest beaches) and 8,000 B.P. (14C oldest dating). Such results comfort Jónsson idea, proposing the occurrence of such landslide as the result of a rapid paraglacial crisis following the deglaciation period, due to the combined effects of glacial oversteepening, supply water throughout the lava piles during glacial melting, and glacio-isostatic uplift.

EC1-02

Formation of the Hellemobotn (Vuodnabahta) Canyon in Tysfjord, Northern Norway

Håvard Dretvik

University of Bergen, BERGEN, Norway

Hellemobotn canyon is located in Tysfjord County, Nordland, northern Norway. The formation mechanism of the canyon is not fully understood, and this project aims to resolve this by combining field investigations (Quaternary geological mapping, stratigraphy) with the use of ground penetrating radar (GPR) and dating based on cosmogenic nuclides (CN) and optically stimulated lumniscence (OSL).

Hellemobotn is situated at the head of the long, narrow and deep Hellemofjorden (33 W 563824 E 7522364 N) and is surrounded by mountains altitudes from 800-600 m. A large deposit (approx. 2.5 km^2) has been built up between the mouth of the canyon and the head of the fjord. The rather flat top surface at an altitude of 75-60 m has a network of relict channels. The two modern rivers of Stabburselva (Njallajåhkå) and Sørelva (Rávggajåhkå) incise the deposit, and reveal a thick and poorly, unstratified layer of coarse sand and gravel.

The narrow canyon of Hellemobotn is a spectacular landform of large dimensions, about 3 km long and up to 300 m deep. The present watershed (569 m a.s.l.) is located approximately at the border between Norway and Sweden, about 6 km east of Hellemobotn, and the present day catchment area for the canyon is small. The canyon is suggested to have been formed by drainage of large amounts of water. The project objectives are to resolve whether this happened subglacially and/or subaerially, to reveal the source area of the water, and to investigate if the formation occurred in one or multiple catastrophic drainage episodes.

EC1-03

Speleogenesis in the marble karst of north Norway during the last interglacial- glacial cycle

Stein-Erik Lauritzen[1], Rannveig, Ø. Skoglund[2]

[1]*Department of Earth Science, BERGEN, Norway*
[2]*Department of Geography, BERGEN, Norway*

About 2000+ karst caves are known within the Caledonian marbles of north Norway, of which ~50 are longer than 1000 m. Many of them comprise systems of phreatic (sub-watertable) tubes that are found in hanging positions within glacially sculptured landforms (Lauritzen, 2001). The formation of these caves (speleogenesis) has mainly been ascribed to glacier ice-contact - sub-glacial speleogenesis, (Horn, 1935; 1947). Later work has revealed that many of these caves were in existence some 750 kyr BP, (MIS-17), suggesting that the sub-glacial process must have been episodic and quite different from what was first anticipated. Here, we focus on the last interglacial-glacial cycle as a model for previous periods and compile all available data on chemical kinetics, ice volume, sedimentation and radiometric dating. The results support the idea that glacier ice-contact speleogenesis was, on average a slow and episodic process, in good accordance with the findings of relatively small caves of high age.

References:

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Horn, G., 1947. Karsthuler i Nordland. Norges Geologiske Undersøkelse, 165: 1-77.

Lauritzen, S.E., 2001. Marble Stripe karst of the Scandinavian Caledonides: An end-member in the contact karst spectrum. Acta Carsologica, 30(2): 47-79.

EC1-04

Lateral debris accumulations above the glacial equilibrium altitude line: lateral moraines or talus landforms?

Ivar Berthling[1], Geir Vatne[1], Ola Fredin[2]

[1]*Norwegian University of Science and Technology, TRONDHEIM, Norway*
[2]*Geological Survey of Norway/Department of Geography, NTNU, TRONDHEIM, Norway*

In high alpine, permafrost areas of Norway, debris accumulations are sometimes found along glaciers above present equilibrium line altitudes (ELA). Considering a long term negative mass balance trend since the little ice age, they can hardly be explained by an earlier higher ELA. These accumulations are similar in morphology to lateral moraines, and are mainly continuous with lateral moraines beneath the ELA. If such accumulations are considered lateral moraines, they contradict the usual assumption of these landforms developing below ELA due to a divergent flow regime. In paleoclimatic reconstructions, interpreting such accumulations as lateral moraines will give erroneous results.

We suggest that these landforms should be considered talus landforms, developed where the debris input from slopes are higher than the component of glacial transport directed into the glacier. This criterion can be easily met in continental, permafrost areas where glaciers have low mass balance gradients and where the ice laterally may be frozen to its margins.

So far, we have only results based on remote sensing of these landforms. We discuss some selected examples, the significance of these landforms, and the potential for further research.

EC1-05

Reconstruction of the deglaciation in Grødalen, northwestern Norway

Even Vie

University of Bergen, BERGEN, Norway

The thickness and extension of the inland ice in mid-Norway during the Younger Dryas Chronozone and throughout the deglaciation remains to be fully illuminated. Lake stratigraphic analyzes, digital 3D-mapping and field mapping has been done in Grødalen, a mountain valley in the inland of northwestern Norway, to reconstruct the deglaciation history of this area.

In several of the valleys adjacent to Grødalen lateral terraces seem to have exactly the same altitude as the watershed in this valley, at 760 m a. s. l. Because of this, the terraces was by Nordhagen (1929) interpreted as beach shorelines, that was carved by waves in an open, ice dammed lake, covering the whole Åmotan valley system for a period during the deglaciation. Our investigations find no glaciolacustrine sediments in Grødalen. The terraces consist of diamictic material, and we suggest that they can be lateral drainage channels, eroded in till by melt water, between the glacier and the valley side, and controlled by the watershed altitude.

Core samples were taken from a watershed proximal bog at 740 m a. s. l. in Grødalen, and the Vedde ash was proven, which makes Grødalen the highest elevated Vedde-ash locality in Norway. This indicates that the valley was ice free during the later stage of Younger Dryas.

A major sandur is situated immediately distal to the threshold in Grødalen, and is probably synchronous to the terraces and the many eskers in the valley. There is a system of ice wedge polygons on this sandur, and together with a distinct moraine from a rock glacier this indicates a period of permafrost. Perhaps these are the only features in this area that can be correlated to the cold stage and glacial stillstand/readvance that must have deposited the Gikling frontal moraine in Sunndalen. A draft of the glacier surface gradient, drawn from Gikling and eastwards, supports that the much higher elevated Grødalen was ice free during this stage.

ORAL EC 1

EC1-06

Changed character of marine varves west of Billingen after Baltic Ice Lake drainage

Mark Johnson[1], Lovise Casserstedt[2], Rodney Stevens[2]

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The southern, land-based part of the Scandinavian Ice Sheet (SIS) featured multiple highly dynamic, short-lived ice streams that played a major role in controlling the behaviour of the ice sheet margin along a distance of over 1000 km. There are no modern analogues for these ice streams, yet their reconstruction is vital for our understanding of the entire SIS system. New data on some palaeo-ice streams from the last glaciation suggest that the ice/bed interface has been a self-organising system of multiple quasi-steady-states separated by thresholds related to hydrological and geomechanical parameters such as meltwater, drainage capacity of the bed, porewater pressure, strength of the bed sediments, etc. At critical states slight variations in these parameters may have caused dramatic re-organisation of the nature of subglacial processes including switches between erosion, deposition and deformation. Sedimentary and geomorphological record strongly suggests large volumes of meltwater at the ice/bed interface that developed clearly discernible, distributed and channelized drainage systems. We consider this meltwater as the primary factor facilitating fast ice flow by some combination of enhanced basal sliding and substratum deformation.

EC1-07

The Genesis of the Kivijärvi-Lohtaja Interlobate Esker and its Implications for Geomorphology and Deglacial Palaeo-Ice stream Dynamics in the Trunk of the Finnish Lake District Lobe

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The interlobate genesis of Kivijärvi-Lohtaja esker and its relation to behavior of Finnish Lake District ice stream lobe in Finland is described. Interlobate areas between ice lobes are the focus for meltwaters and debris and therefore favourable for genesis of interlobate eskers that form invaluable record of the fluctuations in the meltwater flow activity during the deglaciation. The Finnish Lake District ice lobe has a narrow trunk area connected to a large splayed lobe and two bordering lobes which are typical features of an ice stream. The sedimentological data of the interlobate esker in combination with spatial geomorphology and paleo-ice stream landsystems analysis revealed that the trunk of the ice lobe was divided into adjacent, smaller fast flowing ice masses during the rapid deglaciation. The location of major eskers was controlled by the changing activity of the ice streams and related fluctuation of sub-glacial hydrological regimes. These findings provide an example how glacial landsystems approach can contribute to the future elaboration of geomorphologically based spatial models for ice-stream land-scapes over the area of the past Scandinavian ice sheet.

EC1-08

Why did ice move so fast? Water under the land-based, southern Scandinavian palaeo-ice streams

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The southern, land-based part of the Scandinavian Ice Sheet (SIS) featured multiple highly dynamic, short-lived ice streams that played a major role in controlling the behaviour of the ice sheet margin along a distance of over 1000 km. There are no modern analogues for these ice streams, yet their reconstruction is vital for our understanding of the entire SIS system. New data on some palaeo-ice streams from the last glaciation suggest that the ice/bed interface has been a self-organising system of multiple quasi-steady-states separated by thresholds related to hydrological and geomechanical parameters such as meltwater, drainage capacity of the bed, porewater pressure, strength of the bed sediments, etc. At critical states slight variations in these parameters may have caused dramatic re-organisation of the nature of subglacial processes including switches between erosion, deposition and deformation. Sedimentary and geomorphological record strongly suggests large volumes of meltwater at the ice/bed interface that developed clearly discernible, distributed and channelized drainage systems. We consider this meltwater as the primary factor facilitating fast ice flow by some combination of enhanced basal sliding and substratum deformation.

EC1-09

The active drumlin field at the Múlajökull surge-type glacier, Iceland – geomorphology and sedimentology

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Recent marginal retreat of Múlajökull, a surge-type, outlet glacier of the Hofsjökull ice cap, central Iceland, has revealed a drumlin field consisting of over 50 drumlins. The drumlins are 90-320 m long, 30-105 m wide, 5-10 m in relief, and composed of multiple beds of till deposited by lodgement and bed deformation. The youngest till layer truncates the older units with an erosion surface that parallels the drumlin form. Thus, the drumlins are built up and formed by a combination of subglacial depositional and erosional processes. Field evidence suggests each till bed to be associated with individual, recent surges. We consider the drumlin field to be active in the sense that the drumlins are shaped by the current glacial regime. To our knowledge, the Múlajökull field is the only known active drumlin field and is, therefore, a unique analogue to Pleistocene drumlin fields.

EC1-10

Strain patterns through a drumlin revealed by till-fabric analysis and GPR profiling

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The coupling between a glacier and the materials at its bed forms a central strand in promoting the significance of the subglacial deforming bed within glacier dynamics. As such, the sediments from a subglacial deforming bed should preserve a record of the strain history of the coupled glacier-bed. However, despite considerable research, the actual degree of sediment strain occurring within a subglacial substrates is still poorly understood. This study presents a detailed analysis of sediments comprising a recently exposed drumlin exposed in the foreland of Breðamerkurjökull. Macro- and microfabric data has been collected from 17 locations across the surface and from the interior of the drumlin, which has been dissected by two proglacial meltwater channels. GPR profiling reveals an internal structure that conforms to the model of Boulton & Hindmarsh (1987) for drumlin formation, in which a less mobile core of gravels undergoes compressional deformation due to thrusting, with structures indicating extensional deformation close to the contact with the till that forms a carapace for the drumlin. Detailed analysis of both macro- and micro-fabric is used to infer the nature and degree of sediment strain during drumlin emplacement. The results show a complex pattern of particle fabrics across the drumlin, which in part broadly accords with the 'herringbone' fabric patterns found in similar studies on flutes. However, the detailed analysis and reconstructed picture of sediment strain based on till-fabric analysis is problematic, and suggests that complex mechanisms of sediment deformation are found within drumlins that are not easily reconciled with existing numerical, theoretical and conceptual models of drumlin formation.

EC1-11

Blast it – fracture propagation, sedimentation and deformation during the evolution of hydrofracture systems

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Hydrofracture systems within subglacial to ice marginal settings represent a visible expression of the passage of overpressurised meltwater through these glacial environments and provide a clear record of fluctuating hydrostatic pressure. Micromorphology and X-ray microtomography have been used in a number of detailed studies of a hydrofracture systems cutting both bedrock and modern and ancient glacial sediments from Scotland, Switzerland and Iceland. These detailed studies have revealed that hydrofractures are complex, multiphase systems which were active over a prolonged period accommodating several phases of fluid flow. Bedding or layer-parallel, conduits (sills) may be linked to steeply inclined to subvertical, transgressive dykes which, in some examples, can be shown to have developed along contemporaneous fractures and normal faults. Individual hydrofractures typically comprise three main stages of fill:

- Stage 1 - Initial fracture propagation, followed by the introduction of a thinly laminated clay, silt and fine sand fill. The clay lined the hydrofracture walls, sealing the adjacent wall-rock reducing its permeability;
- Stage 2 - Repeated reactivation of the hydrofracture and deposition of a thinly laminated sequence of coarse silt to fine sand. Sedimentary structures (cross lamination, graded bedding) provide a record of palaeoflow and fluctuating porewater pressure, as well as deposition within open, fluid filled voids or cavities which temporarily formed during the development of the hydrofracture system; and
- Stage 3 - Late-stage liquefaction of earlier sand and silt fills and injection of cross-cutting veinlets of remobilised sediment, possibly in response to stress release during subsequent brittle failure.

The repeated reactivation of the hydrofracture may also lead to the erosion or liquefaction of earlier formed sediment fills, as well as localised deformation (folding, faulting) of these deposits. A comparison of the results of this study with published engineering 'hydrofrac' data indicates that: (1) changes in the style of sedimentation can be directly related to the fluctuation in overpressure during hydrofracturing; and (2) the overpressures required to reactivate the hydrofracture will, in general, decreases over time. However, micromorphological evidence has also been found showing that a sudden increase in overpressures within an established hydrofracture can lead to the failure of the adjacent wall-rock and the 'rerouting' of fluid flow within the system. The development and repeated reactivation of subglacial hydrofracture systems has the potential to dramatically increase the permeability of the bed, facilitating the migration and evacuation of meltwater beneath glaciers and ice sheets.

EC1-12

The landscape architecture of the forefield of Eyjabakkajökull, a surge-type glacier in Iceland

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A new geomorphological map of the forefield of the Eyjabakkajökull surge-type glacier in Iceland is presented. The map is based on field mapping and aerial photography from 2008 that covers c. 58 km^2, including the Eyjabakkajökull glacier tongue and its entire forefield. When viewed in the context of glacial landsystems, the map identifies landforms that can be regarded as characteristic of glacier surging; in particular, crevasse-fill ridges, concertina eskers, long flutings, hummocky and ice-cored moraines, pitted outwash plains, and glaciotectonic

ORAL
EC 1

end moraines. In addition, landforms that are common for many glacial environments but less typical of surging, were also identified and mapped; specifically, kames, sinuous eskers, sandar, braided channels, and outwash fans. Periglacial landforms like collapsed palsas and frost-crack polygons were mapped as well. Eyjabakkajökull has experienced surges every 21-40 years during the past ~2200 years (Striberger et al. 2011); hence, the large-scale landscape architecture is likely a result of dozens of surges. However, the glacial sediments and landforms presently identified in the forefield result from the most recent and historically known surges of Eyjabakkajökull in 1890, 1931, 1938 and 1972. The association of sediments and landforms in the Eyjabakkajökull forefield is diagnostic of glacier surging and may serve as a modern analogue in palaeoglaciological reconstructions.

Reference:

Striberger, J., Björck, S., Benediktsson, Í.Õ., Snowball, I., Uvo, C.B., Ingólfsson, Ó., Kjær, K.H. 2011. Climatic control of the surge periodicity of an Icelandic outlet glacier. Journal of Quaternary Science 26, 561-565.

EC1-13

Mapping the Surface and Surface Changes of Icelandic Ice Caps with LiDAR

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Icelandic glaciers have an area of ~11000 km² and store a total of ~3600 km³ of ice, corresponding to ~1 cm rise in global sea level. As a part of and following the International Polar Year (IPY), an accurate digital terrain model (DTM) of Icelandic ice caps is being produced with airborne LIDAR technology. It is important that the glaciers are accurately mapped now when rapid changes have started in response to warming climate. The mapping is organised by the Icelandic Meteorological Office and the Institute of Earth Sciences of University of Iceland and carried out by the German company TopScan. Financial support has been provided by the Icelandic Research Fund, Landsvirkjun (the National Power Company of Iceland), The Icelandic Public Road Administration, Reykjavík Energy Environmental and Energy Research Fund, the Nordic Klima- og Luftgruppen fund (KoL) and the National Land Survey of Iceland. As of now more than 7500 km² have been surveyed in this effort including Hofsjökull, Mýrdalsjökull, Eyjafjallajökull, Drangajökull and the southeastern and northern ice flow basins of the Vatnajökull ice cap. Several smaller glaciers and ice caps such as Snæfellsjökull, Eiríksjökull and Tungnafellsjökull have also been surveyed and most of Langjökull (~900 km²) was mapped by LiDAR in 2007 by the Scott Polar Research Institute. The mapping includes a 500-1000 m wide ice-free buffer zone around the ice margins which displays many geomorphological features related to glacier action and the new DTMs are already being used in geological investigations of the proglacial areas that have been surveyed. The new DTMs are also being used for comparison with ice surface measurements from satellites and in connection with ice flow modelling. The DTMs are useful for various glaciological and geological research including studies of jökulhlaups, subglacial lakes and ice cauldrons formed by subglacial geothermal areas and they will be used for bias correction of glacier mass-balance measurements. Preliminary comparison of the LiDAR DTMs with older maps confirm the rapid ongoing volume changes of the Icelandic ice caps which have been shown by mass-balance measurements since 1995/1996. In addition to the LiDAR surveys, a reanalysis of available digital photogrammetric maps of the ablation areas of the glaciers from the 1990s is being carried out using the new LiDAR DTMs in the proglacial areas and on nunataks as a reference to reduce systematic bias in the earlier maps. This will make it possible to obtain an accurate estimate of ice volume changes of Icelandic ice caps during the last 10-20 years. The LiDAR DTMs will be available in the public domain for scientific research, map production and other use.

EC1-14

Hofsjökull ice cap: 25 years of mass-balance measurements and related research

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Located in the central highlands of Iceland between altitudes of 600 m and 1790 m, Hofsjökull (860 sq. km) is the third largest ice cap in Iceland. The year 2012 marks the 25th anniversary of mass-balance measurements on the ice cap, which were initiated in 1987. The mass-balance record is the longest from an ice cap in Iceland, and the positions of several outlet glaciers have been recorded since the 1930's. Large areas of the ice cap are inaccessible due to crevasse fields and mass-balance studies have thus been confined to three transects on the Blágnípujökull, Sátujökull and Þjórsárjökull catchment areas, which in total comprise about 40% of the ice-cap area. Measurements of winter accumulation and summer ablation have been carried out at fixed locations from the outset of the program, but in recent years rapid retreat of the ice cap has forced the relocation of the lowest elevation stakes on all three transects. The mass-balance of Hofsjökull has been negative every year since the start of measurements, except for the glacial years 1988-89, 1991-92, 1992-93 and 1993-94 (results for 2010-2011 are not ready by the time of abstract submission). The net annual mass balance averages -0.6 m/yr since the start of measurements on the N- and SE-transects, and -0.5 m/yr on the SW transect. The most negative mass balance values were obtained in the summers of 1991 and 2010, when ash from the volcanoes Hekla and Eyjafjallajökull greatly enhanced summer melt rates.

This presentation will review the history of the Hofsjökull mass-balance program and outline results from related studies on the ice cap. An overview will be given on year-to-year variations in mass balance and equilibrium line altitude (ELA) on the three transects, along with estimates of total mass loss from the three basins since 1987. The presentation will also include examples from ice-velocity measurements, runoff modelling, an ice core study at the summit of the ice cap and recent LiDAR measurements of surface elevation.

EC1-15

High resolution glacier catchment monitoring: the Virkisjökull Observatory, southeast Iceland

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Glaciers are evolving rapidly in the current period of climate warming. Consequently, dynamic glacial and geomorphic processes now operate at rates that can be monitored and recorded over short periods, generating valuable insights into drivers, mechanisms and rates of change in glaciated catchments. To this end an 'Earth Observatory' has been operated by BGS at Virkisjökull in SE Iceland since September 2009. This 8 km long, climatically sensitive outlet glacier of the southern extremity of Vatnajökull, has undergone marked change in the last 20 years, with an acceleration in thinning and retreat rates over the last 5 years. The foreland displays a broad suite of landforms, many in the process of formation, including: medial, push, thrust block and annual moraines; kettle holes, meltwater channels, sandur deposits and outwash terraces; and an excellent example of an englacial esker in formation.

The observatory is committed to monitoring the evolution of the glacier, its foreland and the wider catchment, and links to local climate. Our approach involves a combination of dedicated high resolution continuous monitoring of the key environmental parameters of the catchment (climate, hydrology, glacier seismicity), and repeat surveys of both the evolution of the landscape, and the variation in surface and subsurface catchment hydrology.

Three automated weather stations have been installed at the glacier terminus, adjacent to the icefall, and at the Equilibrium Line Altitude. Two stream gauges have been installed monitoring the main fluvial outlet from the catchment, specifically to record the influence of local climate on glacier ablation and groundwater/ surface water relationships. Finally a glacier seismic network of four broadband sensors, situated around the glacier margin, are recording up to 200 glacier seismic events per day, enabling leads and lags between daily weather patterns, basal hydrology and glacier motion to be established.

Terrestrial LiDAR surveys are completed each year enabling inter-annual comparison of DEMs of an area of 5 km^2 of the glacier margin and foreland. GPR and passive seismic profiling have been completed across the foreland to establish basin architecture and sediment/buried ice relationships. Sediment permeability studies are undertaken to ascertain the seasonal influence of groundwater on catchment hydrology.

Initial findings have revealed: clear links between local climate and rapid changes in foreland geomorphology; dynamic processes of sediment transport and gravitational mass-movement in esker formation; and clear links between local climate and glacier seismicity. We will present preliminary results from the most recent LiDAR survey, and those from hydrological and hydrogeological studies conducted in September 2011.

EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments

ORAL EC 2

EC2-01

Mid and Late Holocene glacier changes in Greenland

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During the mid-Holocene glaciers in Greenland reached a minimum, and the margin of the Inland Ice was up to 80 km behind its present day position. During the Neoglaciation, glaciers expanded. At a number of sites reworked marine fossils from the Holocene thermal maximum have been reported from areas that were later deglaciated. A review of sites with reworked marine fossils will be presented, together with new data.

During the past decades, most glaciers in Greenland have receded rapidly and lost mass at an accelerating rate. At the margin of some ice caps, dead but extremely well preserved in situ plants of Salix and Cassiope are emerging. The plants must have been covered by snow that turned into ice, and they have been preserved below the ice until now.

Radiocarbon age determinations of plants from east Greenland found in bedrock lees show ages corresponding to the Medieval Warm Period. This indicates that ice caps are now reaching an extent similar to that experienced by the Norse people when they arrived in Greenland around 1000 years ago. Analyses of organic debris found adjacent to the in situ plants indicate summer temperatures similar to the present. Remains of in situ Salix plants have also been found near the margin of an ice cap in north-west Greenland. Similar material has been found at many sites on Baffin Island in the eastern Canadian arctic. Radiocarbon ages from Baffin Island cover the time interval 300-1450 AD.

The Medieval Warm Period was followed by the Little Ice Age, which is well known from Iceland, where sea ice was extensive. Glaciers in Greenland reached a maximum, and plants were buried by snow and ice.

EC2-02

The climatic signal in the stable isotope record of the NEEM SS0802 shallow firn/ice core from the NEEM deep drilling site in NW Greenland

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By studying paleoclimate one gets the opportunity to understand the interactions of complex processes that control long term climate, which complements the study of today´s climate and its evolution. One of the best kept data on paleoclimate is found in polar ice cores where water isotopes have during many decades

ORAL
EC 2

been used as proxies for past temperature and indicators for variations in the hydrological cycle. The chemistry of past atmosphere can be studied in the ice and in gas-bubbles that gets trapped in glacier ice through snow-ice transition.

Ice core research in Greenland goes back to the 60´s and since then several deep ice cores have been studied to detect and understand past climate variations. The latest deep ice core project "NEEM"in northwest Greenland aims at retrieving a complete ice core that includes the Emian interglacial period, around 140.000 years ago. The Eemian climate is thought to be about 5°C warmer than present climate and could therefore be used to predict future climate changes in a warmer world.

The NEEM deep ice core project included drilling shallow cores with the aim to get a high resolution isotopic profile for the last ~300 years and its correlation with measured, available climate parameters. This will enhance our understanding of the climatic system and aid interpretation of the climate signal reflected in the isotopic record from the NEEM deep ice core.

In the present study the 80 m shallow core, NeemSS0802, was analyzed for oxygen and hydrogen at the Institute of Earth Sciences, University of Iceland. Results on the annual isotopic cycle, correlation between temperature and volcanic events detected in the core and correlation between the isotopic record and available climatic parameters, like NAO, NATL ssT, sea ice cover and Greenland/Iceland temperature, will be presented.

EC2-03

Climate and volcanic reconstructions from the Greenland ice core records

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In exploring past climate conditions and in the search for the triggers, processes, and feedbacks responsible for past climate change, ice cores have been instrumental, providing a highly attractive combination of long records, high temporal resolution, and good dating control. Over the past two decades, high-resolution examination of the GRIP, GISP2, and NorthGRIP ice cores have provided new insights into both interglacial and glacial climatic behavior, and the best-resolved of these records make it possible to reconstruct variations in the climatic régime of the North Atlantic region on annual scale or better. This degree of temporal resolution, combined with data derived from a wide variety of climate proxy indicators, makes it possible to map out the nature of abrupt climate changes in considerable detail and to identify leads and lags in the climate system.

However, until recently, dating differences between records and poorly quantified uncertainties have limited the possibility for robust comparisons. Based on a combination of existing and new data series from the DYE-3, GRIP, and NGRIP ice cores as well as tight synchronization of the records using signals of mainly volcanic origin, The Greenland Ice Core Chronology 2005 (GICC05) is the most extensive attempt at providing a consistent set of time scales for the Greenland ice cores. Since the advent of GICC05, this time scale has been transferred to parts of the GISP2, NEEM, Camp Century, Renland, and Hans Tausen ice cores, and has been used as basis for Antarctic ice core dating efforts as well. The combined ice core records provide important insights into both past climatic conditions on local, regional, and global scale and provide a comprehensive record of past volcanic activity.

Synchronized Greenland and Antarctic ice core records reveal important new facts about the relative timing of north-south climate variations across the deglaciation. We observe clear coupling between Antarctic and Greenland temperature records consistent with the bipolar seesaw hypothesis in which warm Greenland periods align with periods of Antarctic cooling, and vice versa. New data allows this analysis to be extended across the deglaciation and confirms that the bipolar seesaw is active even on centennial time scales.

EC2-04

Middle to Late Pleistocene stratigraphy and Kara Sea Ice Sheet margins on the Taymyr Peninsula, Arctic Siberia: current status and future plans

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Fluid flow in faults has lately gained much attention due to its impact on production in hydrocarbon fields and its potential influence on the sealing capacity of cap rock. In the modeling of such systems detailed understanding of fault architecture is crucial.

The present study, conducted in the Northumberland Basin of northeastern England comprises four extensional fault systems with a normal offset ranging from 10 to 200 meters. The faults affect Carboniferous coal-bearing sediments. The four studied localities are situated northeast of Newcastle where faults are well displayed in three dimensions along cliff sections and the beach. Three of the faults occur in a sequence of alternating shale, siltstone, sandstone and coal-beds, whereas the fourth also cuts a limestone unit.

The data used include aerial photographs, LiDAR scans and field data analyzed by traditional statistical methods (fault architecture, fracture frequency diagrams, orientation data and thin sections). The field study included the following steps:

1) The outcrops were studied by the use of aerial photography to determine the traces of the most important faults,
2) the master faults were studied in outcrops and the general pattern of displacement and the fault architectures were established,
3) fracture frequency diagrams covering footwall, hanging wall and fault cores were generated,
4) and the relation between fault core lenses and high strain zones (fault rocks and fault smear products) was determined.

The fracture frequency diagrams indicate more intense deformation on the hanging wall side than on the footwall side. However, most deformation was accommodated in the fault core. Fault-related folds and drag-structures are evident, and various contractional structures are observed, especially in fine-grained rocks and coal.

The steep geometry of the faults is ascribed to reactivation and/or mechanical inhomogeneities related to lithological contrasts. The fault core thickness is related to the amount of displacement, and is proportional to the amount of lens-shaped rock bodies within the core. The lenses are thicker relative their length axes than examples previously reported in the literature. We conclude that the individual fault systems exercise great control on lens dimensions.

Complex fault geometries are evident both in macro an micro scale and indicate several stages of deformation, compatible with 1) syn-sedimentary / soft-sediment normal faulting, 2) post-consolidation normal faulting 3) tectonic inversion. The complex geometry associated with the multistage structuring is likely to influence fluid flow across and along the studied fault zones. Whether the fault systems are sealing and how they affect fluid flow is strongly influenced by the lithology, since sandstone and limestone produce drag structures and confined lenses, whereas shale contributes to smear along fault planes.

EC2-05

Lake Lögurinn, Eastern Iceland – recording the Holocene meltwater and surge history of Eyjabakkajökull

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The Lagarfljót Project has been a collaborative effort to (a) reconstruct climate oscillations in eastern Iceland over the past millenia by examining varved sediments in an 18 m long sediment core retrieved from Lake Lögurinn, (b) construct a paleo-surge record of Eyjabakkajökull based on "surge fingerprints" in Lake Lögurinn sediments, and (c) reconstruct the Holocene glacial history of Vatnajökull as expressed by meltwater variations identifying glacial (meltwater input) and non-glacial (no meltwater input) periods in the sediment sequence.

Our results show that glacial meltwater transport to Lake Lögurinn since deglaciation of the basin >10.5 ka BP has varied significantly during the Holocene, and these variations are directly associated with changes in the extent of the Eyjabakkajökull outlet glacier. By ca. 9 ka BP glacial meltwater input to the basin had almost disappeared, and there was no or very little meltwater input to Lake Lögurinn in the early- and mid-Holocene. This implies that Eyjabakkajökull (and eastern Vatnajökull) probably had disintigrated completely by ca. 9 ka BP and did not return until the onset of Neoglaciation in eastern Iceland, ca. 4.4 ka BP. The Holocene Thermal Maximum, as inferred by biological productivity in Lake Lögurinn, is dated to 7.9-7 ka BP.

Glacial surge behavior of Eyjabakkajökull can be traced back to 2.2 ka BP. This study suggests that surge periodicities of Eyjabakkajökull over the past 1700 years have varied because of mass balance changes of Eyjabakkajökull controlled by climatic fluctuations. Finally, our study shows that the expansion of Eyjabakkajökull during the coldest phase of the Little Ice Age in eastern Iceland was likely associated with not only lower summer temperatures (shorter melt season) but also increased winter accumulation (precipitation).

EC2-06

History of glacier variations of Vatnajökull´s southeast outlet glaciers during the last 300 years – a key to modelling their response to climate change

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The evolution of the non-surging outlet glaciers of southeast Vatnajökull since the 17th century has been studied by the use of geomorphological field evidence, historical accounts, maps, photographs, and satelite images. The documentary record of glacier variations and detailed information about glacier geometry is unique for studying the response of these glaciers to climate change. Volume calculations since the Little Ice Age maximum (reached between 1870 and 1890 for most of the glaciers), through the 20th century and beginning of the 21st century, reveal a loss of tens of km^3 for these outlet glaciers. To study the connection of glacier variations and climate change we use a coupled glacier mass balance and flow model (Aðalgeirsdóttir et al., 2011). The finite element flow model is based on shallow-ice approximation and Weertman-type sliding. A degree-day-mass balance model uses records from meteorological stations located away from the glacier, and is calibrated to annual mass balance observations at 23 stakes on southern Vatnajökull since 1996. Local temperature data is available since 1884 and local precipitation data since 1932. Maps from the 20th century, satelite images, GPS measurements and Little Ice Age frontal and lateral moraines (indicative of maximum glacial extent) constrain the model.

Preliminary results from the model runs indicate that the degree-day mass balance model underestimates the mass balance in the accumulation areas of some of the glaciers. This is supported by dynamically downscaled precipitation from the mesoscale atmospheric model WRF 3.0 in 3 km grid, as well as from a linear orographic precipitation model (Crochet et al., 2007, Jóhannesson et al., 2007). Hence the estimated winter mass balance was upgraded for this area with data from the WRF 3.0 model, which has a different precipitation distribution compared to the mass balance map. New stake measurements in 2010 on Breiðabunga revealed this greater accumulation. The deficit of mass is accounted for in the new upgraded mass balance grid. Surface lowering in the accumulation area still persists in the model runs, but to a lesser extent. The glaciers do advance in the climate of the cold period 1960-1980, as expected, and show little change during the following two decades, when the net balance of most of the Icelandic ice caps was close to zero (e.g. Gudmundsson et al., 2011).

Next steps include finalizing the mass balance model with winter accumulation composed of a distributed precipitation model and mass balance data, and summer melting derived from a degree-day mass balance model. The model will be used to simulate the 20th century glacier variations and compare the results with known volume changes, and future response for the next 100-200 years according to certain climate scenarios.

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EC2-07

A new Svalbard land-ocean deglaciation chronology of the northern Barents Sea ice sheet

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The timing of the deglaciation of the northern Barents Sea ice sheet (BSIS) documented in terrestrial and offshore records from the Svalbard archipelago is reviewed. The last review of terrestrial and marine data was published by Landvik et al. (1998, Quaternary Science Reviews, 17). In the present investigation we update this information with new cosmogenic nuclide data and marine sediment data.

The timing of deglaciation of this part of the Barents Sea ice sheet is based on radiocarbon ages from marine cores and terrestrial deposits. Previous studies concentrated on coastal and fjord settings, due to access difficulties to interior areas of the archipelago. We present new cosmogenic nuclide (CN) ages from northern Svalbard of formerly unexplored inland areas. To be able to compare our CN dates with radiocarbon dates from foraminifera and mollusk shells from glaciomarine mud we have to overcome two challenges. Firstly, the environmental setting of the dated material has to be evaluated with respect to their validity for an initial disintegration of the BSIS. Secondly, the specific problems and uncertainties of both methods have to be taken into account before we can venture a reconstruction of a chronology. The marine carbon dates were corrected for reservoir age and all radiocarbon ages were calibrated using Calib 6.0, INTCAL09 and Marine09.

Initial ice retreat began on the western shelf edge of Svalbard at 20.5 ka (Jessen et al., Quaternary Science Reviews, 29) and in the western fjords and in Storfjordrenna south of Svalbard around 19-18 ka (Rasmussen et al. 2007, Quaternary Research, 67), which are similar to ages recorded in the Fram Strait (Jones and Keigwin, 1988, Nature, 336). Erratic boulders in inner parts of Svalbard suggest a parallel rapid downwasting of land-based parts of the BSIS between 18.5-16 ka.

The northern BSIS disintegrated more rapidly than previously assumed, based on new CN dates in Nordaustlandet. Inner fjords and lowlands in Nordaustlandet became ice-free 15-13 ka and these deglaciation ages are in good accordance with the marine deglaciation ages of eastern Svalbard. Marine dates show that the area east of Svalbard south of Kvitøya was deglaciated before ca 15 ka.

EC2-08

New data on Late Weichselian ice stream configuration in Kongsfjorden, NW Svalbard

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New information on ice configuration, ice dynamics and development of deglaciation of the Late Weichselian Kongsfjorden ice stream has been obtained from detailed landform mapping and cosmogenic exposure age dating in the Kongsfjordhallet area, including the Knølen Mountain on the northern shore of Kongsfjorden, NW Svalbard.

The minimum Late Weichselian ice thickness for the area is reconstructed by mapping surficial till up to ca. 500 m a.s.l. and obtaining ages of around 17 ka of erratic boulders. This yields a considerably thicker ice, and a higher surface gradient, than suggested by Lehman & Forman (1992) and Landvik et al. (2005). The landform succession, as well as the dating results from erratic boulders at different elevations, suggests a gradual lowering of the ice surface. A large lateral moraine complex continuing into a horseshoe-shaped end moraine on the fjord bottom (described by Lehman & Forman 1992) was deposited at ca. 15 ka. The shape of the moraines and the steep ice surface gradient suggest that the ice dynamics in Kongsfjorden had changed from ice stream behaviour to a slower flowing outlet glacier by this time. An Early Holocene advance of local glaciers is shown by moraine lobes cross cutting the Late Weichselian lateral moraines (Peterson 2008).

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EC2-09

Last deglaciation of Kveithola, NW Barents Sea as revealed by seafloor geomorphology and seismic stratigraphy

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Marine geophysical methods were used to survey the seafloor and sub-seafloor sediments of the Kveithola trough, NW Barents Sea. The resultant dataset includes approximately 1750 km^2 of multibeam echo sounder data, sub-bottom profiler data and single cannel seismic data. The multibeam data reveal a seabed geomorphology dominated by striking parallel linear features (trending E-W), superimposed on which are 4-5 large transverse ridges. Such landforms are frequently associated with fast flowing ice streams and are interpreted as megascale glacial lineations and morainal banks respectively. The observed geomorphic features suggest a glacial origin for the seabed sediment. However, sub-bottom profiler data show that the landforms are not formed directly on the seafloor, but are inherited from a deeper buried surface. The seismic stratigraphy of Kveithola reveals that the palaeo-surface represents the final signature of an ice stream which had a complex deglaciation history during and after the last glacial maximum. Several stages of ice stream retreat and readvance have been identified and compiled in a conceptual model and deglaciation curve. After the ice stream retreated from Kveithola the palaeo-surface was draped by a glacimarine sediment blanket. As ice withdrew further, meltwater plumes and icebergs entering Kveithola from more distal sources led to deposition of sediment drifts in the trough.

EC2-10

Re-examining the stratigraphy of the Poolepynten coastal cliffs, Svalbard – implications for the natural history of the polar bear (Ursus maritimus)

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A subfossil jawbone of a polar bear (Ursus maritimus) recently discovered at Poolepynten, western Svalbard, was suggested to be of last interglacial (Eemian) or Early Weichselian age. Complete mitochondrial genome study of the Poolepynten jawbone suggested that the phylogenetic position of the ancient polar bear lies almost directly at the branching point between polar bears and brown bears, revealing a unique morphologically and molecularly documented fossil link between living mammal species.

The precise dating of the subfossil jawbone has, however, remained somewhat challenging. It was determined by radiocarbon to be older than 45 ka BP (kilo-years before present), and one age determination with infrared-stimulated luminescence - together with the stratigraphic position of the bone - suggested it was probably 130-110 ka old. A complicating factor was that an earlier study of unit A in the Poolepynten stratigraphy, where the polar bear jawbone was later discovered, had revealed a possible hiatus: amino-acid ratios in subfossil mollusc shells and the foraminiferal species composition suggested that unit A might in fact be two units of considerably separate ages. This led to our reinvestigation of the Poolepynten stratigraphy, where the focus was on (a) determining if there was unambiguous lithostratigraphical evidence for unit A being one or more units, and (b) to re-date the sequence using state-of-the-art optically stimulated luminescence (OSL) dating technique.

We have now revised the lithostratigraphy of the Poolepynten coastal cliffs, and show that unit A is in reality three units, which we tentatively label A1-A3. Two fossiliferous shallow-marine units (the lower A1 unit and an upper A3 unit) are separated by an erosional discordance and a thin unit of beach gravels (labelled A2). This signifies that the shallow-marine units A1 and A3 belong to two separate regressional events, and, consequently, to two separate deglaciation sequences. Our revision of the chronology for units A1 and A3, based on three new OSL dates, confirm this and suggest last interglacial (Eemian) age for unit A1 and Early Weichselian age for unit A3. The subfossil polar bear jawbone was discovered in unit A1, so our new stratigraphic and chronologic data match with it being of Eemian age, 130-115 ka old.

EC2-11

Postglacial uplift and relative sea level changes in Finnmark, northern Norway

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The outer coast of Finnmark in northern Norway is where the former Fennoscandian and Barents Sea ice sheets coalesced. This key area for isostatic modelling and deglaciation history of the ice sheets has abundant raised shorelines, but only a few existing radiocarbon dates constrain their chronology. Here we present three Holocene sea level curves based on radiocarbon dated deposits from isolation basins at the outermost coast of Finnmark; located at the islands Sørøya and Rolvsøya and at the Nordkinn peninsula. We analysed animal and plant remains in the basin deposits to identify the transitions between marine and lacustrine sediments. Terrestrial plant fragments from these transitions were then radiocarbon dated. Radiocarbon dated mollusk shells and marine macroalgae from the lowermost deposits in several basins suggest that the first land at the outer coast became ice free around 14,600 cal yr BP. We find that the gradients of the shorelines are much lower than elsewhere along the Norwegian coast because of substantial uplift of the Barents Sea. Also, the anomalously high elevation of the marine limit in the region can be attributed to uplift of the adjacent seafloor. After the Younger Dryas the coast emerged 1.6 - 1.0 cm per year until about 9500 - 9000 cal yr BP. Between 9000 and 7000 cal yr BP relative sea level rose 2 - 4 m and several of the studied lakes became submerged. At the outermost locality Rolvsøya, relative sea level was stable at the transgression highstand for more than 3000

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years, between ca 8000 and 5000 cal yr BP. Deposits in five of the studied lakes were disturbed by the Storegga tsunami ca 8200 - 8100 cal yr BP.

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EC2-12

Once upon a time under the ice divide: provenance, transport and exposure history of glacial erratics at Rendalssølen (1755 m a.s.l.), southeastern Norway

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Provenance studies and geomorphological mapping are used to study Weichselian palaeo-ice flow at the mountain Rendalssølen (1755 m a.s.l.) in southeastern Norway. The mountain is mantled by openwork blockfield at elevations above 1100 m a.s.l., which is mostly autochtonous, but must by definition be allochtonous on the steep slopes. Glacially transported cobbles and boulders have been systematically collected at the southern part of the mountain (summit at 1688 m a.s.l.). Together with numerous incised meltwater channels, the erratics indicate that Rendalssølen has been ice covered at least once. Clast lithological analysis will further be used to identify the source areas of the glacial erratics and hence to reconstruct past ice movement directions (cf. Juliussen and Humlum 2007, ZfG 51).

Rendalssølen is situated within the area that is believed to have been occupied by the ice divide during the Last Glacial Maximum. Geomorphological mapping shows that landforms and deposits associated with contrasting thermal regimes coexist in the area. Large-scale marginal moraines, Rogen moraines, as well as flutings are preserved together with lateral meltwater channels. Rogen moraines and flutings in addition to lateral meltwater channels indicate the presence of a cold-based (low-erosive) ice sheet with unfrozen patches. Such conditions would not allow the formation of large-scale marginal moraines (but their preservation). The interpretation of the relative age relationships and preservation beneath cold-based ice is furthermore supported by aerial photos showing parallel lineations superimposed on the marginal moraines.

At the 1688-summit glacial striae on in-situ bedrock show an orientation towards S-SE, whereas till macrofabrics from the marginal moraines (at about 900 m a.s.l.) reveal different orientations. The 2D results (inclination only) show an orientation from SW that differs from the 3D (inclination and declination) results, which show an orientation from SE. The aberrating results from the striae and the till fabrics supports the complex glaciation history of the area.

A complex thermal regime is also evident from surface exposure dating using nuclides: apparent 10Be exposure ages up to ~180 ka are obtained on in-situ bedrock at 1660 m a.s.l. (Linge et al. 2006, QSR 25). At 1200 m a.s.l., however, glacially eroded bedrock gives ~50 ka, whereas glacially transported boulders give ~10 ka.

Ongoing work includes sediment analysis and dating as well as mapping from aerial photos.

EC2-13

The late Plio-Pleistocene outbuilding of the mid-Norwegian continental shelf: seismic sequence stratigraphy reflecting ~ 30 glaciations

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A great number of ice ages and periods with globally lowered temperature have affected the Earth since the onset in late Miocene time of the present ice-house climate regime. The oxygen isotope curve obtained from deep-marine sediments are the fundamental record of global temperature changes during Plio-Pleistocene, whereas glacial deposits are evidences of previous glaciers or glacial ice sheets. In the North-Atlantic domain there are three main storages of glacially derived sediments. (1) Ice-rafted detritus (IRD) in deep-marine sediments reflect ice-sheets that advanced into the sea. The IRD record reflects a stepwise initiation of large-scale glaciations and from about 2.75 Ma onwards a synchronous ice sheet development was established in the circum North Atlantic region. (2) In Iceland at least 20 glaciations the last 4 million years have been identified by glacial sediments preserved on land or in coastal basins between volcanic beds dated by geochronological methods. (3) Sedimentary sucessions on the shelves of NW-Europe, Iceland, East Greenland and Svalbard form prominent records of the history of large Plio-Pleistocene ice sheets that reached the coast and partly extended across the shelves.

The Plio-Pleistocene sedimentary succession of the mid-Norwegian continental shelf were formed by the basinward progradation of a series of sequences with internal clinoform geometry, bounded below by a Regional Downlap Surface (RDS), dated to about 2.8 Ma, and above by an Upper Regional Unconformity (URU), an erosional surface overlain by glacial and glaciomarine deposits related to the last two glaciations, besides a thin veneer of postglacial sediments. The RDS formed the sea bed at depths up to 400-500 metres close to mainland Norway just after depositon of the late Miocene-early Pliocene Molo Formation. A large accommodation space was available for the Naust Formation with its clinoform sequences. On high-quality seismic lines ~30 westward dipping sequences have been identified in the Naust Formation between the RDS and the URU. Individual sequences are bounded by (a) toplap truncation, (b) toplap truncation combined with onlap and (c) onlap. In landward direction the sequences are bounded by the URU and seaward by westward dipping strata. The sequences have all internal clinoforms with varying seismic facies reflecting various types of glacial sediments deposited beneath and at front of ice margins of advancing ice sheets.

We interpret each of the ~30 westward dipping sequences as formed during the advance and retreat of individual continental ice sheets, reaching the shelf from highland Scandinavia. The ice sheets have been mostly grounded, causing glacial erosion into glacial sequences formed during the previuos advance of continental ice sheets. Internal geometry and seismic facies of individual sequences can be related to well established models for dynamic behaviour of ice sheets on marine shelves. The ice sheets were likely split into several ice streams with varying sediment load and depositional capasity, explaining the absence of some sequences in some of the studied lines.

The Norwegian continental shelf may thus have preserved a glacial record covering much more glaciations than previously interpreted.

EC2-14

Cold-based palaeoglaciers and 10Be surface exposure dating

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Surface exposure dating using in situ cosmogenic ^{10}Be has been performed to trace the spatial and temporal progress of the last deglaciation in east-central southern Norway. The preservation of undisturbed pre Last Glacial Maximum sedimentary deposits, often superimposed by thin/discontinuous till or scattered boulders, confirms past cold-based glaciers.

A cold-based and low-erosive ice cover is expected to result in rock surfaces containing cosmogenic nuclides from multiple exposure episodes, however, the majority of the ^{10}Be ages are around 10-12 ka, suggesting an onset of ice-free conditions commencing between the Younger Dryas and the early Holocene. Any older ages could invariably be explained by inheritance. However, two settings are difficult to align with the conventional understanding of the area. The first setting is exemplified by a cirque situated in a tributary valley displaying at least two marginal moraines at ca. 1200 m asl giving exposure ages of 13.1-10.7 ka, hence constraining the elevation of a potential valley glacier to below this altitude prior to the Younger Dryas. The second setting is a large sandur deposit down-valley at ca. 690 m asl where exposure dating of surface pebbles gives 14.0-12.3 ka, in agreement with older OSL ages of near-surface sand, and with younger radiocarbon ages from kettle holes. Both settings are well drained and little sensitive to exhumation by permafrost degradation.

Accepting that the spatial and temporal distribution of glaciers might have been more irregular than previously thought requires a re-assessment of ages in the 10-12 ka interval. Boulder-bedrock pairs showing 10-12 ka are accepted as reflecting the duration of exposure, although they do not necessarily reveal when glacial erosion last occurred. Boulders (9-19 ka) from marginal moraines may be interpreted to support either late LGM formation, where apparent young ages (9-12 ka) result from exhumation, or younger moraine formation (where apparent old ages (18-19 ka) result inheritance).

EC2-15

Sub-till glaciofluvial and glaciolacustrine sediments on the Småland peneplain – their age and implication for glacial history within the south-western distribution area of Fennoscandian Ice Sheets

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Was there any Fennoscandian Ice Sheet (FIS) during MIS3 and, if so, what was the extent of it? This is at present a hot research topic into the glaciation history of Scandinavia through time. The classic view from the 90'ies is a quite limited extent during MIS4, followed by deglaciation in MIS3, and from where the FIS regrew at its final push towards the Last Glacial Maximum position (LGM) during MIS2.

This scenario is now challenged from two very different standpoint positions; from the studies of Houmark-Nielsen, there were two prominent ice advances during MIS3 into Denmark (the Ristinge, c. 50±4 kyr BP, and the Klintholm ice advance, c. 32±4 kyr BP), resulting from rapid out-flowing ice through the Baltic Basin. This view thus also rejects flow of FIS ice into Denmark during MIS 4. Opposing to this are the reinvestigated and redated stratigraphic records from central and northern Sweden and Finland, suggesting close to ice-free conditions at this time (studies by Helmens, Hättestrand, Salonen, Alexanderson, Wohlfarth, among others). How to reconcile these very different scenarios?

Between the study areas of above - northern Sweden/Finland versus Denmark and southernmost Sweden - lies then the rest of southern Sweden as a more or less white area when it comes to our knowledge of older strata older than the LGM glaciation/deglaciation. However, there are numerous observations from the south Swedish Småland peneplain that sorted sediments at places are overlain by till, and that these often form cores within large drumlins. The preferred view has been that these sediments were deposited during the last deglaciation, and then remoulded into drumlin form during an ice margin oscillation.

A project was set-up for localizing as many of the previously known sites with till-capped sediments as possible in the area around Växjö. Based on assessment of sediment sequence suitability for OSL dating, trenches were dug with excavator for sediment logging and sampling for OSL dating. Out of 24 excavated sites, 15 sites revealed clastic sorted sediment below till (more or less glaciotectonically disturbed glaciolacustrine and proglacial sandur deposits), whereas two sites exposed highly compressed peat and gyttja, new sites for interglacial Eemian deposits. A total of 45 OSL ages revile two markedly different age groups of these sediment sequences; an older group falls approximately between 48-56 kyr for seven sites, while a younger group is c. between 28-36 kyr for five sites. If these two "time boxes" have a true temporal meaning, then these passing glacial environments occurred during MIS 3 (c. 60-30 kyr ago), i.e. during relatively warm, interstadial conditions which per se might be seen problematic, especially as a number of recent reviews of the glaciation history of Fennoscandia suggest very limited ice coverage during MIS 3. At the same time the latest revision of Danish glacial stratigraphy, suggesting the first Weichselian ice advances into the SW perimeter of the FIS distribution area are from MIS 3, namely the Ristinge and Klintholm ice advances, fits well with the OSL-dated deglacial sediment successions from Småland.

EC2-16

How long the glaciations do lasted during Weichselian in Finland?

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The duration of the stadials and interstadials during Weichselian period, i.e. past 115,000 years, has been discussed a long time in Finland and Scandinavia, and in other glaciated terrains, too. From the old theory of one single glacial phase has been turned into the multiphase idea. Based on the different oxygen isotope curves from the ice cores and marine sediments the knowledge of variable climate conditions during the ice ages has been increased. It seems that glaciers disappeared several times also from the central areas of glaciated terrains during the ice ages.

The centre of the Scandinavian Ice Sheet was located several times in Finland during Quaternary. Till stratigraphy is composed of several till beds being the most complete in northern Finland with six till beds. Furthermore, the observations of tens of inter-till stratified sand and gravel deposits were done. Many of them were included organic peat and gyttja having unreliable radiocarbon ages 45 ka or more i.e. indicating the limit of the dating method to be reached (e.g. Hirvas 1991).

During last decade, many of the earlier sratigraphical key sections were re-examined and dated by Optical Stimulated Luminescence (OSL). The determined ages of Weichselian age form two groups: older 115-70 ka (MIS 5) and younger 55-22 ka (MIS 3). New dating results prove that the extent of glaciers and the length of glaciations were mostly short through Weichselian in Finland. Middle (MIS 4) and Late Weichselian (MIS 2) stadials lasted longer, and according to Sarala (2005) and Salonen et al. (2008) they were probably the only stages when glaciers covered central and southern Finland. In northern Finland there are also tills that were interpreted representing the Early Weichselian glacial advances, but based on the OSL dates they lasted only a short time. Instead, during the MIS 3 northern Finland seems to be ice-free for a long time (cf. Mäkinen, 2005; Auri et al. 2008; Sarala & Eskola 2010; Sarala et al. 2010).

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EC2-17

Weichselian stratigraphy and glacial history of Kriegers Flak in the southwestern Baltic Sea

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The southwestern Baltic Sea basin has had a complex Weichselian history with repeated ice advances interrupted by longer periods with ice free conditions. During the Late Weichselian much of the older sediments was eroded or deformed and the early history of the Baltic Sea basin is therefore poorly understood. In this study the stratigraphy and palaeoenvironmental history of Kriegers Flak, a shallow area in the southwestern Baltic Sea, has been investigated. The stratigraphy is based on geotechnical descriptions of forty sediment cores (15-40m long) and shallow seismic profiles retrieved during a survey for a potential wind turbine park. Clast lithological analysis of samples from twelve of these cores was used for correlations while 18 radiocarbon dates (7 non-finite) and 8 OSL ages were used for age constraints. Foraminfera, macrofossil and pollen analyses, stable isotopes and Mg/Ca ratios on foraminiferas were all used to infer the palaeoenvironmental conditions and changes. Seismic profiles and core correlations indicate a generally horizontal stratigraphy without substantial glaciotectonism or erosion. Many of the cores reach down into the Cretaceous/Paleogene limestone and the oldest OSL ages of 147±11 and 119.5±7.5 ka indicating that the cores include all of the preserved Weichselian sediments at Kriegers Flak.

In the eastern part of Kriegers Flak an interstadial succession was identified between glacial sediments. It was divided into three units, A, B, and C. The lowermost unit A overlies a glacial diamicton with a gradational contact. A low diversity benthic foraminifera fauna indicates low salinity and cold water. OSL dates give ages of 71.8±4.4 and 86.4±5.7 ka but might overestimate the true age. A hiatus separates Unit A from the overlying unit B which consists of interbedded clay, silt, sand and organic sediments (peats and gyttjas). OSL and radiocarbon ages indicate an age of 42 to 36 ka BP. Macrofossil and pollen indicate a treeless open tundra landscape, possibly with birch and pine in sheltered positions. Unit C is characterised by renewed clay deposition and indications of reworked material and is separated from underlying unit B with another hiatus. OSL ages from this unit points to an age of 29-26 ka while radiocarbon dated macrofossils suggest an age of 39-40 ka BP and are considered reworked.

The following depositional history is suggested for the interstadial succession:

- Following the deglaciation of a MIS4/MIS3 ice advance a brackish environment existed on Kriegers Flak.
- A forced regression, probably due to a combination of isostatic rebound and decreasing global sea levels, led to a

lower relative water depth and eventually to the emergence of land at Kriegers Flak.
– Between 42 and 36 ka BP an open tundra landscape with lakes and wetlands developed on Kriegers Flak.
– At around 29-27 ka BP the area was once again flooded, probably due to the damming of the Baltic basin by ice advances from Norway.

EC 3 – Permafrost and periglacial processes

EC3-1

Permafrost in Iceland and Norway

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Globally, the distribution of mountain permafrost has been mapped and monitored mainly in locations with relatively continental climates characterized by a stable snow cover and low winter temperatures. In contrast, there is a paucity of systematic ground temperature investigations from maritime mountain areas such as Iceland and transitional areas between the Scandinavian mountain permafrost zone and the continuous permafrost in Svalbard. Knowledge of the present distribution and thermal characteristics is crucial for assessing the response of permafrost to climate change and its geomorphological and geotechnical impact.

Intensive field-based studies on the distribution of permafrost and the dynamics of selected periglacial landforms, such as rock glaciers, have been carried out in northern (Tröllaskagi peninsula) and eastern Iceland since 2003. Since then ground thermal monitoring has continued at four sites. This presentation reviews and synthesises the main results of the 8 years of monitoring, and draws lines to former and future geomorphic process dynamics and landscape development. The results are further compared to extensive ground temperature monitoring and transient heat flow modeling across Norway and Svalbard.

EC3-2

A new assessment of distribution and activity of permafrost landforms in the Tröllaskagi peninsula, northern Iceland

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The formation of rock glaciers and ice-cored moraines are constrained to areas subjected to permafrost, and the presence of such landforms is commonly used as a direct indicator of present or former permafrost conditions. In Iceland, a rock glacier inventory was derived from air photo interpretation by Guðmundsson (2000), and in this context the extend of possible ice-free areas especially during Pleistocene in northern Iceland was controversially discussed.

In the present study we used recently published air photos (2002-07), ALOS PALSAR data (2007) and field mapping, and re-examined the Tröllaskagi peninsula for permafrost landforms. In this re-examination, active rock glaciers are defined by steep front slopes and deep surface ridges and furrows indicating movement, which is also shown by the ALOS PALSAR data. They are also related to clear source areas, facilitating material supply. Inactive rock glaciers are mapped based on the same criteria as the active rock glaciers, but where no surface movement is detectable. The active and inactive permafrost landforms were categorized as one group, namely intact landforms, because of difficulties in establishing whether a landform is moving or not based on singular aerial imagery, and also to expand the sample for statistical purposes. Relict rock glaciers, however, show distinct collapse structures and often have extensive vegetation cover. The formation of these landforms is discussed in relation to existing glaciers or creep in talus slopes, distinguishing between moraine-derived and talus-derived landforms. Ice-cored moraines are here characterized as over-sized moraines in front of small glaciers, and are stable geomorphic features in permafrost environments where the moraine sediment is thicker than the active layer. Ice-cored moraines are considered active features when they appear stable, but do not necessarily possess indications of creep.

This study will discuss present and relict permafrost distribution based on the mapped rock glacier and ice-cored moraines in Tröllaskagi. In addition, various characteristics of the landforms such as the state of activity are given. This study supports the previous inventory which indicated evidence of typical rock glacier formation at low elevations, indicating long ice-free and cold periods prior to the onset of the Holocene Atlanticum.

Reference

Guðmundsson, Á. (2000). Frerafjöll, urðarbingir á Tröllaskaga. MSc thesis. University of Iceland, Reykjavik. 322 pp.

EC3-3

Typology of sorted patterned ground sites in Skagafjörður (Northern Iceland) by using a factor analysis of mixed data

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Although scientists have been studying patterned ground features for a century, further works are needed for improving our knowledge about their formation mechanisms and their environmental conditions of development. Patterned ground is quite widespread in Iceland, though their observations are still lapidary, in particular in the Northern part. One of the queries needing deeper knowledge deals with the relationships between feature intrinsic characteristics and environmental conditions at site scale. Hence, we have decided to carry out fieldwork in Skagafjörður, attempting a typology of sorted polygon areas according to different environmental characteristics.

To fulfill this issue, we have investigated 75 polygon sites, equally distributed across the fjord between 20 m and 960 m a.s.l. Each site includes ten polygons, i.e. a total of 750 features were studied. Then, all polygon areas have been associated with three groups of explanatory variables (latitude, topography and soil variables), determined either with a regional DEM (resolution of 30 m), or during fieldwork, and in laboratory for grain-size analyses. To define homogeneous polygon sites as a function of the three groups of variables, we have used a factor analysis of mixed data and a complementary hierarchical classification of principal components, particularly suitable for this objective. In addition, we have analysed the variance of each so-defined class to test for significant differences in feature (mesh) diameter between each group.

Results reveal three homogenous areas of sorted polygon features. The first one is characterised by low altitude, high wetness index, low insolation, small clast length and kame terrace absence; the second one by high insolation, high valley depth, low latitude, low terrain ruggedness and kame terrace presence; finally the last cluster is associated with high altitude, low valley depth, low wetness index, large clast length, high terrain ruggedness, till deposits and high fine content. Altitude and type of drift appear to be the most discriminant factors for all three classes. In addition, ANOVA tests have shown that mean polygon diameter is significantly different by class: rather small in the two first clusters and large in the last one. We have highlighted that three variables are significantly correlated with the polygon size as well: proportion of fine material ($r=0.35$), altitude ($r=0.51$) and overall clast length ($r=0.97$). This positive correlation between polygon size and clast length is confirmed whatever the polygon area and scale considered (site and feature scales).

EC3-4

Permafrost degradation in West Greenland

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Important aspects of civil engineering in West Greenland relate to the presence of permafrost and mapping of the annual and future changes in the active layer due to the ongoing climatically changes in the Arctic. The Arctic Technology Centre (ARTEK) has worked more than 10 years on this topic and the first author has been involved since 1970 in engineering geology, geotechnical engineering and permafrost related studies for foundation construction and infrastructures in towns and communities mainly in West Greenland. We have since 2006 together with the Danish Meteorological Institute, Greenland Survey (ASIAQ) and the University of Alaska Fairbanks carried out the US NSF funded project ARC-0612533: Recent and future permafrost variability, retreat and degradation in Greenland and Alaska: An integrated approach.

This contribution will present data and observations from the towns Ilulissat, Kangerlussuaq, Sisimiut and Nuuk. They are situated in continuous, discontinuous and sporadic permafrost zones. We will show examples of detoriation of permafrost related to present local scale climate observations and large scale climate and permafrost simulations modeled numerically with the GIPL model driven by HIRHAM climate projections for Greenland up to 2075.

The engineering modelling is based on a risk assessment methodology based on a flow diagram which classify the risk of permafrost degradation causing settlement and stability problems for buildings and infrastructures based on relatively simple parameters. It is planned as decision and planning tool for town planners and engineers in local municipality governments and to consulting engineers and contractors in Greenland, which also may be used in other arctic regions. Risk is classified in four categories: Low, Limited, Medium and High based on environmental properties as surface conditions (rock or sedimentary basins), soil grain size classification (gravel, sand, silt and clay) and ice content in the ground. The model uses ground thermal conditions quantified as the Permafrost Thaw Potential, which is defined as the potential active layer increase due to climate warming and surface alterations.

Using this methodology it is expected that mapping of vulnerability in towns and construction areas together with proposed adaption and mitigation technologies will be of practical use to technical institutions and public as well as a general tool for the scientific community.

The presentation will focus on the application of the Risk Evaluation diagram used in the selected towns in different permafrost zones and is illustrated with present observations of permafrost detoriation in West Greenland.

EC3-5

Temperature measurements providing evidence for permafrost thickness and talik occurrences in Kangerlussuaq, West Greenland

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The present study is motivated by the requirement to understand the effect of permafrost and glaciation on the thermal and hydrological behavior of crystalline rock during long-term disposal of nuclear waste. Glacial conditions with growth of ice sheets and permafrost will likely occur in Fennoscandia and Canada during this time perspective. To advance the understanding of the impact of glacial processes on the long-term performance of a deep geologic repository, the Greenland Analogue Project (GAP) has been established by the Swedish, Finnish and Canadian nuclear waste management organizations (SKB, Posiva and NWMO). The GAP project is a field and modeling study utilizing the ice sheet and the sub-surface in West Greenland as an analogue of the conditions expected to prevail in Fennoscandia and Canada during future glacial cycles.

Within the GAP project three drillholes have been drilled during 2009-2011 and equipped with fiber optical Distributed Temperature Sensing (DTS) cable, in the Kangerlussuaq area, West Greenland. DTS is a technique where an optical laser pulse is transmitted through a passive optical fiber, which acts as temperature sensor.

One of the drillholes was drilled beneath a lake to study a presumed through talik. Given that taliks may provide hydraulic pathways through permafrost, they can potentially act as concentrated discharge points for radionuclides, in the case of release from the repository. The lake is located in a lineament structure and forms a 35 m deep elongated basin (1200 x 300 meters). Based on the results from the DTS-profiling the transition from permafrost to talik takes place at 20 m depth, i.e. at the shoreline of the lake. The two other drillholes were drilled near each other and approximately 0.5 km from the Greenland ice sheet, while the lake drillhole is situated 1 km from the ice sheet. The second and the third drillhole were drilled to measure permafrost depth, via installed DTS-cables, but also to take hydrogeochemical samples and monitor pressure from depths beyond the permafrost layer.

Our results suggest that in the study area, located about 350 - 500 m above sea level, 200 km from the sea and in the vicinity of the Greenland ice sheet, permafrost is about 300 m thick in areas distant from lakes and rivers. Forward conductive heat transfer modeling based on our temperature data and petrophysical information from the bedrock suggests that water bodies with diameters exceeding about 200 m would support the existence of through taliks. Given that about 20% of the surface area in Kangerlussuaq is covered by proglacial lakes larger than 500 m in diameter, the permafrost layer is abundantly perforated by through taliks. These taliks provide the only available pathways for water to be transported up or down through the permafrost, thus their distribution needs to be included in hydrogeological modeling of this Arctic landscape. Our study illustrates and confirms the usefulness of the DTS technique for temperature measurements in the Arctic environment, where drillholes are impossible to keep open for a long time, also allowing monitoring of permafrost depth over time.

EC3-6

Geophysical investigations of a pebbly rock glacier, Kapp Linné, Svalbard

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Pebbly rock glaciers (Ikeda & Matsuoka, 2006) differ from bouldery' rock glaciers with respect to lithological content, mean size of clasts and rock glacier dimensions; however few pebbly rock glaciers have been subjected to detailed investigations. This presentation reports on pebbly rock glaciers close to Isfjord Radio on Kapp Linné, Svalbard, and their internal structure based on a detailed DC resistivity profiling campaign and GPR measurements.

Kapp Linné is located on the northern part of the coast of Nordenskiølds land, western Svalbard. The pebbly rock glaciers have developed along Griegaksla at the transition between talus slopes and the strandflat area, similar to on Prins Karls Forland (Berthling et al. 1998, 2007) and further south on the coast of Nordenskiølds land (Kääb et al 2002).

The DC resistivity measurements were carried out in July 2007, and the GPR measurements in April, 2008 as part of the IPY project 'Permafrost Observatory Project: A Contribution to the

ORAL
EC 3

Thermal State of Permafrost in Norway and Svalbard (TSP Norway)'. We used ABEM equipment, an alongslope electrode spacing of 10 m, and additional measurements along the central part of the rock glacier with 2 and 5 m electrode spacing. Spacing between resistivity lines were 10 m and 20 m. We also collected a resistivity profile along a neighbouring talus slope and a talus cross profile. The GPR profiles were collected with RAMAC equipment, using 25, 50 and 100 MHz RTA (snake) antennas.

We present interpretations of the resistivity profiles, based on boundary conditions provided by the GPR profiles. We compare the properties of the profiles collected with different electrode spacing as well as the profiles collected on and to the side of the rock glacier system. The resistivity is highest on the talus cone above the rock glacier, while on the rock glacier itself resistivity decreases. On the northern part of the rockglacier (profile 7-8) higher resistivity reach further down into the rock glacier. The northern part of the rock glacier is longer, lacks an inner depression and does not display a very sharp transition between rock glacier surface and front. Talus resistivity is higher above the rock glacier than on neighbouring talus slopes.

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EC 4 – Climate change impacts in the Nordic region during the 21st century

EC4-01

Climate scenarios for the Nordic Region until 2050: results from the CES project

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The Climate and Energy Systems (CES) project aimed at investigating how conditions for production of renewable energy in the Nordic area might change due to global warming. Within the framework of the project a number of climate scenarios for the Nordic and Baltic region were produced by regional climate models (RCMs). The RCM scenarios were analyzed in the context of a larger ensemble of RCM scenarios from the European FP6-project ENSEMBLES. The large number of RCM-simulations generated together in these two projects, forced by a range of GCMs, is unprecedented. Results from these scenarios show large changes in both temperature and precipitation in the region. Examples include changes in summer temperature that increase within 2°C over most of the region for the period 2021-2050, in comparison with the control period 1961-1990. Further, increases in winter temperatures will be more variable and most pronounced (up to 4°C) in the eastern and northern areas. The largest precipitation increase will generally be seen in winter. In summer, there is a larger uncertainty and the possibility that precipitation will decrease in southern parts of the region cannot be excluded. Wind speed changes are generally small with the exception of areas that will see a reduction in sea-ice cover, where wind speed is projected to increase.

Even if the ensemble of RCM simulations is relatively large, it still covers only a part of the total uncertainty related to future climate change. Therefore the RCM scenarios are put in a wider context by comparing them to the output of a large number of global climate model (GCM) simulations. The results clearly indicates that one should be careful with drawing far-reaching conclusions based on individual model simulations

EC4-02

Climate change scenarios for Iceland

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During the past few decades Climate Change Scenarios for Iceland have been the focus of extended research.

The earliest published scenarios appeared in Bergþórsson et al. (1987), using results from equilibrium experiments with the GISS climate model (Hansen et al., 1983, 1984). While this study gave insight into how Icelandic climate might change in response to increasing CO_2 levels, it did not address changes in other climate variables.This was done by Jóhannesson et al. (1995), who used statistical downscaling results previously obtained by Kaas (1993, 1994), as well as results from four different climate models (with the GFDL CM3 as the primary reference). The estimates, together with bounds based on past natural variability, were used for the reports by the Icelandic Science Committee on Climate Change (Ministry for the Environment, 2000, 2008).

The next published study focusing on climate projections for Iceland was by Jónasson (2004), who used an auto-regressive model of past climate variability to determine forced warming trends.

As part of the Climate and Energy (CE) project (Fenger, 2007), and its Icelandic counterpart, the Veður og Orka (VO) project, various climate change predictions for Iceland were made, using an ensemble of six GCMs and RCMs from the PRUDENCE project. The CE project also examined RCM results for Iceland based on the HIRHAM model (Haugen and Iversen), focussing especially on smaller spatial scales and seasonal time scales.

Finally, climate change scenarios for Iceland based on GCM models from the CMIP-3 dataset were generated for the Icelandic Science Committee on Climate Change (Ministry for the Environment, 2008).

Several common threads stand out in regional climate change projections for Iceland. The rate of 21st Century warming in various GCMs on an annual basis varies from 0.2-0.3 K per decade, with more warming in winter than in summer. Precipitation is predicted to increase along with air temperature, with trends ranging between 0.5-1.8% per decade, but without consistent seasonal differences. Furthermore, the RCM results from the CE project showed enhanced warming in the interior and towards the northeast of Iceland. These model results, however, showed seasonal differences in warming rates that were inconsistent with other simulations.

This study examines in more detail the various differences in regional climate predictions for Iceland in the 21st Century, specifically for future changes in surface air temperature (SAT) and total precipitation. Several GCM simulations are analyzed, together with those RCM runs, that were performed for the Climate and Energy Systems (CES) project and as part of the Ensemble-based Predictions of Climate Changes andtheir Impacts (ENSEMBLES) project (van der Linden and Mitchell, 2009). Specific topics addressed in this study include spatial patterns of SAT and TP trends within the proximity of Iceland, such as land-sea differences and changes with terrain elevation, as well as seasonal differences. Additionally, the impact of driving GCMs on RCM runs will be investigated.

EC4-03

Downscaling precipitation in Scandinavia in a future climate scenario

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Precipitation is simulated over selected areas in W-Norway, Central Sweden, Denmark and S-Finland at different resolutions. The simulations are carried out with the WRF model with microphysics parameterized by the WSM3 scheme. The simulations are forced by a global simulation by Arpege model , run by the Bergen group (BCCR) on a T159c3 irregular grid. The simulated period is 1 September 2020 to 31 August 2021. The scenario chosen is the SRES A1B. Values of sea surface temperature (SST) are calculated as ERA40 SSTs plus smoothed SST anomalies from ECHAM5/MPI-OM, corrected for drift.

The highest horizontal resolution (3 km) gives the greatest stratiform precipitation and maximum number of extremes. However, the sensitivity of accumulated precipitation to horizontal resolution is only moderate, except in the Norway region, where the 3 km domain gives about 50% greater precipitation than the 9 km domain. The large increase of precipitation in the mountainous regions of Norway is expected. This increase is related to direct forcing of ascending motion above the mountains that is not resolved at the coarse resolutions. The precipitation extremes that appear at the fine resolutions (9 and particularly 3 km) are much more pronounced in Norway than elsewhere. This difference must be associated with strong winds and rising motion over the mountains. In spite of mountains being present inside the Swedish domain, the total impact of increased resolution is much less in that region, than at the West coast of Norway. This difference is presumably related to the height and the spatial scale of the mountains.

In spite of the land being relatively flat both in the Denmark and the Finland regions, simulated stratiform precipitation increases with resolution. The sensitivity in Denmark is very limited, but the signal is more clear in Finland. There is a precipitation maximum aligned with the coast of Southern Finland. This maximum becomes more pronounced when resolution is increased, indicating that increased resolution may enhance coastal convergence and that this effect may be important in climate context. A similar feature can be detected in the Denmark domain.

ORAL
EC 4

EC4-04

Precipitation over Iceland simulated in a future climate scenario at various horizontal resolutions

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Flow over Iceland and precipitation is simulated for the periods 1961-1990 and 2021-2050. The simulations are carried out with the WRF model with microphysics parameterized by the WSM3 scheme. The simulations are forced by a global simulation by Arpege model , run by the Bergen group (BCCR) on a T159c3 irregular grid. The scenario chosen is the SRES A1B.

EC4-05

The effect of climate change on runoff from two watersheds in Iceland

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To investigate the effect of climate change on the hydrological regime in Iceland, future projections of runoff were made for two watersheds with the WaSiM hydrological model. The application of WaSiM in Iceland has recently been improved from former use by: i) improving the representation of groundwater by activating the model's groundwater module; ii) improving the representation of seasonal changes in the evapotranspiration scheme; and iii) by applying glacier melt parameters calibrated by mass balance measurements instead of river discharge data. The projections were made for the period 2021-2050 and compared with the reference period 1961-1990. The runoff projections are based on thirteen different climate scenarios. Monthly δ-changes, based on the climate scenarios, applied repeatedly to selected base years are used to construct the future climate input for the hydrological model. This methodology preserves the internal climate variability of the climate model runs.

The selected watersheds have different hydrological properties and climate characteristics. Sandá í Þistilfirði, vhm 26, is located close to the coast in the north-eastern part of Iceland and Austari-Jökulsá, vhm 144, is located in the northern part of the central highland with a 10% glacier coverage. Average warming for both watersheds between the reference period and the scenario period is on the order of 2°C. A precipitation increase of 16% is projected for Austari-Jökulsá and an increase of 3% for Sandá í Þistilfirði.

During the reference period 1961-1990, snow storage has a dominating effect on the discharge seasonality and snowmelt originated spring floods are the largest floods of the year for both watersheds.

Compared with the reference period, the magnitude of spring floods is predicted to decrease in 2021-2050 and they will appear earlier in the year. The timing of maximum snow melting is predicted to be about a month earlier for both watersheds and the magnitude of the mean yearly maximum snowmelt is predicted to decrease by 5-70%. The time with considerable snow cover is predicted to diminish from 7 months to 3-5 months per year depending on watershed. Mean yearly maximum snow thickness decreases by 0-80%.

Winter flow is predicted to increase on average due to a higher number of melt events at relatively high and flat heath areas of the watersheds. For Sandá í Þistilfirði, vhm 26, the snowmelt generated spring/summer discharge peak largely disappears and the seasonal discharge becomes more evenly distributed with higher winter discharge. For Austari-Jökulsá, vhm 144, runoff from the glacier will increase substantially due to increased snow and ice melting. The share of glacier originated runoff in the total annual volume is predicted to increase from 20% to 25-30% and the duration of glacier runoff is predicted to increase by nearly two months, reaching further into the spring and autumn. The increase of annual glacier melt, assuming unchanged glacier geometry, is predicted to be in the range from 75-150% depending on scenario. This leads to a late summer discharge maximum caused by increased glacier runoff. The discharge peaks caused by snowmelt and glacier melt will become more distinct and appear as two separate summer maxima with the one caused by glacier melt the largest runoff peak of the year.

Compared to the period 1961-1990, a warming of about 1°C has already been observed for both watersheds during the period 2000-2009, causing considerable discharge changes in the same direction as the predicted future changes.

This study was done as a part of the Nordic research project Climate and Energy Systems, (CES) and the Icelandic research project "Loftslagsbreytingar og áhrif þeirra á orkukerfi og samgöngur", (LOKS).

EC4-06

Some hydrological consequences of glacier variations

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Glaciers can have a dominating effect on runoff characteristics within their regime. The most spectacular example of this effect are the jökulhlaups (glacier outburst floods) brought about by failures of glacier dams. Furthermore, the seasonal distribution of discharge in a glaciated basin is considerably different from that of a non-glaciated basin. It is worthwhile to try to forecast what changes the oscillations of glaciers might bring about.

During the first decade of the 21st century glaciers in Iceland have retreated faster than ever before during historical time. Marginal lakes at glaciers have changed substantially and so does the danger of jökulhlaups. Several lakes that burst periodially during the 20th century, have dissappeared altogether.

Lakes at glaciers may be separated into three categories

– Proglacial lakes
– Ice-dammed, marginal lakes
– Subglacial lakes

Proglacial lakes vary in surface area and hypsometry depending on the advance and retreat of the glacier terminus. The last two categories are ephemeral, i.e. when ice dams fail, the lake either disappears completely or the water table falls considerably. In many cases the ice dam repairs itself, the lake forms again and the process is repeated, leading to periodic occurrence of jökulhlaups.

In a climate leading to fast retreat of glaciers proglacial lakes are expected to increase in size and number, particularly after an extended period of glacier advance. These lakes have great effect on turbidity in glacial rivers and also on the rate of ablation due to calving of icebergs. It is important to monitor these lakes and lagoons to keep track of parameters that affect the runoff of glaciers. With changing glaciers ice dammed lakes may disappear and new ones may be formed. Such lakes are potentially hazardous because of the danger of jökulhlaups. These need to be mapped and monitored. The best way to monitor ephemeral lakes and lakes changing in size is by remote sensing. Remotely sensed data can be satellite images, vertical aerial photographs and/or oblique aerial photographs. The proglacial lakes also decrease the sediment transport to the ocean. Thereby, they have effect on the coastline and nutrition in coastal waters.

In front of retreating glaciers rivers tend to collect into fewer courses. Likewise, when glaciers advance, the rivers tend to occupy new courses. This can cause both problems and benefits for the road authorities and hydropower production. During recent times several cases of rivers in Iceland leaving their course have left some bridges passing over dry riverbeds or grossly oversized bridges on small rivers. In some cases these changes can be predicted.

EC4-07

The Impact of Climate Change on Glaciers and Glacial Runoff in the Nordic Countries

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Possible changes in glacier mass balance and consequent changes in glacier margins and land-ice volumes are among the most important consequences of future climate change in Iceland, Greenland and some glaciated watersheds in Scandinavia. Global sea level rise, observed since the beginning of the 20th century, is to a large extent caused by an increased flux of meltwater and icebergs from glaciers, ice caps and ice sheets. The increased flux of meltwater from land-ice has, apart from rising sea levels, potential global effects through the global ocean thermohaline circulation. It has also local effects on river and groundwater hydrology of watersheds adjacent to the glacier margins, with societal implications for many inhabited areas. Changes in glacier mass balance and glacier geometry for several ice caps and glaciers in the Nordic countries have been modelled with mass balance and dynamic models to estimate the future response of the glaciers to climate change as specified by a family of climate change scenarios developed within the Nordic CES project. Many glaciers and ice caps are projected to essentially disappear over the next 100-200 years. Runoff from presently glaciated areas may increase on the order of 50% or more with respect to the 1961-1990 reference period in the next few decades for typical glaciated watersheds in the Nordic countries. The simulated runoff increase is in most cases not sensitive to the dynamic response of the glaciers during the initial decades of the runoff simulations, e.g. during most of the time period 2021-2050 covered by the CES climate scenarios, as we find that the reduction of ice volume and ice-covered area has little effect compared with a fixed ice-cover. After 30-50 years, depending on the climate scenario and the size of the glaciers in question, the results of coupled model simulations start to diverge from runoff simulated with a fixed ice-cover and after more than ~100 years the simulated glacial discharge component is crucially dependent on realistic simulation of the decreasing ice volume. The expected runoff increase may have practical implications in connection with the use of water in various sectors of society. Changes in water divides and changes in river courses may also have important consequences.

One of the goals of the CES project was to investigate the uncertainty of the climate development over the next several decades by employing many different climate change scenarios that allow the separation of a deterministic climate trend from the natural variability of the climate. The scenarios show considerable annual and decadal variations in temperature and precipitation which lead to substantial future variations in runoff superimposed on a rising trend and a slow reduction in ice volume. Coupled mass-balance and ice-dynamic modelling or mass-balance/glacier-scaling and hydrological modelling was carried out for three ice caps in Iceland (Langjökull, Hofsjökull and S-Vatnajökull), three ice caps and partly glaciated catchments in Norway (Midtdalsbreen, Nigardsbreen/Nigardsbrevatn, Fønnerdalsvatn), two glaciers in Sweden (Storglaciären and Mårmaglaciären) and mass balance modelling for the Paakitsoq area in Greenland. The results indicate that substantial changes in ice volumes and glacier runoff may be expected in the future and that the glaciers are already considerably affected by human-induced climate changes. Glacier changes and runoff variations in the next few decades will nevertheless be much affected by natural climate variability as they have been in the past and predictability is, in addition, limited by scenario-related uncertainties.

ORAL EC 4

EC4-08

Climate change impacts on renewable energy sources in the Nordic and Baltic region until 2050

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The Nordic and Baltic project Climate and Energy Systems was initiated in 2007 with the aim of studying the impacts of projected climate change on the development and production of renewable energy in the Nordic region up to the mid-21st century. This presentation gives an overview of main results published in the final report resulting from the project.

Energy production in the Nordic countries already relies heavily on renewable energy sources, but their use varies widely across the region due to important differences in climatology, geology, topography and ecosystem characteristics. Hydropower dominates in mountainous Norway, where precipitation is high and glacial runoff contributes to reservoirs, whereas wind power is of prime importance in Denmark due to strong coastal winds. In Finland, biomass is extensively used for energy production due to the extensive forest cover and Iceland's volcanic and glacial environments create conditions for extensive geothermal energy and hydropower utilization. Sweden currently leads the EU countries in the share of renewable energy production (from various sources) and the country´s 2020 target is to increase the share of renewables to 50% (up from 44.7% in 2009). The Baltic countries are also steadily increasing the share of renewable energy in their total energy production.

Research groups within the CES project analyzed past records of climate and runoff, produced climate scenarios for the Nordic and Baltic region with main focus on the period 2021-2050 and modelled climate impacts on hydrology and hydropower systems. Furthermore, analyses of the effects of projected climate changes on glaciers and glacial runoff, wind strength and biomass production were carried out. The project also involved risk analyses and modelling of the impact of climate changes on the generation of and demand for electricity in the Nordic region. Main findings of the working groups can briefly be summarized as follows:

Important climatic and hydrological changes have already been observed throughout the Nordic and Baltic countries. Annual temperatures have risen, precipitation has increased in parts of the region and the seasonality of runoff has changed with spring floods occurring earlier in the year. Multi-model averages indicate that temperature in the Nordic and Baltic region is likely to increase by 1-3 °C in the winter months (DJF) in 2021-2050 as compared with 1961-1990, and by 1-2 °C in the summer months (JJA). Precipitation increase will likely be 10-20% during winter for most of the region, but smaller during summer. Projected changes in wind speed are small and highly uncertain. Simulations indicate that runoff will increase until 2021-2050 in the studied watersheds, thus increasing the potential for hydropower production. The runoff increase will be particularly large in glaciated regions, due to dramatic decrease in glacier volume. The frequency of large snowmelt floods is likely to decrease. The importance of wind power will increase, even though large wind speed changes are not expected. For forested regions, scenarios indicate that changes both in climate and thinning regimes may substantially increase the production potential of biomass energy. Energy system modelling predicts a 12% increase in average electricity production from hydropower in the NordPool area until 2020. Risks and opportunities resulting from projected climate changes have also been assessed in a series of case studies.

EC4-09

Is the oceanic heat transport towards the Arctic changing?

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The heat carried northwards by warm ocean currents is one of the reasons that large regions in the Arctic are relatively warm and large sea areas free of ice. By far most of the oceanic heat transport is carried by three current branches that import warm water from the Atlantic Ocean into the Nordic Seas across the Greenland-Scotland Ridge. This Atlantic inflow is influenced by wind forcing and freshwater input to the Arctic, but the predominant forcing seems to come from cooling of the ocean by the atmosphere in the Arctic region. This cooling makes the surface waters become denser and induces sinking of water in many parts of the Arctic, which generates a bottom-near overflow of cold dense water through the deep passages of the Greenland-Scotland Ridge. Together with water sinking in the Labrador Sea and adjacent areas, the water deriving from the overflow forms the deep branch of the North Atlantic thermohaline circulation (THC) that ventilates the deep waters of the World Ocean and the removal of water from the Arctic region by the overflow generates sea level slopes that drive a northward transport of water and heat. With global climate change, the Arctic atmosphere is expected to warm and freshwater input to the Arctic to increase, both of which may act to slow the mechanism that drives these flows, and climate models predict a weakening of the North Atlantic THC. This presentation addresses the question, whether the weakening has already been initiated and what regions may have been affected. Based on observations and model results, we conclude that the volume transport of the Atlantic inflow to the Nordic Seas has not weakened consistently during the last half century. This conclusion is not, however, necessarily in conflict with the model predictions because the other source for the North Atlantic THC, the Labrador Sea, has only had weak convection since the mid-1990s. This weakening has also contributed to a westward retraction of the subpolar gyre, which in turn has allowed warmer waters to enter the Nordic Seas. Thus, there is no indication that global warming has reduced the oceanic heat transport towards the Nordic Seas and Arctic Ocean. On the contrary, it may have contributed to a warming of the inflow and increased heat transport.

EC4-10

Modelling the Arctic hydrological cycle – the Devil is in the details

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To understand climate change and provide credible projections of future Arctic climate change, climate models have become one of the main tools. However, these models are far from perfect and appear to be suffering from severe biases in particular when it comes to represent Arctic condition. There are many reasons why this may be. Some of the climate feed back processes that are particularly important in an cryospheric enviromnent are yet not fully understood, therefore surely they cannot be represented accurately in climate models. The Arctic is not isolated fom the rest of the world, so model deficiencies elsewhere may influence model performance in the Arctic. But even if the situation was such that we had a complete understanding of the mechanisms at play, current state-of-the-art model resolution does not allow us to handle the Arctic climate syststem adequately. Here, I will summarize the incompleteness of Arctic modelling, but also demonstrate that model resoultion at so far unheard of scales, actually does facilitate improved possibilities to capture the many important fine scale Arctic climate interactions, hence suggestions that future efforts can take advantage of model improvemnets. In particular, I will address issues related to the surface mass balance of the Greenland Ice Sheet and coastal permafrost conditions as depicted by climate modeling using a 4-5 km model grid, including some discussions of climate change projections.

EC4-11

The recently discovered North Icelandic Jet and its role in the Atlantic Meridional Overturning Circulation

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The Atlantic Meridional Overturning Circulation plays a major role in the Earth's climate. The Denmark Strait Overflow Water is the largest contribution from the Arctic Mediterranean to the lower limb of the Atlantic Meridional Overturning Circulation. Until the beginning of this century the main source of this water was generally assumed to be carried to the Denmark Strait by the East Greenland Current. This notion has recently been challenged with the discovery of the North Icelandic Jet (NIJ) which represents a distinct pathway for the Denmark Strait Overflow Water to the sill. The NIJ is a weakly-baroclinic, relatively narrow current that flows along the continental slope north and northwest of Iceland. It is centered at the 600 m isobath which is close to the sill depth of Denmark Strait. Recent measurements have shown that this current carries about half of the total overflow through the Denmark Strait. This implies that the formation mechanism and the geographical area of formation of the Denmark Strait Overflow Water may be different than previously assumed. This in turn has ramifications for the way in which the overflow water is affected by climate change. An extensive measurement campaign was initiated in August 2011 with the aim to reveal the spatial and temporal structure of the current and also to trace its origin, which seems to lie east of the Kolbeinsey Ridge.

EC4-12

The Global Cryosphere Watch

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The Global Cryosphere Watch (GCW) is a new international mechanism under development by WMO, intended to support all key cryospheric in-situ and remote sensing observations. The cryosphere collectively describes elements of the Earth System containing water in its frozen state, including solid precipitation, snow cover, sea ice, lake and river ice, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. Frozen water and its variability and change in the atmosphere, on land, and on the ocean surface has direct feedbacks within the climate system, affecting energy, moisture, gas and particle fluxes, clouds,

precipitation, hydrological conditions, and atmospheric and oceanic circulation. The cryosphere provides some of the most useful indicators of climate change, yet is one of the most under-sampled domains of the Earth System. Improved cryospheric monitoring is essential to fully assess, predict, and adapt to climate variability and change.

GCW will facilitate basic research; provide data, information and products useful for the management of energy and water resources; contribute to programs focusing on mitigation and adaptation to climate variability and change and provide information for decision making and policy development related to hazard warnings. Focal points to GCW have already been nominated in over 30 countries from all WMO regions. These focal points will be involved in the development of GCW and will help integrate the global initiative with their national plans. Partnerships are currently being identified with government agencies and institutions that measure, monitor, or archive cryosphere data and information from in-situ and satellite research, and from operational networks and model sources. International bodies, such as the International Permafrost Association (IPA), the World Glacier Monitoring Service (WGMS), the Global Precipitation Climatology Centre (GPCC) and various national institutions have already indicated their willingness to support GCW.

The implementation of the Global Cryosphere Watch is foreseen to occur in three stages:

1. The GCW definition phase (2007-2011) is now completed. Following a review of the feasibility study for developing and implementing GCW, WMO endorsed the next steps for developing GCW with the guidance of its EC Panel of Experts on Polar Observations, Research and Services (EC-PORS).
2. The GCW Implementation Phase (2012-2019) will be coordinated by WMO and its partners. It will focus on developing and implementing GCW through tasks and activities that will form the GCW Implementation Plan.
3. The GCW Operational Phase (2020 onward). Once the framework is established, GCW enters its Operational Phase. It will continue to evolve to improve service delivery and support decision-making in response to the needs of users and technological opportunities.

Based on a feasibility study and continuing consultation with WMO Members and potential partners by the EC-PORS GCW Task Team, initial key tasks were identified for implementation. These include the initiation of pilot and demonstration projects, the establishment of cryosphere reference sites, development of an inventory of satellite products for GCW, development of a web portal, capacity building, communication and outreach activities and general monitoring of scientific progress.

This presentation will outline the aims and structure of the Global Cryosphere Watch and discuss liaisons with ongoing Nordic projects on cryospheric research and climate change adaptation.

THEME: ENDOGENIC PROCESSES (EP)

EP 1 – Tectonic evolution of the North Atlantic area

EP1-1

The Transscandinavian Igneous Belt – a large magmatic arc formed along a rotating Proto-Baltica

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The Transscandinavian Belt, which mainly comprises felsic intrusive rocks with co-magmatic extrusive rocks, is one of the largest bedrock features in the Fennoscandian Shield. In terms of rock chemistry and age determinations the Transscandinavian Igneous Belt (TIB) is well characterized. However, so far there is no general agreement regarding formation of TIB, or even which bedrock units should be included in the term TIB.

The main part of TIB consists of three geographically separate parts. The Småland-Värmland in the south, followed by the Dala granites and porphyries, and further north, in central Sweden, by the Rätan granite. The two first comprise both c. 1.8 and 1.7 Ga rocks, whereas Rätan seems to be a 1.7 Ga batholith. Further to the northwest, Precambrian windows in the Caledonides suggest a continuation of TIB towards the coastland of northern Norway where 1.8 Ga (high metamorphic) granitoids and mafic plutons dominate the Proterozoic basement. More speculative suggestions link TIB to c. 1.75 Ga granitoids in Spitsbergen and/or across southern Greenland into Canada. At the southern end the Småland Värmland belt clearly continues into Blekinge, southeasternmost Sweden, where felsic magmatic rocks with ages around 1.77-1.75 Ga represents deformed and metamorphic TIB units. In a similar manner the basement gneisses of the Sveconorwegian units in southwestern Sweden represents highly deformed and metamorphosed 1.70-1.65 Ga TIB units, but possibly also slightly older non-related calcaline units.

TIB comprises mostly granitic to quartzmonzonitic intrusions and co-magmatic rhyolitic rocks. Spatially associated mafic and ultramafic rocks occur, and magma mixing and mingling features are ubiqitous. A majority of the TIB rocks are sub-alkaline I-types. More calc-alkaline affinities can be found in the far south. In the south-central Dala part, more A-type rocks are common. S-type intrusions do exist along the eastern margins but are very scarce. The mafic TIB units originated from a depleted mantle, no undisputed plume component has been recognized.

Up to 100 age determinations have shown that TIB was formed in episodes from c. 1.86 to 1.65 Ga, where the periods 1.84-1.81 and 1.75-1.71 Ga seem to be quiet. Spatially it is also evident that TIB was formed in an marginal setting to the Svecofennian Domain, and where older rocks can be recognized in contact with the TIB rocks they are c. 30-40 m.y. older than the adjacent TIB units.

The variation in chemistry and ages of the different TIB units can be explained by a model in wich TIB rocks form in a continental margin subduction setting along the southwest coast of Proto-Baltica (all directions relate to present directions). The subduction could have been of 'slab roll-back' type with a steep subduction zone, and with extensive upwelling of astenospheric mantle and underplating of Svecofennian units. This enabled formation of large volumes of felsic rocks along the continental margin in two parallel branches; south of the Svecofennian Skellefte and Bergslagen regions respectively. Closure of the Bothnian Basin at c. 1.84-1.82 Ga terminated the northern branch. Between 1.82 and 1.75 Ga TIB grew towards the south in a stepwise, episodic manner, following a southward migrating subduction zone. Docking of Proto-Baltica (Fennoscandia) with Sarmatia and Volgo-Uralia at c. 1.8 Ga to form Baltica resulted in an anti-clockwise rotation of Fennoscandia. After that TIB units continued to form in the southwest, but the relative change of subduction direction also led to an 'overriding' subduction zone in the central part, resulting in partial melting of the 1.8 Ga TIB rocks and formation of the A-type 1.7 Ga rocks.

EP1-2

Structure and evolution of NE Atlantic conjugate margins

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The sedimentary basins at the conjugate continental margins off Norway and Greenland and in the western Barents Sea developed as a result of a series of post-Caledonian rift episodes until early Cenozoic time, when complete continental separation took place. The late Mesozoic-early Cenozoic rifting was related to the northward propagation of North Atlantic sea floor spreading, but also linked to important tectonic events in the Arctic. Prior to that, Late Paleozoic rift basins formed between Norway and Greenland and in the western Barents Sea along the NE-SW Caledonian trend. Late Jurassic-Early Cretaceous rifting was the dominant, composite tectonic episode which gave rise to prominent NE-trending structures in the NE Atlantic. Following rifting, a wide region subsided and was covered by thick Cretaceous strata. Aptian-?Albian rifting is documented locally off Mid-Norway, onshore East Greenland and in the SW Barents Sea. A distinct Late Cretaceous rift event, with onset in middle Campanian, is documented on the conjugate mid-Norway and East Greenland continental margins, and is characterised by large-scale normal faulting and locally by low-angle detachment faulting within thick Cretaceous strata. The Late Cretaceous rifting between Norway and Greenland was taken up within the De Geer Zone and pull-apart basins formed in the SW Barents Sea and in the Wandel Sea Basin in NE Greenland. The rifting culminated in crustal breakup and accretion of oceanic crust near the Paleocene-Eocene transition, accompanied by large-scale igneous activity associated with the North Atlantic Large Igneous Province. Passive rifted margins developed off mid-Norway and central East Greenland, and along the north-

ORAL EP 1

ern Barents Sea during opening of the Norwegian-Greenland Sea and Eurasia Basin, respectively. The western Barents Sea-Svalbard and NE Greenland margins developed as predominantly sheared margins along the De Geer Zone megashear system linking sea floor spreading in the Norwegian-Greenland Sea and the Arctic Eurasia Basin. There is a well-defined along-strike margin segmentation and the various segments are characterized by distinct crustal properties, structural and magmatic styles, and post-opening history of vertical motion. Releasing and restraining bends in the sheared margin gave rise to transtensional and transpressional deformation, respectively. The continent-ocean transition is confined within a narrow zone at the sheared margin segments, but is more obscure and partly masked by volcanics at the rifted margin segments. Following breakup, the subsiding margins experienced modest sedimentation until the late Pliocene when large wedges of glacial sediments prograded into the deep ocean from uplifted areas along the continental margins. The outbuilding was probably initiated in Miocene time indicating pre-glacial tectonic uplift of Greenland, Fennoscandia and the Barents Shelf. The NE Atlantic margins also reveal evidence of Cenozoic compressional deformation.

EP1-3

Opening of the North Atlantic & Norwegian – Greenland Sea – Lessons from the South and Central Atlantic Ocean

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It is now becoming more widely accepted that continental plates are not necessarily large rigid bodies but instead are composed of a number of deformable micro-plates.

Along the length of the divergent boundary of the Atlantic Mid Ocean Ridge, the spreading center is offset by regularly spaced transform boundaries. These can be traced shoreward as deep seated crustal fracture zones beneath the sediment cover, as described offshore Angola by Duval et al., 1991 and offshore Gabon by Meyers et al., 1996.

Lister et al., 1986, described upper plate and lower plate passive margins, separated by a detachment fault, which give rise to asymmetric conjugate margins after final continental break up. The upper plate is characterized by a narrow continental shelf, with relatively little sedimentary accommodation space. It is relatively unstructured and has experienced uplift related to underplating. While on the opposite side of the mid ocean ridge, the conjugate lower plate is characterized by a wide continental shelf, which has abundant sedimentary accommodation space. It is complexly structured and exhibits bowed up detachment faults. Transfer faults offset marginal features and can cause the upper/lower plate polarity to change along the strike of the margin.

The Fram Strait is a transform margin, which was initiated in the Eocene as a result of the onset of spreading in the North Atlantic and Norwegian - Greenland Sea. This is a result of the North American Plate sliding past the Eurasian Plate during the opening of the North Atlantic and Norwegian - Greenland Sea. The easiest direction for space relief for the squeezed sediments is vertical and a zone of downward tapering wedges and up-thrust margins is created: This structure is not necessarily symmetrical and the faults coalesce and anastomose with depth, creating a positive flower structure of transpressional origin.

These zones of long-lived crustal weakness can be subsequently reactivated during later tectonic episodes, the concept of "tectonic inheritance" associated with Wilson cycles, the opening and subsequent closure of an ocean.

The Eastern Seaboard of the North American Continent has experienced at least two complete Wilson cycles. The Proterozoic Grenville Orogeny closure of an ocean formed the Rodinia supercontinent, which was subsequently broken up with the opening of the Iapetus Ocean in the Cambro-Ordovician. Basement related zones of weakness (failed rift arms) in the Appalachian Range form the location of the fractures zones for the opening of the Iapetus Ocean and also influence the Siluro-Devonian Caledonian Orogeny deformation (recesses and salients) during the subsequent ocean closure, forming the Pangaea supercontinent. These same zones of crustal weakness are reactivated once again during the breakup of Pangaea, and influenced the location of the fracture zones in the Mesozoic opening of the Atlantic Ocean (Thomas, 2006).

Using the Southern and Central Atlantic Oceans as analogues, the integration of gravity, magnetic and seismic data has been used to construct a simple symmetrical spreading model for the opening of the Norwegian - Greenland Sea between Iceland and the Fram Strait. Continued reactivation of the various fracture zones gives rise to inversion structures and complex compressive and transpressive/transtensional features, which are recognized on the Jan Mayen Micro-Continent.

The recognition of different structural styles and the complex interaction between structure and sedimentation, has opened the way for new exploration concepts and plays in the Norwegian - Greenland Sea region, which will be discussed during the course of the presentation.

EP1-4

Submarine fieldwork on the Jan Mayen Ridge; integrated seismic and ROV-sampling

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Prior to the onset of the opening of the northern part of the Atlantic Ocean, the Jan Mayen Micro-Continent (JMMC) was part of Greenland and Norway. In latest Palaeocene to earliest Eocene (anomaly 24), JMMC was involved in extensive intrusive and extrusive activity associated with the continental breakup process and the initial establishment of the Ægir spreading ridge. The geology of the Jan Mayen micro-continent is unexplored, where the DSPD shallow bore holes from 1974 is the most reliable data in the area. These holes penetrated late Eocene.

As part of the process for opening the Norwegian side of the delimitation line for petroleum exploration the Norwegian Petroleum Directorate (NPD) carried out a seismic acquisition program during the summer of 2011. In addition to this the NPD, in collaboration with the University of Bergen (UiB), also carried out a ROV sampling campaign on the western part of the Jan Mayen Ridge. By using the ROV on the outcropping strata on the steep part of the ridge, local rock samples were gathered. These samples are in the process of being analyzed in the NPD and also at the UiB.

Preliminary results of the analyzed material indicate that the sequences of strata depicted in the seismic sections include rocks of Palaeozoic, Mesozoic and Cenozoic age. Analyses of the rock samples also seem to have a bearing on the modeling of the temperature history of the area. The results have demonstrated that ROV is a suitable tool to recover geological information at great water depth in this kind of geological setting.

EP1-5

The significance of new aeromagnetic surveys for a better understanding of the crustal and basin structures in the Barents Sea

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The post-Caledonides tectonic history of the southwestern Barents Sea (SBS) is mostly dominated by extensional tectonics. While deposition of a continental nature took place locally during Late Paleozoic-Early Mesozoic in the syn- and post-orogenic collapse basins, marine sedimentation was by far the dominant input from the Late Paleozoic to the present day. Evidence for early rift episodes has been documented in the Late Paleozoic and renewed rifting episodes in the mid-Carboniferous were associated with a change to a more arid climate. During this period and until Early Permian, most of the grabens of the Western Barents Sea area were sites of extensive salt deposition. Mobilisation of Paleozoic salt began in the Early Triassic and since then the diapirs have undergone several phases of development. The architecture of the Mesozoic grabens and associated platform in the SBS is presently relatively well constrained by seismic and well calibration. However, the geometry and regional architecture of the deep pre-Permian basins still remain unclear and poorly constrained. North of the Finnmark Platform, thick Paleozoic basins such as the Ottar and Maud basins have earlier been identified on seismics. The presence of deeply buried salt pillows (e.g Samson and Norvag domes) also suggests that the pre-Permian saliferous basins may also extend towards the north underneath the thick Triassic-Jurassic Platform recognised on the Bjarmeland Platform.Long-believed interpretations suggest that these deep Paleozoic basins are almost sub-parallel to the Mesozoic grabens system and may extend over most of the SBS and follow a dominant NE-SW to NNE-SSW regional trend. In light of new aeromagnetic surveys combined with gravity and seismics, we challenge this interpretation and propose a different tectonic model for the pre-Permian basin development. We have now covered most of the SBS with new, modern, reliable and high resolution aeromagnetic data acquired as part of the NGU aeromagnetic mapping program of the SBS (2006-2009). These new surveys confirm most of the previous structural elements but new features appear and illustrate the complexity of the basement architecture. We propose an updated tectonic scenario in which the Caledonian nappes initially swung from a NE-SW trend close to Varanger Peninsula to NW-SE across the Nordkapp Basin and the Bjarmeland Platform. The magnetics correlate perfectly with the onshore structures and easily explain the formation of the transfer zones that segment the Nordkapp Basin offshore. On the Bjarmeland Platform, the dominant magnetic grain is clearly NNW-SSE. We show that this pattern reflects a regional pre-Permian system involving several Caledonian thrust sheets that possibly collapsed and controlled the Post-Caledonian Paleozoic rift development of the SBS during Paleozoic time. Contrary to the previous models, we believe that the pre-Permian basins have dominantly a NNW-SSE orientation in most of the Bjarmeland Platform and we do not see magnetic evidences that could support the long-established NE-SW or NNE-SSW regional trends previously proposed for the Paleozoic rift system. The BAS-06, BASAR-08 and BASAR-09 data acquisition was financed by Det norske oljeselskap, Eni Norge, the Geological Survey of Norway, the Petroleum Directorate and Statoil.

EP1-6

Puzzle of Icelandic rift-jumps/migrating transform zones in North Atlantic

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North Atlantic opened in steps since the breakup of Pangea, leading to large igneous provinces, uplifts, subsidence, small shallow and deep water ocean basins. The main mechanism in this evolution has been the relocation of active rift zones, or rift/ridge-jumps. Three of the latest rift-jumps took place in Iceland over only 15 Ma, all in the direction of southeast. Reorganisation of plate boundaries produces complex structural domains, which include simultaneously active rifts, extinct rifts, transform zones, and microplates.

Iceland undergoes magmatism, crustal flexuring, large extensional faulting, major unconformities, and seismicity at its active plate boundaries. But it lacks sedimentary basins due to its high position above sea level. The complex tectonic of Iceland is symptomatic of past and present rift/transform interactions. Presently, the active rifts are the Western (WRZ) and the Eastern (ERZ) Rift Zones, and the active transform zones, the Tjörnes Fracture Zone and the South Iceland Seismic Zone (SISZ). The earliest rift off Vestfirðir, active ~ 24 Ma, shifted to Snæfellsnes Rift Zone (SRZ) ~ 15 Ma. Around 5-7 Ma, a second shift occurred from SRZ to WRZ, during which a piece of crust, the Borgarfjörður Rift-Jump Block (BRJB) formed between the rift zones of West Iceland. Since 3 Ma, a third rift-jump occurs from WRZ to ERZ during which the Hreppar Rift-Jump Block (HRJB) formed in South Iceland.

We conducted 15 years of outcrop studies south of 65°N in the BRJB, HRJB and in the active SISZ where a continuous tectonic evolution of rift-jump processes over the last 15 Ma is visible in the three adjacent domains. The crust of the BRJB is eroded down to 1.5 km, the HRJB to 0.5-0.7 km, and the SISZ has not yet been subject to major erosion. Selected tectonic observations of the combined 1.5 km crustal section demonstrate several effects of rift-jumps.

Under the WNW extension, NNE normal faults and eruptive fissures dominate in rifts. Earthquakes occur in the SISZ primarily on N-S dextral strike-slip faults, then on ENE, E-W, WNW and NNW sinistral strike-slips sets. The five sets of Riedel shears compensate the sinistral motion across the transform zone. In the older BRJB and HRJB, only 1/3 of fracture population strikes NNE. The other 2/3 are Riedel shears, produced during the jump of the rifts where the transform faults of Borgarfjörður and Hreppar migrated in the same direction as the propagating/receding rifts. Fracture density decreases upwards in the crust. Dykes are thick deep in the crust but thinner in the upper 1/2 km where metre-scales sills contribute to the build-up of the crust. Faults of any ages and sets are steeply-dipping and all have normal-slip. Their throw reaches hundreds of metres in the older BRJB, tens of metres in the HRJB, and 1-2 m during Holocene earthquakes. Offsets of strike-slips also decrease from 30 m in the older crust to 2 m during present-day earthquakes. The rare reverse faults are associated with intrusions. Dykes are frequently injected into Riedel shears, mainly the N-S dextral strike-slip faults, some of which were eruptive, indicating leaky transform zones. Presently, dykes are likely to be injected into the Riedel shears of the SISZ at depth, as these sets are among the permeable fractures in the low- and high-temperature fields from the SISZ to Reykjanes. Although Iceland is on the trace of the NW dykes of Greenland -Scotland, its tectonic pattern results from plate reorganisations where fractures form during rift-jump process but reactivate over time. Many tectonic features of Iceland are evocative of other active and extinct plate boundaries such as Vøring Spur, Jan Mayen ridge/transform, Mohn and Aegir Ridges.

EP 2 – Structure and processes of the Earth's crust

EP2-1

Structural and K/Ar illite geochronological constraints on the brittle deformation history of the Olkiluoto region, SW Finland

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Old, cratonic crystalline basements present compelling evidence of complex brittle deformation histories. Unfortunately, their typically long geological evolution and the repeated structural reactivation of pre-existing structures can obscure much of the evidence that is necessary to unravel these histories. In addition, in complex geological settings, such as the Precambrian shields, poor exposure commonly hinders acquisition of sufficient and relevant structural data.

At Olkiluoto Island in SW Finland, where a deep repository of spent nuclear fuel is under construction, thorough geological and geophysical investigations are being used to compile a site descriptive model, which provides a comprehensive description of the site and its regional setting. As part of this study a unique fault-slip data set consisting of more than 2000 striated brittle faults was collected. We have investigated the regional brittle deformation history through the analysis of a number of outcrops containing key structural relationships and by applying iterative stress inversion procedures on the available fault-slip data so as to generate distinct paleo-stress tensors attributable to specific tectonic events. By comparing our paleostress tensors with known paleostates of stress of southern Scandinavia and by using absolute and relative time criteria, it was possible to define the effects of a number of specific tectonic events in SW Finland. Uniaxial compression of late Svecofennian age with a regional NNW"- SSE $\sigma 1$ axis was active soon after 1.75 Ga ago, when brittle deformation was first accommodated in the region. A younger transpressive paleostress field with a NE-SW $\sigma 1$ axis was active soon after and it caused significant reactivation of some of the structures formed during the first shortening event. A phase of ESE-WNW extension is constrained by a number of stress tensors and direct field evidence and is tentatively assigned to the Gothian phase and the time of rapakivi magmatism. Subsequent NE-SW extension is interpreted to have accommodated upper crustal stretching and the formation and infill of the NW-SE-elongated Satakunta graben between 1.6 and 1.3 Ga. A well-constrained phase of c. NE-SW shortening, hitherto not described elsewhere in Fennoscandia, post dated rapakivi magmatism and c. 1260 Ma olivine diabase sills. Later E-W compression is assigned to the early stages of the Mesoproterozoic Sveconorwegian orogeny. This was followed by almost coaxial extension resulting from the late Sveconorwegian orogenic collapse at the Meso-Neoproterozoic boundary.

In order to add absolute time constraints to this conceptual model, selected fault gouge samples were collected for K/Ar dating of authigenic illite. K/Ar ages range in total from 561.3 ± 11.2 Ma (Neoproterozoic-Ediacaran) to 1451.7 ± 29.3 Ma (Mesoproterozoic-Calymmian). Structural analysis of the dated fault cores made it possible to assign tight time constraints to several of the faulting episodes, thus strengthening the presented structural scheme.

EP2-2

S-wave velocity structure of southern Norway from P receiver functions and surface wave dispersion

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Recent seismic experiments have given new information about Moho depth, P-wave and S-wave velocity structure in the crust and upper mantle in southern Norway. These new results have shown that there is an intriguing structural difference between a slow uppermost mantle in southern Norway and a fast uppermost mantle in neighboring parts of Sweden, despite the crust being of similar Sweconorwegian age. Several tectonic events reflected in the crustal history of southern Norway can be responsible for this difference in mantle properties, but we need information that connect the structure of the crust and the uppermost mantle in order to discuss the tectonic processes responsible.

By combining information from P receiver functions and surface wave dispersion measurements, we determine the S-wave velocity structure of the crust and uppermost mantle in the area. The P receiver functions are sensitive to velocity contrasts, whereas surface wave dispersion curves provide information about absolute S-wave velocities. The joint inversion of P receiver functions and surface wave dispersion therefore reduces the non-uniqueness of the problem and gives better resolved information on the S-wave velocity structure of the lithosphere. The data set is from permanent stations in Norway and Sweden and from the temporary broadband experiment MAGNUS, providing a dense coverage of the study region.

EP2-3

Meso- to Neoarchaean evolution of mid- to lower crustal rocks from the North Atlantic Craton of South-East Greenland

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The southeastern part of Greenland is a remote and poorly explored part of the Archaean North Atlantic Craton. Rocks in South-East Greenland include migmatitic orthogneiss, narrow bands of mafic granulite, paragneiss and ultramafic rocks, which are interpreted to represent an exposed piece of the mid- to lower crust metamorphosed at granulite facies. The protoliths to the orthogneisses took place episodically by ca. 2865 to 2730 Ma. Mafic granulite, paragneiss and ultramafic rocks could, at least in places, represent the basement into which the granitic rocks intruded. Alkaline rocks and carbonatites intruded in two pulses at ca. 2720-2700 Ma and 2680-2650 Ma.

The area is structurally complex with evidence of at least seven deformation events including reclined and mushroom-like fold interference patterns. An early foliation in the early granitic rocks and the basement formed during the > 2790 Ma Timmiarmiut deformation stage (DT), which could represent multiple deformation events that have not yet been recognised. The ca. 2790 - 2700 Ma Skjoldungen Orogeny (DS) folds this early foliation, develops a penetrative foliation, and refolds this foliation progressively in a NE-SW oriented palaeostress field that rotated into NNW-SSE orientation in the last stages of the orogeny. The Skjoldungen Orogeny is characterized by syn-deformational anatexis during ca. 2790-2740 Ma at approximately 800°C and 5-8 kbar, with retrogression in the amphibolite facies at ca. 2730 Ma. The late- to post-tectonic granite and alkaline rocks of the Skjoldungen Alkaline Province intruded approximately 2720-2700 Ma. N-S extension during the Singertat stage (DR) formed discrete shear zones at greenschist facies grades and is coeval with pegmatite, ijolite, and carbonatite emplacement at ca. 2680 - 2650 Ma.

Similar lithology and tectonic process in the Tasiusarsuaq terrane of southern West Greenland and the Lewisian complex in Scotland suggest a possibly large Archaean terrane at that time, which covered around 500-600 km in an E-W direction and approximately 200 km in a N-S direction.

EP2-4

Complex structuring and sedimentation of the southern Pyrenean foreland basins

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The Pyrenean Orogeny resulted from an easterly shear-related transposition followed by counterclockwise rotation of the Iberian plate, colliding with the European plate in Tithonian (145 Ma) to Santonian (85 Ma) times. This caused subduction of the Iberian plate beneath the European plate in the eastern part of the Pyrenees and with a more uncertain configuration of subduction in the Cantabrian Mountains to the west. The subsequent Eocene orogenic movements resulted in top-south in-sequence thrusting in the southern, Spanish part of the Pyrenees, including the development of piggy-back foreland basins. Analogue modeling reveals the complex along-strike geometry of the Orogen and emphasizes the strong influence of the contrasting mechanical strength of the lower crust and upper mantle in this process. A complex kinematic pattern is seen along the southern frontal regions of the Pyrenees, combining south-directed thrusting with an overprint of structures affiliated with transverse tectonic transport. The transverse structuring initiated large-scale faults and folds (e.g. the Foradada Fault and the Mediano and Boltaña anticlines) and associated thrust systems. These features affected the basin floor in the southern foreland basin system Tremp-Graus to the degree that structural features generated growing geomorphological thresholds that influenced the depositional systems and gave rise to the segmentation of the Tremp-Graus, Ainsa and Jaca basins. The thrust system is associated with three stages of development in the Ainsa Basin. The first stage involved top-south contraction associated with the regional transport in the frontal Pyrenees. This was followed by westerly directed thrusting, accompanied by local, gravity-driven extensional faulting on the flanks of growing anticlines. Finally, a stage of top-east thrusting is seen, the significance of which is not yet understood. All these stages of structuring took place under very high fluid pressure, so that many thrust faults are marked by arrays and networks of calcite veins demonstrating several generations of growth, enveloping horses and duplexes of the thrust system. The structuring strongly influenced the sediment transport and deposition in the nearly up to 1000 meter deep, marine foreland basin system during Ypresian-Lutetian. During this stage, the Tremp-Graus Basin became filled with alluvial and shallow-marine sediments; continuing supply of coarse-clastic debrisfrom the axial zone of the Pyrenean mountains bypassed the Tremp-Graus Basin and was transported westward into the deep-marine Ainsa-Jaca basins through submarine canyons and deposited as channelized elongate submarine fans and distal sand sheets, in addition to deposition of large volumes of carbonate-rich mud. In late Lutetian to Barthonian-Priabonian the Ainsa Basin was filled in by deltaic and alluvial sediments, with depositional pattern controlled by a basin morphology shaped by structural ridges, waning tectonically controlled accommodation space and increasing topographic relief of the central Pyrenees due to isostatic uplift.

EP 3 – Structure and stability of minerals

EP3-1

Non-carbonate subglacial minerals, preliminary study

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Bedrock surfaces beneath tempered glaciers are frequently coated by subglacial mineral incrustations. These crusts are millimeter-thick and located where meltwater flow and regelation occurred. They seem to be unstable under atmospheric conditions since they are most abundant close to the margin of retreating glaciers. They also show increasing corrosion signs with increasing distance from the ice (i.e. increasing age of exposure). This implies that the crusts formed under conditions of 0°C temperature and a few bar pressure underneath the flowing ice.

Previous work on sub-glacially formed crusts only described crusts composed of carbonate, on both carbonate and non-carbonate bedrock. However, in this study, non-carbonate crusts were examined in samples from Mexico, Switzerland, Antarctica, Tibet and New Zealand. Crusts were observed under binocular microscope, in thin sections using a polarized microscope in both visible and ultraviolet light, and with a Scanning Electron Microscope (SEM). Chemical analyses were made using an Energy Dispersive Spectrometer (EDS) and by XRF.

The crusts are layered irregularly and contain variable but significant amounts of cemented rock flour with grain sizes <0.2 mm. Two sets of samples (Mexico and Switzerland) were enough thick to contain areas of sufficiently pure cement for chemical analysis.

The cement of the crusts from Mexico, found on intermediary to acidic quaternary lavas of Mount Citlaltépetl, is white and composed of hyalite (opal-AN), organic compounds and traces of sulphur. It is not easy to find a chemical reaction forming opal at 0°C except when taking into account the activity of extremophile bacteria. The amorphous SiO_2 could be a metabolism product of bacteria growing in a wet environment with abundant rock flour, i.e. finely ground crystalline (e.g. Pyrite) and hyaline phases of the volcanic bedrock.

Crusts from Switzerland were sampled on a two-mica schist bedrock at Mount Diavolezza, Canton Graubünden. The cement of these black and yellow crusts is composed of pyrolusite (MnO_2) and limonite (FeOOH). The formation of these minerals at 0°C has not been described so far, therefore, as in the opal crusts, the influence of bacterial activity on their formation must be discussed.

EP3-2

Reycrystallization of submicrometer calcite

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Calcite growth and dissolution are well-understood, but much less is known about calcite recrystallization at dynamic equilibrium. Lab experiments are difficult because the rates are simply too slow and synthetic calcite crystals are usually too large (i.e., > 10 μm) to permit observation of changes with conventional, macroscopic techniques. However, on geological timescales, changes to particles and pores in a porous medium are not negligible. Recrystalization leads to Ostwald ripening, which is responsible for converting sediments to rock during burial diagenesis. The important question is - Why do some calcite-containing sediments recrystallize and others do not? For example, limestone has large crystals whereas the individual elements in the coccoliths of chalk remain submicrometer dimension.

We synthesized submicrometer calcite by bubbling CO_2 through a Ca(OH)2 slurry. We aged the particles in saturated solution at ambient and elevated temperature and pressure (200 °C and 16 bar) and observed particle evolution with scanning electron microscopy (SEM), small and wide angle X-ray scattering (SAXS/WAXS) and BET surface area measurements.

Observation at elevated pressure and temperature showed a two step process of submicrometer crystal evolution. First, crystals grew at the expense of smaller particles and surface area decreased from ~15 m^2/g to ~4 m^2/g. Second, crystal form evolved from multifaced crystals into rhombohedra, calcite's most thermodynamically stable form. Crystal size distribution shows an increasing mean diameter, as expected for Ostwald ripening, i.e. in response to the drive toward decreasing surface free energy. At room conditions, ripening was not observed by SEM or BET, but 45Ca isotope tracer was incorporated.

EP3-3

Encrustations from the 2010 Fimmvörðuháls eruption

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Volcanogenic encrustations are formed during and following volcanic eruptions. They form crusts at craters, on lava surfaces and in lava caves. They tend to be sensitive to precipitation and weathering and are therefore usually short-lived. Volcanogenic encrustations in Iceland were first studied by Níels Óskarsson (1981). In the past two decades an international research group has studied encrustations formed in five eruptions at Hekla 1947-1948 and 1991, Askja 1961, Surtsey 1963-1967 and Eldfell 1973 (Jakobsson et al. 2008). The majority of the minerals are halides and sulphates, while oxides and carbonates also occur. Hydrous minerals are common. A surprisingly large number of different minerals was found to have formed at each eruption. Furthermore, the mineral ralstonite was unexpectedly found to be quite common, while sulphur was rarely found. Among the minerals identified, 32 have not been described from Iceland before. Several minerals were discovered that have not previously been found in nature. Four minerals have been accepted as new minerals by the IMA, two of which have been formally published, eldfellite (NaFe(SO4)2) and heklaite (KNaSiF6) (Balić-Zunić et al. 2009, Garavelli et al. 2010). Volcanogenic encrustations form in short-lived, shallow, relatively dry, high temperature geothermal systems. These are very different from long-lived, deep, high temperature systems with extensive water-rock interaction, characterized by solfataras and abundant deposits of clay.

Two eruptions occurred at Eyjafjöll in Iceland in 2010. First, a basaltic fissure eruption occurred at Fimmvörðuháls on the eastern flank of the volcano. It started on March 20th and ended on April 12th. Two days later, on April 14th an explosive eruption started in the summit crater of Eyjafjallajökull, which lasted until May 22nd. The magma erupted at Fimmvörðuháls was a porphyritic transitional basalt, the majority of which solidified as lava. The same type of basalt was involved in the explosive eruption at Eyjafjallajökull, where it was mixed with transitional rhyolite, forming transitional benmoreite and trachyte (Sigmarsson et al., 2010), much of which was dispersed as very fine grained ash. This study focuses on volcanogenic encrustations formed on or at the surface of the craters and lava flow on Fimmvörðuháls.

Encrustations have been sampled at Fimmvörðuháls once during the eruption, at three separate times in the following months of 2010, and once in 2011. Continued sampling at regular intervals, will enable a study of possible changes in the mineralogy of the encrustations with declining temperature and reduced degassing. Very high gas temperatures were recorded during sampling, or up to 800°C. The conditions are quite unusual. Volcanic ash from the Eyjafjallajökull eruption has been baked into a crust of tuff on the hot surfaces of craters and lava. This has provided favorable conditions for the formation and preservation of volcanogenic encrustations beneath the tuff crust. Preliminary results of XRD and SEM analysis will be presented at the meeting. So far, 7 minerals have been identified: thenardite (Na2SO4); ralstonite (NaXMgXAl2-X(F,OH)6 · H2O); mineral "HD"(NH4(Fe,Co)2F6); and probably aphthitalite ((K,Na)3Na(SO4)2); carnallite (KMgCl3· 6H2O); anhydrite (CaSO4); and halite (NaCl). Mineral "HD"has previously been found in Surtsey, Eldfell and Hekla. It is a new mineral that has yet to be formally defined. During the eruption, thin white coatings were observed on the fresh lava. Such coatings also appeared on samples collected while hot. The coatings were found to be thenardite, a readily soluble mineral that is quickly washed away.

EP3-4

Rich mineralogy of the fumaroles on Eldfell volcano, Heimaey, Iceland

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ORAL EP 3

The fumaroles on the crest of the Eldfell volcano have been active since its formation during eruption in 1973 until today. During a recent examination of fumaroles in 2009 the temperature at some vents was exceeding 450º C and profiles exhibiting rich mineralogy have been opened. The samples have been analyzed by X-ray diffraction and electron microscopy. Our investigations reveal zonation in fumarolic vents depending on the depth and temperature. The hematite and anhydrite are omnipresent and silica appears both as cristobalite in the lower parts and opal in the upper one. There is a spectrum of sulphate and fluoride minerals which populate different zones of the fumaroles. The mineralization at highest measured temperatures at deepest excavated depths of 70-80 cm is characterized by sulphates of Na, Mg and Al which at lower depths and temperatures are replaced by sulphates of Na, K and Mg, finally to be replaced by a zone of fluorides at the very top of fumarole and temperatures at or lower than 200º C. The known minerals are hexahydrite, löweite and tamarugite, which, being sulphate hydrates, might also be formed successively to sampling, sulphate langbeinite (K2Mg2(SO4)3) found in the middle zone and fluorides ralstonite, jakobssonite (CaAlF5) and leonardsenite (MgAlF5·2H2O) (the latter two recently defined by our group on samples collected in 1988). There have been additionally determined new minerals which partly correspond to potentially new minerals indicated in teh work of Jakobsson et al. (2008) which are presently fully defined chemically and crystallographically. They are sulphates Na3Al(SO4)3 and NaMgAl(SO4)3 from the deepest parts of fumaroles, Na2Mg2(SO4)3 equivalent of langbeinite, mixed with the latter in the middle parts, and fluoride AlF3 in the surface layer together with several other fluorides still under investigation. The composition of fumarolic material on recently active Icelandic volcanoes changes due to the chemistry of magma and predominating gas compositions. This was shown by Jakobsson et al. (2008) by a comparison of fumaroles at Surtsey consisting predominately of sulphates, those of Eldfell being of mixed character and those at Hekla dominated by fluorides. The present results show that the composition also varies significantly locally due to the change in temperature of deposition of the ascending volcanic gases.

Jakobsson, S.P., Leonardsen, E.S., Balic-Zunic, T., Jónsson, S.S. (2008) Fjölrit Náttúrufraedistofnunar 52.

EP 4 – Igneous and metamorphic processes

EP4-1

Metamorphic Map of Sweden

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The Metamorphic Map of Sweden is collaborative initiative involving scientists and students from Sweden and its neighboring countries. The aim of this initiative is to work towards a map of the P-T facies of metamorphism in Sweden as a function of time, using geothermobarometry software, such as THERMOCALC. The project comprises a set of undergraduate level theses each of which aims to elucidate the P-T-t history of a given area. Our intention is for the metamorphic map of Sweden to become a collaborative initiative involving scientists and students, not only from Stockholm and Uppsala, but from anywhere in Sweden and from our neighboring countries. Ongoing projects include Utö, Gällivare, Koster Archipelago and Romelåsen. The first project to be completed was conducted on Utö. It has confirmed that the deformation zone (Bandserien, Sundius 1939), that can be traced at least 80 km SW-NE along the coast from Ålö in the south to Skarprunmarn in the north, represents not only a tectonic boundary but a metamorphic boundary, with moderate T - low P metamorphism to the SE and high T - low P metamorphism to the NW. Other study areas which are currently advertised include Arjeplog, Blåsjön-Härbergsdalen, Garpenberg, Ramsele, Snasahögarna, Sundsvall, Värmland and Åreskutan.

EP4-2

Geothermobarometric investigation of St Persholmen, Utö as part of the Metamorphic Map of Sweden

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I present results of a geothermobarometric investigation of St Persholmen, Utö, in the south central part of Sweden. This is part of a wider effort to build a metamorphic map of Sweden. Utö is part of Bergslagen which is one of Sweden's ore regions with concentrations of iron, copper and sulfides. Rock types from this region have been dated to around 1.91-1.89 Ga (Stephens et al. 2009). The rocks on Utö are considered representative of Bergslagen and record the closing of an ocean starting with subduction followed by volcanic episodes and orogeny (Talbot 2008). The rocks which crop out on St Persholmen are thought to represent the remains of this orogeny where greywackes from the oceanic stage have been preserved at the base of the mountain range (Stålhös 1982). Two rock types from St. Persholmen were selected for geothermobarometric studies. These were metagreywackes from the SE and NW sides of St. Persholmen. Metagreywacke from the SE was schistose, whereas metagreywacke from the NW showed evidence of migmatisation. This could reflect reworking in an accretionary prism, melting at the base of a mountain range or fluid-rock interaction. After petrographic and mineral chemical analysis of these samples, I used the computer programs AX and THERMOCALC to determine the temperature and pressure of metamorphism. For the schistose metagreywacke, I obtained a temperature of 538 ± 36°C and a pressure of 3.1 ± 1.3 kbars, whereas, for the migmatised metagreywacke, I obtained a temperature of 756 ± 133°C and a pressure of 3.8 ± 3.2 kbars. These data are consistent with a terrain boundary passing through St. Persholmen (Sundius 1939). Furthermore, two generations of muscovite provide evidence of fluid-rock interaction and at the NE coast of Persholmen the occurrence of sillimanite indicates a high grade of metamorphism.

EP4-3

Small scale metasomatism of mafic gneiss in the Norwegian Caledonides associated with brine infiltration – Fluid inclusions, SEM-CL and mineralogical record of the fluid infiltration

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The uppermost stratigraphic layer of a 250 meter thick sequence of metasediments in the Bjellaatinden area, Northern Norway, consists of a hornblende-biotite gneiss. The gneiss is cross cut by sub vertical, slightly arched, 2 - 10 cm thick quartz veins with an alteration halo up to 5 cm into the unaltered gneiss. The zoned alteration assemblage includes sericite, dickite, chlorite, calcite and muscovite. Hornblende is gradually altered to biotite, and plagioclase is increasingly sericitized towards the vein. Biotite is completely replaced by chlorite , and muscovite and calcite dominate closest to the quartz vein. The Fe/Fe+Mg ratio increases in biotite when partly altered to chlorite, and increases slightly in chlorite (0,55) compared to biotite (0,50) in the unaltered zones. Titanite is the main Ti-mineral in the unaltered gneiss, while ilmenite + rutile dominate in the alteration zone. An earlier hydrothermal mineral assembly consisting of scapolite (Me55-60) and biotite is also recognized

Three types of fluid inclusions in quartz are described: Saline (ca. 40 wt% NaCl equiv.) water rich, gas rich, and low saline water rich. Multiple generations of fluids are indicated by several trails consisting of separate gas rich, saline water rich and low saline water rich inclusions. In some areas all three types occur together and are indicative of co-existence of different fluids in an immiscible fluid system. SEM-CL reveals three different types of quartz: Low lumicent, with a broad peak from 420 - 650 nm, hosting late, gas rich inclusions, higher lumicent, with a peak around 500 nm, hosting the saline fluid inclusions, and high lumicent with a peak around 500 nm scarce of fluid inclusions. Low saline, water rich fluids are mostly found in high lumicent quartz with a peak around 400 nm inside the alteration zone. Low density fluid inclusions are found in scapolite and vein quartz related to scapolite.

Microthermometry of the saline fluid inclusions revealed a bimodal distribution of total homogenization temperatures (Th), but with stabile salinity measured by halite melting at ca. 300 °C and Th (liquid + vapour liquid) ranging from ca. 450 °C to ca. 250 °C. Semi quantitative EPMA analysis of decrepitated fluid inclusions showed major Na, Ca and Fe, and minor K and Mn. Mineral breakdown may be responsible for the elevated Fe and Ca levels in the fluids, and the increased K level in the alteration zones are due to interaction with a originally K rich fluid.

EP4-4

Intra-orogenic magmatism in southwestern Finland: heat source for the late Svecofennian metamorphism?

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The source of heat for granulite facies metamorphism is often ambiguous and both mantle and crustal sources are possible. The Palaeopoterozoic late Svecofennian Granite-Migmatite belt (LSGM) in southern Finland is a ~150 x 500 km zone of anatectic granites and migmatites that were formed during the late orogenic stage (Ehlers et al. 1993). Kukkonen and Lauri (2009) modelled the heat production in LSGM and concluded that heat produced by radioactive decay was responsible for the large-scale crustal melting.

We have studied plutonic rocks in southwestern Finland that can be classified as intra-orogenic, i.e., they were intruded during a period between the two main Svecofennian orogenic cycles: the Fennian and Svecobaltic orogenies (Lahtinen et al. 2005). The zircons were dated by laser-ablation (LA-MC-ICPMS) at the Geological Survey of Finland. The mafic/intermediate rocks from Rauma yielded an age of 1865 ± 9 Ma, from Turku an age of 1860 ± 5 Ma and from Korpo an age of 1852 ± 4 Ma. The adjacent garnet-bearing Korpo granite is 1849 ± 8 Ma in age. Zircons from the granite also include inherited Archaean and older Palaeoproterozic zircons, as well as metamorphic c. 1.82 Ga rims. The mafic-intermediate rocks are high-K and shoshonitic intrusions, high in Fe, P, F and LREE, and were intruded as subhorizontal sills. The Korpo diorites and granites form hybrids where in contact. The granites show typical features of being crustal-derived.

These findings combined with other data (e.g. 1838 ± 4 Ma gabbro in Pajunen et al. 2008) show that mafic magmatism during the intra-orogenic period is relatively common and, consequently, brought heat from mantle, producing at least local crustal melting. We infer that heating from mantle- and crustal-derived intra-orogenic magmatism combined with heating from radioactive decay were responsible for the high late orogenic heat flow in southern Finland that culminated in granulite facies metamorphism and large-scale crustal melting at c. 185-1.81 Ga.

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EP4-5

Crystallization-induced melt migration in columnar basalts

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Columnar jointed basalt from Hrepphólar in southern Iceland display spectacular internal structures when cut. These structures follow the overall orientation of the columns and display semi-circular to circular features when cross-cut. It was previously believed that these internal structures formed as a result of alteration due to circulation of meteoric water within the column-bounding fractures after emplacement. However, new field observations of viscous fingering within the columns and the fact that approximately 80% of the semi-circular features are found within the column whereas the remaining 20% are cut by the column-bounding fractures clearly shows that these internal structures must have formed prior to crack-propagation (and are thus primary magmatic features). Here we present the results of textural and petrological analyses through a cross-section of a column, in combination with magnetic susceptibility and anisotropy measurements of the same samples. The variation in textures and geochemistry can be attributed to the presence of diffuse banding caused by variations in the modal proportions of the main phenocryst phases (i.e., plagioclase, clinopyroxene, olivine and titanomagnetite/ilmenite). Orientation of plagioclase laths and titanomagnetite crystals (based on measurements in thin sections and AMS-measurements) are consistent with vertical flow alignment. Nowhere in the column can evidence for downwards flow be found (excluding the possibility of small-scale convection cells generating these features). It is proposed here, that the volume decrease associated with solidification (typically 10-15 vol.% for basaltic systems) and the increasing weight of the overlying crust results in upwelling of partially crystallized material into the centre of the columns. Numerical modeling indicates that the isotherms within individual columns become steeper with increasing depth in a lava flow (allowing for larger displacement distances). We propose that this upwelling can be a rather common phenomenon in nature, but without the presence of chemically distinct compositions (or textural banding) it can be difficult to recognize such features in the field.

EP4-6

Is formation segregation melts in basaltic lava flows a viable analogue to melt generation in basaltic systems?

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Pahoehoe sheet lobes commonly exhibit a three-fold structural division into upper crust, core and lower crust, where the core corresponds to the liquid portion of an active lobe sealed by crust. Segregations are common in pahoehoe lavas and are confined to the core of individual lobes. Field relations and volume considerations indicate that segregation is initiated by generation of volatile-rich melt at or near the lower crust to core boundary via in-situ crystallization. Once buoyant, the segregated melt rises through the core during last stages of flow emplacement and accumulates at the base of the upper crust. The segregated melt is preserved as vesicular and aphyric, material within well-defined vesicle cylinders and horizontal vesicle sheets that make up 1-4% of the total lobe volume.

We have undertaken a detailed sampling and chemical analysis of segregations and their host lava from three pahoehoe flow fields; two in Iceland and one in the Columbia River Basalt Group (CRBG). The Icelandic examples are: the olivine-tholeiite Thjorsa lava (24 cubic km) of the Bardarbunga-Veidivotn volcanic system and mildly alkalic Surtsey lavas (1.2 cubic km) of the Vestmannaeyjar volcanic system. The CRBG example is the tholeiitic 'high-MgO group' Levering lava (>100? cubic km) of the N2 Grande Ronde Basalt. The thicknesses of the sampled lobes ranges from 2.3 to 14 m and each lobe feature well developed network of segregation structures [1,2,3].

Our whole-rock analyses show that the segregated melt is significantly more evolved than the host lava, with enrichment factors of 1.25 (Thjorsa) to 2.25 (Surtsey) for incompatible trace elements (Ba, Zr). Calculations indicate that the segregation melt was formed by 20 to 50% closed-system fractional crystallization of plagioclase (plus minor pyroxene and/or olivine). A more striking feature is the whole-rock composition of the segregations. In the olivine-tholeiite Thjorsa lava the segregations exhibit quartz tholeiite composition that is identical to the magma compositions produced by the nearby Grimsvotn and Kverkfjoll volcanic systems during the Holocene. The Surtsey segregations have whole-rock composition remarkably similar to the FeTi basalts from adjacent Katla volcanic system, whereas the segregations of the Levering flow are identical to the 'low-MgO group' basalts of the CRBG. Is this a coincidence or does volatile induced liquid transfer, as inferred for the formation of the segregations, play an important role in magma differentiation in basaltic systems?

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EP4-7

Stability of götzenite in peralkaline nephelinite at Nyiragongo, D.R. Congo

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In a joint project between NGI and China Geological Survey (CGS), funded by the Norwegian Ministry of Foreign Affairs, we assess landslide problems in the NW China loess region. The Heifangtai area consists of villages along the Yellow River, and a farming community on a plateau 100m above the river level. The farmers were moved here in the late 1960'ies and a large irrigation project was initiated, pumping water from the river to the plateau. 12-15 years later, the area started to experience significant landslide problems, with many fatalities and large economic losses. The project aims at understanding the landslide processes and suggesting robust mitigation measures.

Managing the water balance in the area is the key problem. However, the local stratigraphy allows different solutions for drainage, being most important near the steep slopes of the plateau. The project includes significant data acquisition over several years, including laser scanning of the whole area, infiltration tests, pumping tests and other in-situ tests in boreholes, in-situ and laboratory geotechnical testing, chemical analyses, hazard and risk mapping, tsunami analyses (from landslides into the Yellow River), etc. The project poses cultural and socio-economic challenges. This is a poor region, and the costs of any large scale mitigation measures to be suggested must be acceptable to both the local and central authorities.

We will present preliminary results of landslide hazard assessment, including stability calculations for the Heifangtai slopes, as well as suggested solutions for mitigation measures to reduce the risk for the villages along the Yellow River.

THEME: EARTH RESOURCES (ER)

ER 1 – Geothermal Research and exploitation

ORAL
ER 1

ER1-1

Key Issue in Climate Mitigation: Capacity Building in Renewable Energy Technologies in Developing Countries

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Amongst the top priorities for the majority of the world´s population is access to sufficient affordable energy. There is a very limited equity in the energy use in the world. Some 70% of the world´s population lives at per capita energy consumption level below 1/4 of that of W-Europe, and 1/6 of that of the USA. Two billion people, a third of the world´s population, have no access to modern energy services. A key issue to improve the standard of living of the poor is to make clean energy available at prices they can cope with. World population is expected to double by the end of the 21st century. To provide sufficient commercial energy (not to mention clean energy) to the people of all continents is an enormous task.

The renewable energy sources are expected to provide 20-40% of the world primary energy in 2050, depending on scenarios. The technology has been developed for the main renewable energy sources. There is already a significant professional experience for exploration, construction and operations of renewable energy installations, but the experience is mainly confined to the industrialized countries. A key element in the mitigation of climate change is capacity building in renewable energy technologies in the developing countries, where the main growth in energy use is expected. An innovative training programme for geothermal energy professionals developed in Iceland is an example of how this can be done effectively. The mandate of the United Nations University Geothermal Training Programme is to assist developing countries with significant geothermal potential to establish groups of specialists by offering six month specialized training for professionals already employed in geothermal research and/or development. The trademark is to give university graduates engaged in geothermal work intensive on-the-job training in their fields of specialization (www.unugtp.is). The trainees work side by side with geothermal professionals in Iceland (the majority with ISOR-Iceland GeoSurvey, www.isor.is). Specialized training is offered in geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, chemistry of thermal fluids, environmental studies, geothermal utilization, and drilling technology. In 1979-2011, 482 scientists/engineers from 50 developing countries have completed the 6 month courses. In many countries in Africa, Asia, C-America, and E-Europe, UNU-GTP Fellows are among the leading geothermal specialists. The UNU-GTP also organizes Workshops and Short Courses on geothermal development in Africa (started 2005), Central America (started 2006), and in Asia (started 2008). The courses may in the future develop into sustainable regional geothermal training centres.

The key to the success of the UNU-GTP, is the selection of the UNU Fellows. Candidates for the specialized training must have a university degree in science or engineering, a minimum of one year practical experience in geothermal work, speak English fluently, be under 40 years of age, and have a permanent position dealing with geothermal at an energy company/utility/research institution/university in their home country. Site visits are conducted by UNU-GTP representatives to countries requesting training. The potential role of geothermal in the energy plans of the respective country is assessed, and an evaluation made of the institutional capacities in the field of geothermal research and utilization. Based on this, the training needs of the country are assessed and recipient institutions selected. All qualified candidates are interviewed personally.

ER1-2

Iceland Deep Drilling Project (IDDP) – Status in 2012

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The Iceland Deep Drilling Project (IDDP) is being carried out by an international industry-government consortium in Iceland (HS Orka, Landsvirkjun, Reykjavik Energy, Orkustofnun, Alcoa and Statoil), in order to investigate the economic feasibility of producing electricity from supercritical geothermal reservoirs. Modeling suggests that producing superheated steam from a supercritical reservoir could potentially increase power output of geothermal wells by an order of magnitude. To test this concept, the consortium planned to drill a deep well in each of three different geothermal fields in Iceland, at Krafla in NE-Iceland, and at the Hengill and Reykjanes fields in SW-Iceland. In 2009 the drilling of the first deep well, IDDP-1, was attempted in the active central volcano at Krafla, but this drilling had to be terminated at 2.1 km depth when intersecting 900°C rhyolite magma. The well, IDDP-1, was completed with a sacrificial casing cemented inside the production casing with a perforated liner, open in the lowest 100 m section of the drillhole. After a long heat-up period and a series of flow tests the well proved highly productive, capable of producing some 30-40 MWe from 410°C superheated steam during a flow test undertaken in 2011.

After the initial flow tests in the summer of 2010, improvements were made to the wellhead and flowline to meet the demanding conditions. This included adding a second 2500 Class master valve, scaling the main flowline up to DN500 PN25 (500 mm wide with pressure rating of 25 bar) to lower flow velocity and addition of a 4”2500 class flowline as an alternative. The flow test resumed on May 17th 2011, but due to resonance in the flow line and some resulting damages the well had to be shut in again for further modification. The 4th flow test then began on the 9th of August and lasted until the 11th of August 2011 when a 12”Class 1500 operating valve failed. Steam temperature then was 410°C, at 40 bar pressure, and enthalpy close to 3150 KJ/Kg. Power output potentially between 30-40 MWe. The well had to be shut in again for yet another modification of the flow line to accommodate a double 4"valves to undertake a wet scrubbing pilot test, which resumed late-September 2011. The status of the well in January 2012 will be discussed.

Preparation is ongoing for drilling well IDDP-2 to 5 km depth into the saline high-temperature field at Reykjanes in SW-Iceland. The drilling may take place as early as 2012-2013. The design of the IDDP-2 well will benefit from lessons learned during drilling of the IDDP-1 at Krafla. A review on the geological and geophysical characteristics of the Reykjanes field, is provided based on relatively new geological, geophysical and drillhole data. An IDDP workshop on the engineering and scientific research to be organized for and implemented in IDDP-2 is being planned for late May or early June 2012. Further information at www.iddp.is.

ER1-3

Induced and triggered seismicity in Icelandic geothermal systems

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Today 5 high temperature geothermal systems in Iceland are being exploited or explored by drilling to produce electricity. All these fields are located within active volcanic complexes. In Hengill in SW-Iceland 433 MW of electricity are being produced in two power plants at Hellisheiði and Nesjavellir. On the Reykjanes peninsula, 176 MWe are being produced in two power plants at Svartsengi and Reykjanes. In N-Iceland 60 MWe are installed in the Krafla volcanic complex and drilling and testing of new wells are being performed at Þeistareykir where at least 100 MWe are planned to be installed. The effluent from the power plants is re-injected into the ground partly in Krafla, Reykjanes, Svartsengi and Nesjavellir and completely at Hellisheiði. The purpose is twofold, to avoid pollution and to maintain the reservoir pressure.

Natural earthquake activity is common in all these fields and is monitored by the national seismological network of the Icelandic Meteorological Office. In addition local networks have been set up and operated by Iceland GeoSurvey and others, permanently in Krafla and temporary networks at Hellisheiði, Reykjanes and Þeistareykir. The purpose is to monitor earthquakes that might be related to drilling, borehole tests, production or reinjection.

Clear examples of induced seismicity have been found in Krafla, Reykjanes and Hellisheiði. The events occur in swarms that are usually connected to onset of injection, change in injection rate or stimulation activity in boreholes. An earthquake swarm observed at Reykjanes might also have been triggered by sudden pressure drop in the reservoir due to strongly increased production.

Most of these earthquakes are quite small and need a local network close the drilling or injection sites. In Hellisheiði, however, earthquakes with magnitude between 3 and 4 have been measured and felt in the village Hveragerði and the suburbs of Reykjavík in September 2011.

In February 2011 ISOR installed five seismic stations around a drill site at Hellisheiði during drilling of a 2 km deep injection well. Four pressure gauges were also installed in nearby boreholes. Shortly after a circulation loss was observed in the borehole an earthquake swarm was initiated that clearly defined the fault which the water was lost into. The fluid pressure increase caused by the circulation loss was less than 10 bars so obviously the fault was critically stressed prior to the drilling and the fluid loss triggered the earthquakes.

During drilling of the IDDP well in Krafla in 2009 the well penetrated the top of a magma layer close to 2 km depth. A total circulation loss was observed at the top of the magma, in a zone of very high temperature gradient. The circulation loss was followed by a swarm of microearthquakes most of them with magnitude between -0,5 and 0,5 and mainly above 2,2 km depth. The earthquakes started close to the bottom of the well and moved gradually to the side and upwards along an inclined plane. This plane is presumably a permeable fissure that connects the molten rock and the geothermal field and is a potential target for drilling.

Iceland GeoSurevy is a partner in a large European Project, GEISER, led by GFZ-Potsdam. It aims at research into induced seismicity related to geothermal energy production and defining measures to mitigate the effects of induced seismicity. For that purpose data from Iceland and several other places of known induced seismicity are analysed and modelled in the GEISER project.

ER1-4

Evolution of the Hengill Volcanic Center, SW-Iceland

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The Hengill central volcano is situated at a ridge-ridge-transfrom triple point in SW-Iceland. It has reached an intermediate stage towards a mature central volcano which has not yet formed a caldera but has produced minor amounts of intermediate and rhyolitic rocks, the only volcanic system in the Reykjanes Peninsula to do so. The Hengill volcanic system hosts a large high-temperature geothermal field with a total of over 100 boreholes with a range from 800 to 3300 m depth. Samples from nine wells spread around Hengill area were taken and give an unique opportunity to view the core of an active volcano and the birth and evolution of an active central volcano. Although samples were often highly altered the chemical trend of majority of the samples conforms well with the chemical trends derived from fresh rock of the Reykjanes Peninsula. The sample suit shows a typical overall trend for subalkaline silicic centers in the Icelandic rift zones and covers the the entire basalt range. Results show that the Hengill volcano produces primarily olivine tholeiites. Reconstruction of palaeo landscape in the Hengill area based on borehole data imply that the production of basalts started some 0,4 my ago and first appearance of evolved basalts was possibly during the Holsteinian interglacial (~200 kyr) marking the birth of a an central volcano.

ER1-5

Hydrothermal dissolution of olivine and pyroxene in the Hellisheiði geothermal field, SW-Iceland

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The Hengill volcanic complex, SW-Iceland, is located at a triple junction where the active rift zones of the Reykjanes Peninsula and the Western Volcanic Zone meet the South Iceland Seismic Zone, a seismically active transform zone. The majority of rock formations in the area are of olivine-tholeiite composition and are mostly hyaloclastite formations (tuffs, breccias and pillow lavas) that formed sub-glacially. Basalt lava flows from interglacial periods and from the Holocene occupy the lowlands and are therefore less common in the volcanic centre. During the past few years, extensive drilling at the Hellisheiði geothermal field within the Hengill volcanic complex has yielded vast amounts of data on hydrothermal alteration and alteration zones of a 2-3 km deep section through an active rift-zone. Alteration zones within the Hengill volcanic centre are as follows: zeolite-smectite zone (<200°C), mixed-layer-smectite zone (~200-230°C), chlorite zone (~230-240°C), chlorite- epidote zone (~240-280°C) and epidote-actinolite zone (>280°C).

This study involved characterising the primary olivine and clinopyroxene in the Hellisheiði geothermal wells and their subsequent alteration by electron microprobe analyses. On the one hand the alteration of these primary minerals in olivine-tholeiite lava flows was examined to determine whether progressive alteration is discernible. All subsurface lava flows have gradually been buried beneath younger formations and have been altered accordingly. Chemical weathering at the surface is gradually followed by geothermal alteration as temperatures rise with increased burial depth. On the other hand the somewhat different geothermal alteration of olivine-tholeiite dykes and intrusions is addressed. Fresh intrusive rocks cool down to the prevailing temperature conditions in their surroundings and start to alter accordingly. The fresh intrusions should therefore record the primary alteration of the current active heat source.

The results from the electron microprobe analyses suggest some differences between lava flows and intrusives. This is more pronounced in the pyroxene alteration, especially in different chemical composition of actinolite from intrusives and lava flows, repectively, which is attributed to less oxidation of the intrusives. More significant, however, may be the different modes of alteration: in the lavas with increasing temperature from pyroxene via chlorite, in the intrusives with decreasing temperature directly from the original pyroxene.

ORAL
ER 1

ER1-6

Structure and composition of clay minerals in the Hellisheiði Geothermal Field, SW-Iceland

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Clay minerals predominate in the secondary minerals formed by hydrothermal alteration of basaltic rocks in geothermal areas. In the most altered hyaloclastites, up to 80-90% by volume may be replaced by clay minerals and as much as 60% of the basaltic lavas. Not only are the the clay minerals quantatively the most significant alteration minerals, but also they respond quickly to temperature changes in the geothermal system and can therefore be useful for interpretation of the thermal history of a geothermal field. (Hrefna Kristmannsdóttir; 1975, 1979)

Clay minerals from drill-cuttings from seven geothermal wells in the Hellisheidi geothermal field were separated and analysed along with whole-rock cuttings from their surroundings. Clay minerals were initially defined as the grain size fraction below 2 micrometers and separated by settling from Ultrasonic-wave generated particle suspension. The sample set represents all major stratigraphic units of the uppermost 3 km of the Hellisheidi crustal section. Samples from different stratigraphic units were collected as well as samples from intrusions in the lower section of the formation.

There is a marked difference in the alteration history of the subsiding stratigraphic units and the intrusives. While the alteration of intrusives such as dykes takes place within the prevailing alteration facies the alteration of the subducting strata represents a progressive alteration from the lowest to the highest facies.

Structural evolution of clay minerals with increasing depth and temperature is characterized by initial smectite-type structures through mixed-layer minerals at about 500 m depth towards homogeneous chlorite below about 700 m. The complicated small-scale chemical diversity of clay minerals in otherwise similar surroundings may be assigned to material transfer by geothermal fluid, presumeably during numerous alteration events.

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ER1-7

Opaque minerals in geothermal well HE-42, Hellisheiði, SW Iceland

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The Hengill central volcano is located in SW Iceland, at the junction of three tectonic systems that form a triple point. The Hellisheiði high temperature area is associated with the Hengill central volcano. During Reykjavik Energy's exploration and exploitation of the Hellisheiði geothermal field, 57 wells and 17

reinjection wells have been drilled. During this drilling a lot of information has been gathered and the understanding of the stratigraphy, alteration, location of aquifers and formation temperature on Hellisheiði is much better. The stratigraphy of Hellisheiði is dominated by hyaloclastite and pillow basalt and interlayed with lava successions. Intrusions are quite frequent from 1000 m below sea level.

In this research the composition of opaque minerals (sulfides and oxides) from the Hellisheiði strata has been studied. Samples from drill cuttings from well HE-42 were analyzed with a microprobe at the University of Iceland. The opaque minerals are of two kinds; firstly, minerals that replace primary minerals and secondly minerals that precipitate from the geothermal fluid. The composition of these minerals can yield information about the conditions in the cooling magma and the alteration of the primary minerals as well as giving insight to the conditions of the geothermal system.

Four different types of sulfides were detected, pyrite, pyrrhotite, chalcopyrite and possible bornite. Pyrite is shown to have a different texture depending on its age.

Oxides of different composition and nature have been analyzed. Magnetite, hematite, ilmenite, maghemite, sphene and possible rutile were detected with the microprobe.

Primary oxides sometime show exolution lamellas with pairs of titanomagnetite and ilmenite which might give information on oxygen fugacity and temperature of the last equlibration of the cooling rock, given they have not suffered from exstensive alteration.

Most oxides fall within the compositional range of ulvöspinel-magnetite series but other oxides have a composition close to pure ilmenite. Sphene was found and possible rutile, both minerals as alteration products of Fe-oxides.

Pyrite is found troughout the well and simply represents volcanic input or flux of sulfur in the hydrothermal fluid. Aquifer pyrite are mature or euhedral indicating sufficient amount of sulfur from hydrothermal fluid and growth in a void sufficiently large.

Deeper, where condition in the system are more reducing, pyrrhotite is also found. Even deeper Cu-sulfides like chalcopyrite were found and possible bornite. The first occurence of chalcopyrite coincides with alteration and breakdown of oxides, plagioclase and clinopyroxen as well as the formation of epidote and pyrrhotite. This reflects increased alteration and oxidicing conditions in the geothermal system. Further studies could reveal if the occurrence of chalcopyrite always coincides with chlorite-epidote alteration zone in Icelandic geothermal systems.

ER1-8

Resistivity from 73 Boreholes in the S-Hengill Geothermal Field, SW-Iceland, compared with Surface Resistivity Data and Alteration Minerals

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Studies of resistivity measured in boreholes in a high temperature system located in the southern part of the Hengill central volcano, SW-Iceland, are introduced. The last known eruption in the Hengill system occurred approximately two thousand years ago. Besides being in an active volcanic zone the S Iceland seismic zone reaches the Hengill area, providing additional fissures and fractures. For high temperature geothermal utilization permeability is of great importance in addition to the heat provided from the roots of the volcanic system given the ambient water supplies which have characterized the Hengill fields. Therefore clearly there are optimum conditions for geothermal utilization in the Hengill geothermal system where already two geothermal power plants are operated, i.e. at Nesjavellir and Hellisheidi. The former one is located in the northern part and the latter one in the southern part of the Hengill geothermal fields. The geothermal steam and water from the boreholes in this study are already partly utilized in the Hellisheidi power plant for electricity as well as direct use.

Over 70 boreholes have been drilled from 1994 to the present in the southern part of the Hengill area. In the presentation, resistivity logs from 73 boreholes in the high temperature field are compared to previously interpreted resistivity from surface measurements (TEM and MT) as well as to a preliminary study of alteration minerals.

Most of the boreholes in high temperature geothermal fields in Iceland are drilled in 3 main sections. Here the available resistivity logs from each section of the wells in the S-Hengill area are combined into one log for each well. These as well as the previously interpreted resistivity model from TEM and MT electromagnetic soundings are inserted into the Petrel software, where the resistivity well logs are averaged to the same resolution as the TEM and MT data. In a recent study well logs from 9 boreholes were studied, whereas here all of the 73 analyzed boreholes are included. The data are inserted into Petrel along the well paths, making it possible to view them in 3D. Looking at a graph with parameter against depth it is possible to select the measured depth i.e. the length along the well path (MD), the vertical depth and to use sea level as a reference. An excellent beginning of analyzing and comparing data is to view the well logs and "pseudo logs" side by side on a similar depth scale and on top of them the markings of the first appearance of the alteration minerals.

In the previous resistivity model from TEM and MT, a high resistivity rock sequence overlies a low resistivity one (cap rock), below which a higher resistivity formation appears. The variation in resistivity was described as being due to the different conduction of alteration mineral assemblages, mostly influenced by the one that produced the highest alteration grade at each depth interval. The comparison between the resistivity from the surface TEM and MT soundings and the resistivity logs shows a good match in many of the wells. A further comparison with alteration zones in the wells also shows that the onset of the smectite zeolite zone correlates relatively well with the lowering of the resistivity, and that the top of the underlying high-resistivity correlates also relatively well with the onset of chlorite alteration.

ER 2 – CO_2 sequestration

ER2-01

Mapping and Estimating the Potential for Geological Storage of CO_2 in the Nordic countries – a new project in NORDICCS

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ORAL ER 2

To reduce human impact on climate changes in the near future it is considered necessary to reduce CO_2 emissions from fossil fuel combustion. This fact has intensified research in methods capable of reducing emissions substantially and one of the methods being looked into is carbon capture and storage (CCS). CCS could relatively fast help to reduce CO_4 emissions form large point sources e.g. power stations, because the technology builds on already existing knowledge from oil and gas production. To be prepared for a possible future implementation of CCS it is, however, important to know where and how much CO_2 can be stored in the sub-surface.

Several EU co-funded projects has mapped the potential for geological storage of CO_2 in Europe, beginning with the Joule II project in 1993, estimating a total storage capacity of 800 giga tonne (Gt), to GeoCapacity estimating a total storage capacity of 360 Gt in 2009. The results from these projects concluded that EU has sufficient storage capacity to store the yearly emission of CO_2 of 1.9 Gt from large stationary point sources. The European projects mapped and estimated the potential storage for hydrocarbon fields, not-mineable coal beds and saline aquifers. The GeoCapacity project concluded that the aquifers have by far the largest storage capacities with a total capacity of 325 Gt. The European projects only included two Nordic countries (Norway and Denmark) and a unified database covering all of the Nordic countries does not exist.

It is clear, that the very different geology of the Nordic countries reflects the variation in CO_2 storage capacity, from the old basement rocks beneath Finland and most of Sweden, across the Caledonian mountains on-shore Norway, the large sedimentary basins in the sub-surface of Denmark and off-shore Norway to the active rift zone in Iceland. This was recently illustrated in a research study comprising an overview of the potential for applying CCS in the Nordic countries, where Finland and Sweden only had limited storage capacity; Denmark and especially Norway large CO_2 storage potential, and on Iceland the basaltic rocks offers the possibility to store CO_2 by mineral trapping, a method where the CO_2 is chemically attached to minerals in the basalts.

In November 2011, the Nordic countries research program - the Nordic Top-level Research Initiative (Nordic Innovation Center), launched NORDICCS - Nordic Competence Centre for CCS. One of the Centers major tasks is the creation of a Nordic CO_2 storage atlas. NORDICCS will build a database of geological information on potential storage sites, improve methods to quantify storage capacity and defining criteria to characterise a safe storage site. Further the option to store CO_2 in basalts will be considered and potential areas mapped.

ER2-02

CO_2 Storage Atlas, Norwegian part of the North Sea

Eva Halland

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Several previous studies have shown that it may to be possible to store large amounts of CO_2 on the Norwegian continental shelf. To get a better idea of where CO_2 can be stored in the Norwegian North Sea, and how much CO_2 that can be stored, a team in the Norwegian Petroleum Directorate (NPD) have used the last two years with CO_2 questions. A CO_2storage atlas is prepared, indicating the possible storage sites and estimated storage capacity. This atlas is published December 2011 and will be presented in my talk.

An active petroleum industry has collected a lot of data offshore Norway over the past 40 years; 2D and 3D seismic, drilled wells and reservoir data. NPD has access to all data collected on the Norwegian continental shelf (NCS). This give us a huge database to embark on. We are also fortunate to have more than 15 years experience with CO_2 storage in subsea reservoirs,(the Utsira Formation and from the Snøhvit field in Tubåen and Stø formations).

In our work we have evaluated the storage possibilities in large saline aquifers, defined structures, abandoned fields, and the use of CO_2 in producing fields to enhance recovery.

With a success rate for hydrocarbons at around 50% on the NCS, around 50% of exploration wells have been proven dry. An assessment of why, has provided us with an interesting number of structures, in terms of CO_2 storage.

Though aquiferes that seems to be most suitable for CO_2storage is not always where the highest petroleum activities are, we could draw on a lot of geological knowledge and a lot of reservoir data from similar formations in order to calculate the storage capacity.

It is essential to define at which level the storage sites and volume estimates can be presented. We established a CO_2 maturation pyramid with 4 levels. We also establish a set of criteria that has to be met before a CO_2 storage site can be recommended. A set of criteria was established, covering both critical factors for reservoir properties and sealing properties.

Safe storage has been our focus, and an evaluation of critical parameters such as sealing, faults and old wells, how the CO_2 plume may be monitored in the reservoir and how potential leakage may be detected rapidly, has been important

ER2-03

CO_2 storage options in the Norwegian part of the North Sea

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The Norwegian Petroleum Directorate (NPD) will publish a CO_2 storage atlas of the Norwegian part of the North Sea in December 2011. The atlas will indicate the possible storage sites together with the estimated storage capacities. This talk will focus on the storage sites NPD has identified, showing the criteria and ranking of the sites.

The NPD has access to all data collected on the Norwegian Continental Shelf (NCS) providing us a huge database. The types of storage sites for CO_2 are saline aquifers, water-filled structures, abandoned hydrocarbon fields and producing fields. In our work we have used wells, seismic and special studies to identify formations/aquifers, structures and abandoned fields where CO_2 can be safely stored.

The Norwegian part of the North Sea contains many sandy formations in the depth of 800-3000 meters below seabed. The talk will give an overview of the possible aquifers and formations where CO_2 can be safely stored. Some of the formations have communicating volumes and these formations have been considered as aquifers.

When ranking the storage sites we have considered critical factors for reservoir and sealing properties:

1) Reservoir quality: capacity, communicating volumes and injectivity
2) Sealing quality: seal and fracture of seal
3) Other leak risks

Each of the above topics has been given a score together with an identification of the data cover (good, limited or poor).

NPD has established a CO_2 maturation pyramid with 4 levels. Each step in the pyramid represents different degree of knowledge and safety level. The bottom level gives a theoretical volume of storage while the uppermost level will be reached when the injection project of a specific site is feasible.

We will go through one of the formations/aquifers in detail showing the checklist for reservoir and sealing properties together with the ranking criteria and the maturation pyramid. The calculation of volumes will also be accounted for. We will also go into details for one water-filled structure.

ER2-04

Methods and experience in qualification of geological CO_2 storage sites.

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For an efficient qualification of a storage site for CO_2 defined criteria and a structured and risk based work process is key. In the qualification of Johansen as storage site for Mongstad a detailed work process was established.

The process is iterative, with each iteration triggered by the need for additional data in order to reduce storage site uncertainty and/or risk. Each cycle includes data collection and assessment, storage complex description, dynamic predictions, and uncertainty and risk assessment. Each finished cycle is concluded with a project status and ad assessment of further work. The idea behind the work process is that the same structured approach is used throughout the screening, storage site selection and site qualification phases of the project. Many of the basic elements are taken from the petroleum industry. However the focus is different on some key aspects. In storage site evaluation the geological assessment must cover the entire storage complex of which the reservoir is just a small central part, the pressure is expected to increase far above original, and the time horizon can cover 1000 years.

The geological models become extreme large and complex, geomechanic analyses and core testing requires improved methods and tectonic analyses are more central than used to elsewhere. New approaches and methods are gradually developed and tried out.

The qualification process is risk driven, aiming to reduce uncertainty and increasing the corresponding level of accuracy in storage complex dynamic forecasting. To aid this process an extensive risk process has been established with defined steps and methodologies to aid the quantification of risk and uncertainty. The level of acceptable risk and uncertainty is predefined for each development stage, and each potential site must meet the set criteria in order to proceed to the next development stage.

The risk/uncertainty evaluation contains elements from both exploration risking and traditional reservoir risking, and involves 4 main processes:

– Probability assessment
– Pore volume and pressure build-up assessment
– Pressure threshold assessment
– Plume migration and pressure conditions

The combined use of the work process and the risk/uncertainty process ensures that each potential CO_2 storage site is matured and evaluated against the same criteria. This will be an important tool for both storage site developers and competent authorities to ensure a common approach to storage site development.

ER2-05

Challenges with qualification of storage sites for CCS in deep aquifers

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In a feasibility study of Carbon Capture and Storage (CCS) safe storage of the captured CO_2 is the most important success factor. Failure to ensure and communicate safe storage will be a serious threat to implementation of CCS. In order to qualify deep saline aquifers for safe storage of CO_2, several challenges can arise.

Suitable deep saline aquifers may preferably be located in areas without hydrocarbon potential in order to avoid conflict with existing and future oil and gas industries. The amount of pre-existing data in such areas is however often limited (e.g. low well density). This makes it challenging identifying storage and sealing formations. This is experienced in the Johansen Storage Site project (potential site for the Mongstad CCS project) where the exploration area covers approximately of 3500 km^2. Only 40 % of this area is covered with exploration wells penetrating the Johansen formation.

To qualify a safe CO_2 storage site a sealing cap rock needs to be proven. In the petroleum industry the presence of a seal is proven with a single well, by the simple fact that oil or gas is found in a geological structure. Proving a sealing cap rock for CO_2 storage must be done by understanding lateral and vertical variations away from the well area and can therefore not be done by one single well.

It is important to determine how much the pressure will increase in the storage formation during injection and how the CO_2 will migrate within the storage complex. The lower the pressure increase, the lower the risk of leakage through cap rock, faults or old wells. The pressure increase is related to total connected pore volume. Thus understanding the pressure communication within the storage complex and to surrounding segments and formations is important. Limited exploration data gives large uncertainties in the estimation of connecting pore volume.

A large geomodel based on limited well data is often the end result when doing such a feasibility study. A large geomodel also leads to challenges related to the level of detail in the geological description, and in achieving an effective reservoir model. It is also important to decide what areas should be included in the 3D grid and what areas could be modeled as boundary effects. One approach is to make a set of models tailored to explore the different mechanisms for CO_2 storage.

To get a good understanding of the uncertainties and risks related to a specific storage site, a risk analysis should be set up. A risk analysis should visualize the need for possible new data to further mature and ultimately qualify the CCS storage site. The aim of such an analysis is to have a systematic approach when handling and ranking the various uncertainties, both to establish a statistical distribution of the outcome, and as a guideline to focus the workforce on the most critical uncertainty parameters. A risking process will also be an important tool in concept selection between several storage sites.

ER2-06

Time-lapse analysis of pseudo-3D seismic data from the CO_2 storage pilot site at Ketzin, Germany

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Capture and geological storage of CO_2 is considered to be a feasible method for reducing carbon emissions. In April 2004, a research pilot project in German town of Ketzin started as the first onshore CO_2 storage test in Europe, and the main objectives of the project were to (1) advance the understanding of the science and practical processes involved in underground storage of CO_2 into a saline aquifer as a means of reducing greenhouse gas emissions, (2) build confidence toward future European CO_2 geological storage, and (3) provide operational field experience to aid in the development of harmonized regulatory frameworks and standards for CO_2 geological storage. Injection started in June 2008 and until the last repeat survey in February 2011 around 45, 000 tons of CO_2 had been injected into a saline aquifer of the Triassic Stuttgart Formation at approximately 630 m depth. Seismic monitoring methods that have been applied at the Ketzin site are comprised of baseline and repeat observations at different scales in time and space. Here are presented time-lapse results from pseudo-3D seismic data measurements at the Ketzin site, which were acquired to link down-well surveys with 3D surface seismic surveys. The main objectives of the "star"surveys were (1) to identify changes in the seismic response related to the injection of CO_2 between the repeat surveys and baseline survey and (2) to compare these results with those from the 3D seismic data. The time-lapse analysis presented here has shown that the time-lapse signature related to the CO_2 injection, i.e. a reflectivity increase centered around the injection well within the Stuttgart Formation, is observable in both pseudo-3D repeat data sets. The results are consistent with the 3D seismic time-lapse studies over the injection site and show that the sparse pseudo-3D geometry can be used to qualitatively map the CO_2 in the reservoir at effort and cost significantly less than the full 3D surveying. The last repeat survey reveals preferential migration of the CO_2 to the west, indicating that the lateral heterogeneity of the Stuttgart Formation strongly affects the plume geometry. Both repeat surveys show that the CO_2 is being confined within the aquifer, implying that there is no leakage into the caprock at the time of the repeat surveys. The same observation was obtained from the 3D data.

ER2-07

On uncertainties in estimating the long-term potential for CO_2 mineral storage

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CO_2 injected in the subsurface reacts with the host rock or sediments to form stable mineral carbonates. Such conversion reactions are commonly slow, and the complete potentials to form carbonates are estimated to require hundreds to thousands of years. Understanding the long-term potential for CO_2 mineral storage requires numerical models including the thermodynamics and kinetics of complex mineral assemblages. We here present errors of simulations mainly related to how mineral rates are expressed in numerical simulations, and uncertainties in parameters required to estimate rates (e.g., reactive surface areas, temperature dependence, rate constants, affinity dependence).

Mineral reaction rates have commonly been calculated using one mathematical expression with an affinity term binding together dissolution and growth rates. The expression has been based on a transition-state-theory (TST) relating dissolution and growth to the bulk surface rather than individual surface units such as kinks and spiral dislocations, and use of it leads to rapid growth even at low temperatures and low super-saturations. This contrasts to laboratory growth rates that are generally orders of magnitude slower than predicted using the TST-bulk-surface expressions. Moreover, laboratory experiments show that the apparent activation energy for growth is much higher than for dissolution of the same minerals.

The largest uncertainties in the kinetic expressions are rate coefficients for nucleation and growth and parameters relating rates to surface areas. Nucleation rates of carbonates are mostly unknown whereas growth rates are only known for a few carbonate minerals. The uncertainty in the timing and extent of carbonate growth may however still be low if the overall conversion reactions are constrained by slow dissolution of the primary reservoir phases. Reactive surface areas have been identified as the single factor with most uncertainty. The reactive surface area is a fraction of the total surface area, and depends not only on the crystallography of the mineral, but also on the reaction history of the mineral assemblage. For example, natural `aged` minerals commonly weather 1-3 orders of magnitude slower than freshly crushed minerals in laboratory experiments.

Finally, the uncertainties in modeling the exact secondary mineral assemblage and the timing of growth are large, but features such as the total potential for carbonate growth in a given setting mainly depends on the primary mineral assemblage and can be estimated with high certainty.

ER2-08

Flux rates for water and carbon during greenschist facies metamorphism estimated from natural examples of carbon sequestration

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The time-averaged flux rate for a CO_2-bearing hydrous fluid during greenschist facies regional metamorphism was estimated to 10 -10.2 ± 0.4 m3.m-2.s-1. This was evaluated by combining 1) Peclet numbers obtained by chromatographic analysis of the propagation of reaction fronts in 33 metamorphosed basaltic sills in the SW Scottish Highlands, 2) empirical diffusion rates for CO_2 in water obtained by Wark & Watson (2003), and 3) calculated time-averaged metamorphic porosities. The latter were calculated using an expression obtained by combining estimated Peclet numbers with the empirical porosity - permeability relationships obtained by Wark and Watson (1998) and Price et al. (2006) and Darcy's law. This approach which utilises natural carbon sequestration in metabasaltic rocks yielded a time-averaged metamorphic porosity of 10-2.6 ± 0.2 for greenschist facies conditions. The corresponding timescale for metamorphic fluid flow was 103.6 ± 0.1 years. By using mineral assemblages to constrain fluid compositions, I further obtained a time-averaged annual flux rate for carbon of 0.5-7 mol-C.m-2.yr-1. This matches measured emission rates for metamorphic CO_2 from orogenic hot springs. These fluxes significantly exceed estimated rates of CO_2 drawdown by orogenic silicate weathering and therefore indicate that orogenesis is a source rather than a sink of atmospheric CO_2.

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ER2-09

The CarbFix project – Mineral seqestration of CO_2 in basalt

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Carbonate minerals provide a long-lasting, thermodynamically stable, and environmentally benign carbon storage host. Mineral storage is in most cases the end product of geological storage of CO_2. The relative amount of mineral storage and the rate of mineralization depend on the rock type and injection methods. Rates could be enhanced by injecting CO_2 fully dissolved in water and/or by injection into silicate rocks rich in divalent metal cations such as basalts and ultra-mafic rocks. The CarbFix project [1] aims at mineral sequestration of carbon in southwest Iceland and will start injection in early 2012. Carbon dioxide and H2S gas mixture will be fully dissolved in meteoric water and injected into basaltic rocks. The initial test injection will contain 0.07 kg/s of the CO_2-H2S mixture dissolved in about 2 kg/s of water. The gas-water mixture will be pumped into the injection well, at 25 bar total pressure and 350 m depth. The pH of the water after dissolution at 25 bar in-situ gas pressure is estimated to be 3.7 and the dissolved inorganic carbon concentration (DIC) to be ~0,7 mol/kg. As the CO_2 charged waters percolate through the rock the dissolution of mafic minerals and glass will consume the protons provided by the carbonic and sulfhydric acids. As a result of these dissolution reactions, combined with dilution and dispersion the pH of the injected water will rise and alkalinity will increase. Concomitantly, the concentration of dissolved elements will increase and alteration minerals will form, resulting in mineral fixation of carbon. Conservative tracers and ^{14}C labelled CO_2 will be mixed into the injected gas and water stream to monitor the subsurface transport and to constrain the carbonate mass balance. If successful, the experiment will be up-scaled.

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ORAL
ER 2

ER2-10

Dissolution rates of plagioclase feldspars as a function of mineral and solution composition at 25°C

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ORAL
ER 2

Feldspars are the most abundant mineral in the Earth's crust and plagioclase is the most abundant of these feldspars. Plagioclase dissolution is therefore a major, and at times dominant, contributor to global weathering rates of silicate rocks. Furthermore, recent experimental work [1] suggest that plagioclase will play a major role during injection of CO_2-rich fluids into crystalline basalt. The dissolution of the basaltic minerals provides the divalent cations that combine with dissolved carbon to sequester carbon in carbonate minerals.

It is therefore surprising, how little work has been performed to systematically measure the dissolution rates of this mineral as a function its composition and the composition of the fluid phase.

Here we report on the dissolution behaviour of the plagioclases, the steady-state dissolution rates of distinct plagioclase feldspars, spanning the compositional range from albite to anorthite. The dissolution rates were measured in mixed-flow reactors at 25 °C as a function of pH from pH 2 to 11. The rates exhibit a U-shape behaviour; rates decrease with increasing pH at acidic conditions, then increase with increasing pH at basic conditions. Similar to past work [2, 3] plagioclase dissolution rates increase with increasing anorthite content at acidic conditions. In contrast, the present study suggests little effect of anorthite content at basic pH.

Interpretation of the dissolution rates of the plagioclase feldspars is challenging because this mineral tends to consist of finely intergrown albite rich and anorthite rich phases. To address this challenge, measured rates have been interpreted assuming the dissolving plagioclase is a mechanical mixture of two distinct end-member feldspars similar to that done recently for the dissolution of crystalline basalt [1].

The experimental results suggest that the dissolution of plagioclase at low pH leads to creation of additional reactive surface area, as the anorthite-rich lamellas dissolve at elevated rates within the plagioclase mineral, therefore, increasing the role of plagioclase dissolution during CO_2 injection into basaltic rocks.

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ER2-11

Reactive transport models of CO_2-water-basalt interaction and applications to CO_2 mineral sequestration

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CO_2 mineral sequestration in basalt may provide a long lasting, thermodynamically stable, and environmentally benign solution to reduce greenhouse gases in the atmosphere. Multi-dimensional, field scale, reactive transport models of this process have been developed with a focus on the CarbFix pilot CO_2 injection in Iceland. An extensive natural analog literature review was conducted in order to identify the primary and secondary minerals associated with water-basalt interaction at low and elevated CO_2 conditions. Based on these findings, a thermodynamic dataset describing the mineral reactions of interest was developed and validated.

Hydrological properties of field scale models were properly defined by calibration to field data using iTOUGH2. Resulting principal hydrological properties are lateral and vertical intrinsic permeabilities of 300 and 1700-10-15 m^2, respectively, effective matrix porosity of 8.5% and a 25 m/year estimate for regional groundwater flow velocity. Reactive chemistry was coupled to calibrated models and TOUGHREACT used for running predictive simulations for both a 1,200-ton pilot CO_2 injection and a full-scale 400,000-ton CO_2 injection scenario. Reactive transport simulations of the pilot injection predict 100% CO_2 mineral capture of within 10 years and cumulative fixation per unit surface area of 5,000 tons/km^2. Corresponding values for the full-scale scenario are 80% CO_2 mineral capture after 100 years and cumulative fixation of 35,000 tons/km^2. CO_2 sequestration rate is predicted to range between 1,200-22,000 tons/year in both scenarios.

The developed numerical models have served as key tools within the CarbFix project where they have strongly influenced decision making. The models were e.g. used as engineering tools for designing optimal injection and production schemes aimed at increasing reservoir groundwater flow in the pilot CO_2 injection Reactive transport simulations imply calcite to be the most abundant carbonate to precipitate but magnesite-siderite solid solution also forms in smaller amounts. Silicate precipitation is modeled to be associated with carbonate formation. Despite only being indicative, it is concluded from this study that fresh basalts may comprise ideal geological CO_2 storage formations.

ER 3 – Hydrology and hydrogeology

ER3-1

Groundwater in Öxarfjördur: origin and composition

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Groundwaters in the Õxarfjördur area NE Iceland have been studied during four years (2007-2010) and possible changes with time monitored. The groundwater system is rather complicated as there is a massive flow of fresh water from the high inland to the sedimentary through at Õxarfjördur as well as inflow of sea water from the coast. The main groundwater flow from the south is through the fissure swarms from the central volcanoes in the active zone of rifting and volcanism. Effluent water from the high-temperature geothermal systems connected to the volcanic systems to the south of the area also flows through the fissure swarms towards north. Consequently some of the groundwaters are luke warm, especially within the Krafla and Theistareykir fissure swarms. Volcanic activity in the Krafla central volcano in the seventies did increase both flow and temperature of the groundwater in the Õxarfjördur area, as well as changing the chemical composition.

The groundwaters in the Õxarfjördur area which are not affected by seawater inflow have very low mineralization (TDS of 50-80 mg/L). The fresh groundwaters are mostly of sodium-bicarbonate type and the luke warm ones are of sodium chloride type. The pH is generally 8-8.7, but highly alkaline waters with pH of 9.5 are also encountered, probably due to reaction with hyaloclastic subsurface rocks. The highly alkaline waters have enriched calcium concentration as compared to magnesium, but are classified as sodium-bicarbonate waters.

Trace elements are very low in concentration and mostly near to their detection limits. Some of the heavy metals showed a very constant concentration during the three years of monitoring. The concentration of Al, Fe, Zn and Cu were however varyable, probably due to environmental effects and contamination. Trace elements connected to geothermal activity like As and Hg have varyable concentrations both in the cold and luke warm waters. Their concentrations in the cold waters are often below detection limit.

The stable isotope ratios in the groundwaters are for δ^2H about -70 ‰ to -81 ‰ and for $\delta^{18}O$ about -10,1 ‰ to -11,5 ‰. In the local cold fresh groundwater in the Õxarfjördur area the values for δ^2H and $\delta^{18}O$ are approximately -73 ‰ and -10.5, respectively. Water from the glacial river Jökulsá and groundwater from the southern highlands have about δ^2H=-99 ‰ and $\delta^{18}O$=-14 ‰. The groundwaters are thus mostly a mixture of local waters and waters derived from higher altitudes in the south. Where there is a seawater component in the groundwaters they become considerably more enriched in ^{18}O and ^2H.

Minor seasonal changes were observed both in temperature and chemistry of the waters, mainly in the luke warm ones, probably due to different mixing rates of cold water with geothermal effluent water.

ER3-2

Groundwater and Geothermal Utilization

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Most Icelandic geothermal power plants are situated in areas where groundwater is abundant. Although the primary purpose is to generate electricity, some of the plants also produce hot water for space heating in nearby municipalities. That is done by heating cold groundwater. The largest geothermal power plants are located close to extremely permeable lava fields and the water is most often derived from the lavas. Cold groundwater is also used in large scale for cooling and dilution of discarded geothermal fluids.

In some cases excess geothermal fluids used at the plants percolates into the lava fields. In such cases the warm water floats upon the cold groundwater and pollutes the freshwater. This can be seen from temperature monitoring of freshwater issuing from natural springs as well as temperature profiles obtained from observation boreholes. In extreme cases wastewater is forming ponds of muddy water on the surface.

Several wells have been drilled in order to minimize the effects of wastewater from the power plants on the groundwater. Some of the wells are shallow; approximately 500 m, intended to flush the wastewater into inert aquifers lying beneath the cold groundwater. In other cases, deep wastewater wells have been drilled, reaching up to 3 km depth. Their purpose is to flush the wastewater into the geothermal system and thus prolong its live span. Such reinjection can occasionally cause earthquakes.

Methods to obtain enough freshwater for geothermal power plants are discussed as well as attempts to avoid serious contamination of ground water in the vicinity of geothermal power plants. Being a nature-friendly power resource, geothermal utilization is also obliged to be groundwater friendly. The definition of acceptable safety and pollution-free power plants might differ from one place to another.

ER3-3

In-situ stresses and fluid flow in fractures of crystalline bedrock – a case study at the site of a potential nuclear waste repository, Finland

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Determination of fluid flow pathways in rock masses plays an essential role in many modern geological applications, including hydrocarbon extraction and mineral exploration but is highly crucial in the planning and safety assessment of underground nuclear waste repositories. While it is widely acknowledged that only a small fraction of the total fracture population in a given rock volume has measurable conductivities, the underlying reasons for the conductivities of specific fractures are generally poorly known. Several mechanisms have nevertheless been proposed, including for example example shear dilation, low normal tractions and mineral precipitations.

A comprehensive geological database has been collected during investigations made at Olkiluoto Island, a site of planned high-level nuclear waste repository located in the crystalline bedrock of SW Finland. In our study, we used data collected from 48 diamond-cored drill holes with depths ranging from 400 to 1000 meters. From the drill cores, the orientations of both conductive and non-conductive fractures have been mapped in great detail and, in addition, flow measurements have been carried out in each drillhole, resulting in a unique data set to be used in further analysis of the hydraulic behavior at the site. In our study we used this fracture database, which contains a total of 38703 fracture observations, together with the flow measurements and detailed stress model of the site to investigate the influence of present day in-situ stresses on the distribution of the orientations of conductive fractures and measured transmissivity values.

The present day in-situ stresses at Olkiluoto indicate a thrust faulting regime, with the $\sigma 1$ orientation changing moderately as a function of depth such that in the upper part of the bedrock (0 to 300 meters depth) the mean orientation is approximately E-W, compared to an WNW-ESE orientation at approximately 300 - 500 meters depth and a reversion to E-W at depths below 500 meters. The relative magnitudes of the principal stresses also vary with depth; in the upper part of the bedrock a pure thrust regime prevails whereas with increasing depth, the stress state changes towards a more transpressive regime.

In order to test whether a relationship exists between the orientations of conductive fractures and in-situ stresses, we calculated the shear and normal tractions on all possible fracture orientations and visualized the results on equal area stereonets and then compared these with the actual distribution of the orientations of conductive fractures. Based on the comparison we observed that the orientations of conductive fractures display characteristic patterns attributed to low normal tractions as predicted by present-day triaxial stress state and, in addition, the highest transmissivities are also associated with the fractures having the lowest normal tractions. Our study therefore shows that the probable orientations and relative transmissivities of conductive fractures may by predicted by combining knowledge of the contemporary stress state with the analysis of the 3D-distribution of the values of shear and normal tractions. A prerequisite for the proposed analysis is however knowledge of the full stress tensor instead of relying on 2-dimensional approximations of the stress state.

ORAL
ER 3

ER3-4

The relative influence of temperature versus runoff on chemical denudation rate.

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Continental weathering and denudation is the most important process regulating the long-term carbon cycle and global climate. The distinct roles of runoff versus temperature in this process are challenging to identify because these two factors commonly co-vary, e.g. rainfall, and thus runoff, tend to increase with increasing temperature. The goal of this study is to gain insight into the relative roles of runoff and temperature on chemical denudation rates. Towards this goal the chemical denudation rates of eight catchments in NE-Iceland have been measured from analysis of river water compositions over a five year period. These rates have been used together with dissolution rate expressions developed from experimental measurements to distinguish the effects of runoff and temperature, independently, in this natural system. River catchments are taken to be analogous to laboratory mixed-flow reactors. Like the fluid in flow reactors, the loss or gain of each dissolved element in river water is the sum of that of the original rainwater plus that added from kinetically controlled dissolution and precipitation reactions. Basaltic glass is the dominant phase in the glacial river catchments. According to Gislason and Oelkers (2003) basaltic glass dissolution rates vary as a function of reactive surface area, temperature, saturation state and fluid composition. The reactive surface area, within each catchment, is related to runoff, while temperature affects through the Arrhenius term and the fluid composition. Chemical denudation rates were found to be linearly correlated to runoff. The linear correlation passed through the origin for all the river catchments which is consistent with the absence of chemical denudation in the absence of runoff. As such, a 1% increase in runoff increases chemical denudation rates by 1% in all studied catchments. For the case of the NE Icelandic rivers, measured water temperatures ranged from 0 to 16° C. A 16° C temperature increase will increase chemical denudation rates by a factor of 7 at a constant runoff. In contrast, instantaneous runoff in NE Icelandic rivers increased by as much as 250 fold from lowest to highest. These observations suggest that a 1 °C increase in temperature will have equal impact on chemical denudation rate as a 10% increase in runoff. Due to this large variation in runoff, it was the most significant factor influencing chemical denudation in our study area. It is clear that the degree to which temperature or runoff dominates variations in chemical denudation in other catchments will depend on the relative variation of these parameters.

Reference:

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ER3-5

Dissolution of volcanic riverine particulate material in seawater: Consequences for global element cycling

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The world's rivers transport material from the land to the oceans in dissolved form and as particulate matter. Although particulate fluxes dominate over dissolved fluxes for the majority of elements relatively little attention has been paid to the role of riverine particulate material, both in the fluxes of elements to the oceans and moderating global climate[1]. The degree to which riverine particulate matter plays a role in the compositional evolution of seawater depends on its dissolution rate after arrival in the ocean. Volcanic islands supply the most easily weathered material to the oceans and are an important component of the global suspended flux. However, the apparent dearth of original volcanic minerals in oceanic drill cores suggests that the dissolution of riverine particulate material in seawater may be an important component of land-to-ocean element fluxes. Iceland is particularly important when considering these processes as elevated mechanical weathering from volcanism and glacial erosion generates large volumes of riverine particulate material.

This study compares laboratory and field analyses of riverine particulate material in the Hvítá river and Borgarfjörður estuary system. Firstly, direct measurements of element release rates of riverine particulate material in seawater through a series of closed-system batch reactor experiments. Elements such as Si, Ca, Mn and Ba show marked increases in seawater concentrations, indicative of particulate dissolution. Other elements such as Li become rapidly depleted in seawater, suggesting element exchange reactions or the formation of secondary phases. Strontium and Neodymium display comparatively little change in seawater concentrations, but analyses of the radiogenic isotopic ratios $^{87}Sr/^{86}Sr$ and εNd show that there is considerable exchange between the fluid and solid phases. Secondly, field measurements of elemental concentrations and $^{87}Sr/^{86}Sr$ across the mixing zone of fresh and saline water in Borgarfjörður provides further evidence of partial particulate dissolution when mixed with saline water. Taken together these results demonstrate a significant role of seawater weathering of riverine particulate material to the fluxes of elements to the oceans. These findings have important implications for marine isotope budgets, as current scientific work looking at land-to-ocean fluxes assumes that riverine material (both dissolved and particulate) is conservatively transferred to the ocean. Based on the changes in isotopes measured in both field and laboratory studies, this assumption must be questioned.

[1] Gislason et al. (2006) Geology, 34, 49-52.

ER 4 – Ore deposits and fossil fuel

ER4-1

Archaean orogens in the North Atlantic craton and related orogenic gold mineralisation in southern West and South-West Greenland

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The North Atlantic craton of Greenland has no producing gold mine, although Archaean rocks cover the entire time span from > 3.6 Ga until ca. 2550 Ma and major accretionary tectonics affected the craton in the Neorchaean. In the recent years, gold exploration in the Godthåbsfjord has identified several gold targets, the most advanced being the Storø and Qussuk gold prospects. Prospects in the south, the Paamiut and Tartoq gold prospects, are less developed. In this paper, we present an overview of the regional orogenic evolution and link the geological history to the known and recently discovered gold occurrences.

The North Atlantic craton is divided into several terranes and blocks. These comprise belts of supracrustal rocks and/or anorthosite complexes that are intruded by tonalite-trondhjemite-granodiorite and minor volumes of late-tectonic granites. The rocks are metamorphosed at amphibolite to granulite facies grades. Greenschist facies metamorphism is restricted to localities around Isua and the Tartoq Group. Based on the tectonometamorphic and magmatic evolution, several orogenic events are recorded at ca. 2950 Ma (Isukasia orogeny), 2850-2830 Ma (Paamiut orogeny), 2760-2700 Ma (Tasiusarsuaq orogeny) and 2670-2580 Ma (Kapisilik orogeny). The so called "golden window"for the formation of orogenic gold deposits in accretionary settings lies mainly between 2720 Ma and 2620 Ma, which suggests that in particular the Tasiusarsuaq and Kapisilik orogenies could be related to gold mineralising systems.

In South-West Greenland two fold-and-thrust systems form a lateral and frontal ramp in the Tartoq and Paamiut gold provinces. The richest gold mineralisation is situated in the frontal ramp and at structurally complex sites along the lateral ramp. Gold mineralisation is favourably situated in second-order structures. The hydrothermal alteration occurred at or near peak metamorphic grades. The timing of mineralisation is not resolved but is bracketed by the metamorphic ages of ca. 2840 Ma and 2720 Ma.

The Tasiusarsuaq orogen is a northwest-vergent fold-and-thrust belt, where a high-grade gneiss terrane, the Tasiusarsuaq terrane, is imbricated resulting in a major terrane accretion event in the Nuuk region at ca. 2720-2700 Ma and back-thrusting further south in the Sermilik region at ca. 2740 Ma. Orogenic gold mineralisation is restricted to the Sermilik area in quartz veins and hydrothermal alteration zones in granulite facies wall rocks, hosted in the back-thrust system.

Major hydrothermal orogenic gold mineralisation is related to the final terrane amalgamation around 2670-2600 Ma, the Kapisilik orogeny. Several major gold occurrences are located close to the 2670-2600 Ma Ivinnguit fault. For example, the mineralisation at the Storø gold prospect has been dated at ca. 2630 Ma, and hydrothermal quartz veins in the Tasiusarsuaq terrane further south formed at ca. 2670 Ma.

In conjunction, at least two major orogenic events are now recognised that formed a suitable setting for hydrothermal orogenic gold mineralisation in the North Atlantic craton. The related structures, fold-and-thrust belts and major fault zones, are spatially associated with the larger orogenic gold occurrences. This relationship enables a better predictability during exploration.

ER4-2

Rock magnetic investigations constraining internal structures and relative timing for gold deposits in southern Finland

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Economic mineral deposits typically incorporate specific magnetic signatures that are widely used for prospecting purposes. Aeromagnetic anomaly investigations of the Geological Survey of Finland (GTK), coupled with other geophysical and geological surveys, have demonstrated that ferromagnetic minerals such as magnetite and especially pyrrhotite form one of the characteristic minerals of the gold-rich zones. In several occurrences in southern Finland it has been shown that pyrrhotite represents sulphidation related to gold mineralization.

We have studied three structurally controlled potential orogenic gold deposits in southern Finland (Jokisivu, Satulinmäki and Koijärvi), formed in different stages of the Svecofennian orogeny at ca. 1.9-1.8 Ga. Our main goal was to test the capability of anisotropy of magnetic susceptibility (AMS) and palaeomagnetic methods to provide new knowledge on internal structures of the deposits and to give some age constraints for the structurally controlled gold formation processes. For that purposes we have also carried out rock magnetic investigations to study the relationship between the magnetic minerals and the gold mineralization.

Magnetic mineralogy of the Jokisivu, Satulinmäki and Koijärvi shear and fault zones are dominated by monoclinic magnetic pyrrhotite that is mainly responsible for the AMS and is also the carrier of remanent magnetization. In Koijärvi, the other magnetic mineral is magnetite. In many samples magnetite has multi-domain grain sizes that do not carry remanent magnetization but do contribute to the AMS. Magnetite most likely represents the primary magnetic mineral of the rocks. Pyrrhotite is implied to be related to later hydrothermal events and to have precipitated simultaneously with gold. The degree of AMS is strong in all formations and the AMS foliation plane follows the overall trend of tectonic structures. In some cases the AMS data show exceptional results. In part of the samples from Satulinmäki the AMS is extremely high and may reflect excess of tectonic stress and/or fluid activity in some areas. In Jokisivu, the AMS data shows deviating directions in the core of an auriferous shear zone. Consequently, based on directional parameters, it is implied that the central part experienced later auriferous fluid infiltration after the main orogenic stage.

We will show that combined use of AMS and palaeomagnetic investigations can be applied to obtain additional information about the internal structures of gold deposits and to provide timing for the hydrothermal system relative to tectonic events.

ER4-3

Au-mineralization in the St. Jonsfjorden area, the West Spitsbergen Fold Belt, Svalbard

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Scree geochemical surveys in the 1980's which were conducted by Norges geologiske undersøkelse (NGU), Store Norske Spitsbergen Kulkompani AS and Norsk Hydro revealed Au anomalies in the West Spitsbergen Fold Belt, including the St. Jonsfjorden area. Follow up sampling in 1991 located Au-anomalous screes in the Holmeslettfjella, Copper-Camp, Motalafjella, Løvliejellet and Bulltinden areas. In addition, it was recognized that the Au mineralization was structurally controlled with highest Au values (up to 14 g/t) along thrust faults. Area was revisitedresampled by Store Norske Gull AS geologists in 2008 and 2009 and the Au-anomalies were confirmed. Furthermore, a few meters wide, outcropping pyrite-arsenopyrite-mineralized zone, with Au values up to 55 g/t in the grab samples, was located inat Holmeslettfjella along a thrust between the Vestgötabreen High-Pressure Metamorphic Complex and Bullbreen Group. In the other locations, Au-anomalous samples were subcrop, boulder or scree samples. In Copper Camp and Løvliejellet, the gold mineralization is related to the same thrust zone as in Holmeslettfjella with grab samples having Au values up to 25 g/t in the grab samples. In the Motalafjella and Bulltinden areas, the hosting thrust is the next major thrust SW from Holmeslettfjella. In addition, in the Bulltinden area, samplingthe location of the mineralized samples suggests that a normal fault to the SW side of the Bulltinden-Motalafjella thrust may also be gold mineralized.

In the Holmeslettfjella area, the gold mineralization is located along a NW-SE striking, about 45° SW dipping thrust. Gold mineralization is hosted by the Motalafjella Formation carbonate rocks and is related to quartz-carbonate-sericite-pyrite-arsenopyrite alteration and gold is refractory (5-20% cyanide leachable). Laser ablation study of arsenopyrite and pyrite confirmed the refractory nature of the gold. Based on the laser ablation study, the Au content of the fine grained arsenopyrite varies from a few g/t up to 1000 g/t with an average about 300 g/t. The rocks are strongly deformed and the samples with quartz-carbonate-sulphide fracture veins have the highest gold grades. In addition to Au and As, mineralized zones are variably enriched in As, Bi, Cu, Hg, Tl, Sb, and Te.

The ages of the rocks in the area range from Mesoproterozoic to Middle Silurian. Rocks have been deformed during the mid-Paleozoic Caledonian orogeny, and in mid-Paleogene (Eocene). The gold age of the gold mineralization is not yet known, but gold mineralized thrust structures have been active during Eocene deformation and NE directed thrusting, which are related to dextral transpression.

The current working hypotheses are: a) that the mineralization is late Paleozoic orogenic gold style related to the Caledonian orogeny, and the mineralization ishas been reworked during the Eocene deformation and formation of the West Spitsbergen Fold Belt, or b) the gold mineralization is Eocene orogenic gold style, or c) a variation of Eocene Carlin style of Au-mineralization in carbonate rocks over faulted Precambrian craton margin.

ER4-4

Gold and silver deposition in Reykjanes geothermal system, southwest Iceland

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Geothermal systems have been recognized for over a century to be the active analog of epithermal ore deposits. The Reykjanes high-temperature geothermal system is on a peninsula close to the ocean in southwest Iceland; the country is the only known location along the length of the Mid-Atlantic Ridge where the largely submarine rift is exposed on land. Reykjanes is a seawater-dominated system with reservoir temperature between 295 to 320°C. Liquid collected at depths of 1350 - 1500 m and 284-295°C, prior to boiling, contains 36-107 µg/kg of Ag and 1-6 µg/kg of Au. Scales were collected at ~700 m to 140 m depth in one of the high-pressure wells (~35 bar at wellhead; 243°C). The scales contain 35 mg/kg Ag at 700 m depth, increasing to 580 mg/kg at 150 m depth; gold concentrations in scale at the same depths ranges from 80 to 125 mg/kg. The silver content of scales in surface pipelines ranges from 100-400 mg/kg at high-pressure (~40 bar), up to 23,000 mg/kg at 22 bar. Gold concentrations in surface scales at high pressure is up to 450 mg/kg, up to 590 mg/kg at 22 bar, and up to 950 mg/kg only few centimeters further downstream, just past the point of sharp boiling and extreme vapor loss.

ER4-5

Oxygen isotope and geochemical constraints on the genesis of the Grängesberg apatite-iron oxide deposits, Bergslagen, Sweden

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The apatite-iron oxide ores in the Grängesberg region, including its northern continuation at Blötberget, represent the by far largest iron ore accumulation in the classic Palaeoproterozoic Bergslagen ore province in central Sweden. Overall, their mineralogy, geochemistry, geometry and host rock relations suggest that they belong to the Kiruna-type of iron oxide deposits.

At Grängesberg, our geochemical data show systematic similarities between ores and variably altered host rocks. Particularly REE patterns of ore-associated alteration assemblages directly mimic those of the apatite-iron oxide ores. They feature high REE contents and similar spider diagram profiles, thereby linking alteration with oxide ore formation. Hence, a hydrothermal component of ore formations is suggested.

The Grängesberg ores exhibit δ18O between -0.4 and +4.9 per mil (V-SMOW), whereas the metavolcanic to metasubvolcanic, c. 1.90-1.87 Ga host rocks exhibit δ18O between ca. +5 and +10 per mil. Our ore datasets partly overlap with published data from the Kiruna deposit, as well as with young Chilean deposits of a comparable type (Nyström et al. 2008), and therefore suggest that the Grängesberg deposits have essentially preserved their primary isotopic character through later overprinting events including regional (Svecokarelian) metamorphism.

A majority of host rock δ18O thus plot within the normal spectrum of igneous rocks. However, most iron oxide ore samples from two drill cores transecting the ore exhibit lighter δ18O, with magnetite ores ranging between +0.2 and +3.4 per mil. This range is consistent with fractionation of oxygen into magnetite in a felsic to intermediate magma at high temperatures (Taylor 1967). The lighter values can be explained by either (or a combination of both) later oxidation of the ores and a hydrothermal process of formation, involving mainly non-magmatic water(s).

The relatively wide variability in δ18O in otherwise similar alteration assemblages is notable, particularly in comparison with the iron oxide ores. Still, it is obvious that later tectonic processes and associated fluid-mediated alteration overprint has affected some of these zones. However, we suggest that subsequent events only marginally affected the isotopic composition of the magnetite ores and that they represent a robust δ18O buffer. The light δ18O associated with the massive iron oxide ores do contrast the data from the metavolcanic host rocks, but a majority can be directly related to oxygen isotope fractionation at high temperature between a rhyolitic to andesitic melt and magnetite.

Based on these isotope systematics, in combination with geochemistry and geological observations, we conclude that the formation of the apatite-iron oxide ores in the Grängesberg district included a hydrothermal component. Nevertheless, the available evidence does not rule out a major mechanism of orthomagmatic ore formation for these deposits, and part of the isotope dataset is most easily explained by such a process.

References:

Nyström, J. O., et al. 2008: Oxygen isotope composition of magnetite in iron ores of the Kiruna type in Chile and Sweden. GFF 130, 177-188.

Taylor, H. P. 1967: Oxygen isotope studies of hydrothermal ore deposits. In: Geochemistry of hydrothermal ore deposits, 109-142.

ER4-6

The role of D2 for the structural architecture of the apatite-iron oxide deposit at Grängesberg, Bergslagen, Sweden

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The only known apatite-iron oxide mineralisations in southern and central Sweden occur between Grängesberg and Idkerberget in the western part of the Bergslagen, where they constitute the largest iron oxide concentrations. The ores are hosted by rhyolitic to andesitic metavolcanic rocks intruded by later subvolcanic rhyolitic to basaltic dykes.

On aeromagnetic maps the narrow and elongated zone of apatite-iron oxide mineralisations appears as an undulating, NE-SW-trending anomaly. This undulating pattern is related to D3 open folds formed during late-Svecokarelian N-S convergence. The magnetic anomaly can be traced continuously between Grängesberg and Blötberget, and north of Blötberget an inferred later fault terminates ore zone. Whether the Idkerberget deposit represents the northward extension or a separate occurrence is not yet resolved. Three deformation phases have been recognised. D1 is most pronounced in metasedimentary units, and appears as upright to inclined isoclinal folds. In the metavolcanic rocks, D1 is mainly expressed as steep to moderately east-dipping crenulation cleavage.

The Grängesberg ore occurs as a number of closely spaced, planar, lens-shaped bodies separated by phyllosilicate-rich zones and variably altered metavolcanic rocks. The mineralisation is c. 1 km long, dipping moderately to the east, and extends to a depth of at least 1.7 km. The structural imprint of D1-D2 is dominated by intersecting foliations, where the angle between S0, S1 and S2 is generally small. Intersection lineations between these foliations are well developed, causing a pencil cleavage. This cleavage was interpreted as a strong stretching feature (Geijer & Magnusson 1944). A local stretching is evidenced by elongated clasts that are flattened and stretched parallel or sub-parallel to the SE plunging lineation. However, prolate D2 strain is focused to the tapering edges of competent bodies, including the apatite-iron oxide mineralisation itself and a small granitic intrusion located adjacent to the ore. In contrast, an L>S fabric is prevailing in the regional, coarse-grained granite in the hangingwall. Kinematic indicators show oblique sinistral dip-slip shear with a top-to-the-NW vertical component emplacing the granite on top of the mineralisation. In the footwall, kinematic indicators are scarce but orientation of the localised stretching lineation is in agreement with a top-to-NW movement. Tight asymmetrical F2 folds are frequent. The location and attitude of these folds are controlled by the competence contrast of the various rocks, illustrated by opposite vergence at the boundaries of competent bodies which act as tectonic lenses. Strain is also accommodated along phyllosilicate-rich zones accentuating the role of competence contrasts for the development of various structural elements. The later D3 had minor impact on the structural style.

The structural expression shows that the competence contrast during D2 is central for 1) strain partitioning, 2) the development of the lens-shape geometry of the ore bodies, and 3) localisation of shear and sites of stretching. It also shows that that the character of tight F2-folds is a local phenomenon, and that D2 is related to reverse movements on a larger scale.

Reference:

Geijer P. & Magnusson N.H. 1944: De mellansvenska järnmalmernas geologi. Sveriges geologiska undersökning, Ca 35.

ER 5 – Petroleum provinces of the NE Atlantic region

ER5-1

Spatial occurrences of selected sandstone bodies in the De Geerdalen Formation, Svalbard, and their relation to depositional facies

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The De Geerdalen Formation (Upper Triassic) has been studied in three different localities in Svalbard with the aim of investigating spatial distribution of sandstone bodies and their relation to the depositional environment. The sandstone bodies of the De Geerdalen Formation are the equivalent to the Snadd Formation, a reservoir unit in the Barents Sea, and it has therefore been of interest to improve the understanding of sandstone body geometry and distribution.

Lidar (Light detection and ranging) data has been a main tool in lateral and geometric data acquisition. Detailed sedimentological logging and facies analysis were the basis on which the geometric information was evaluated. The interpretation of the depositional environment proved more certain with the support of the spatial information.

Various depositional elements interpreted from their facies architecture and their geometry reflect a setting of deltaic nature affected by river-, wave- and tidal processes. In all localities there is an upward shallowing and upward coarsening trend. The southeastern localities at Edgeøya (Klinkhamaren and Slåen/ Siegelfjellet), reflect a proximal environment, of a fluvially dominated delta front. To the northwest, at Botneheia, Central Spitsbergen, the deposits are more reworked and display signs of tide and wave modulation. As deltaic signals are present, the depositional environment is interpreted as a wave influenced distal shelf/prodelta.

Prediction of sandstone distribution can be performed with some control on the depositional environment. In a fluvially dominated delta setting the sandstone bodies are often voluminous. Laterally connected to the voluminous sandstone bodies are thinner laterally extensive sandstone units, yielding good connectivity for a potential reservoir. In a more distal setting with wave domination the sandstone bodies tend to be thin, but laterally continuous, yielding a far less voluminous reservoir.

ER5-2

History of geology and research of the Jan Mayen Micro-Continent and associated exploration risks.

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The Jan Mayen Micro-Continent has been researched since the early 1970´s, especially in regards to its role during the opening history of the North Atlantic. Of special note are the detailed studies of the Jan Mayen Ridge (JMR) between 1985 and 1992 during a joint project between the National Energy Authority of Iceland (NEA), the Norwegian Petroleum Directorate (NPD), and the University of Oslo. In preparations for the first and second licensing rounds on the Icelandic continental shelf in 2009 and 2011, a structural and geological study was initiated with the aim to include more recently acquired data over the area in comparison with known interpretations and publications, to support the NEA during their licensing work. Newly acquired data sets have been incorporated, such as 2D seismic data, high resolution bathymetry, velocity estimates, and seafloor samples, as well as applicable research, in particular concerning the timing of the North Atlantic Opening and the Jan Mayen Fracture Zone. A review of seismic- and OBS-velocity data were included to tie the model to depth, and estimate possible ties to pre-Tertiary formations, outline the basement of the JMR, and, in particular, assist the interpretation of the volcanic formations within the ridge. The results of this study establish a basis for a re-evaluation of the JMR, defining its hydrocarbon potential and describe the exploration risks.

ER5-3

Potential petroleum systems offshore northeast Greenland and outer Vøring margin from conjugate margin studies

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Exploration offshore mid-Norway has resulted in the discovery and development of large oil and gas fields on the Halten and Dønna terraces and the deep water Ormen Lange gas field. Nearly 300 wells have been drilled in this mature area. In addition, several oil and gas discoveries have been made in the deep water Vøring and Møre basins where less than 20 wells have been drilled. Exploration has recently extended into the frontier sub-basalt areas in the western Møre and Vøring basins. In contrast, the petroleum potential offshore northeast Greenland is poorly known due to limited exploration. Seismic acquisition was initiated by the Kanumas Group in the early 1990's and additional surveys were acquired by AWI in the period 1999-2003 and Norsk Hydro (now

Statoil) in 2006. Whereas the Kanumas and Statoil data remain proprietary, recent TGS airborne magnetic/gravity surveys, new TGS seismic data and TGS reprocessed AWI seismic data offshore NE Greenland provide new insight into the crustal architecture and structure of the sedimentary basins offshore northeast Greenland. The geology of the sedimentary basins onshore East Greenland have been studied by the scientific community and oil companies for decades; however no stratigraphic information exists from the offshore areas. Interpretation of stratigraphy and seismic sequences is based on extrapolation of onshore geology and by analogy to seismic interpretations in the Vøring and southwest Barents Sea basins. Seafloor samples collected offshore northeast Greenland and on the Jan Mayen Ridge by TGS/VBPR in the summer of 2011 adds important stratigraphic data and information on potential petroleum systems for the upcoming Icelandic and Greenlandic licensing rounds. The continental margins offshore mid-Norway, southwest Barents Sea and northeast Greenland, and the Jan Mayen Ridge, share a common geological history leading up to breakup in the earliest Eocene. Integrating interpretations from the conjugate margins is therefore important for understanding the petroleum systems. Structural interpretations and gravity/magnetic anomaly maps restored to breakup are useful in delineating basins and highs across the conjugate margins prior to seafloor spreading. Whereas data and knowledge from geology onshore northeast Greenland and offshore the mid-Norway margin may be used to assess the petroleum potential on the northeast Greenland shelf, the structure offshore northeast Greenland may be important in assessing the potential for petroleum traps beneath the flood basalts on the outer Vøring margin.

ER 6 – Environmental Impact and Challenges

ER6-1

Challenges managing environmental impact assessment of geothermal projects

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The regulatory framework in Iceland plays an important role in planning of geothermal projects. Often in the case of potential geothermal areas limited research has been carried out on the capacity of the geothermal resources. Before planning of research or development, geothermal areas will already have been recognized by preliminary field assessment and research, including geological mapping and sampling. Development permits, utilisation permits and permits for operation of the power plant can be issued when the project has been accepted by the Planning Agency after environmental impact assessment (EIA) has been carried out. In some cases plans must be changed or new plans prepared.

It is impossible to plan and prepare a geothermal power plant without the drilling of exploration wells, as this is necessary for further research and modelling on the capacity of the geothermal resources. In some areas the developer must carry out an environmental impact assessment in on exploratory drilling. In Iceland developers are responsible for the EIA and bear the cost. The developer also pays for most of the research on the geothermal resources and collecting necessary environmental data.

Certain types of landscape and habitats are specially protected according to Icelandic law. Amongst these are hot springs and other thermal sources, surface geothermal deposits, volcanic craters and lava fields - all of which are frequent features in high temperature geothermal areas. The time it takes to obtain consent from the authorities depends not only on official policy ore lack of it. Other determining factors are what plans already exist on development and nature conservation in the area as well as what environmental data is available.

Decisions on the feasibility of exploitation are based on the results of exploration drilling. It can be difficult to assess the environmental impact of exploitation at the exploratory stage because of the authorities' demand for detailed information from the developer. At certain locations requirements for an EIA of the exploratory stage as well as exploitation leads to a repeated EIA process with extra expenses and delayed project development. In most cases the developer is not ready to present an EIA of both stages in the same environmental report, because the information gathered during the exploratory stage is required for assessing the effects of exploitation.

The question has been raised on whether the environmental impact of exploitation could possibly be assessed before accepting a project of drilling exploration wells. This could prove difficult because of uncertainties in predicting impacts and the authorities' demand of detailed environmental information before any drilling has been carried out. EIA at the exploratory stage is a great challenge and should perhaps not be the responsibility of the developer.

It is important to develop a simple and flexible regulatory framework in Iceland because of the special nature of geothermal projects. This will enable authorities to make decisions on where to permit exploration and exploitation of geothermal resources at an early stage of project planning. The question is whether authorities should not themselves carry out a preliminary EIA before granting exploration permits - especially in disputed areas. This would prevent developers from performing costly investigations during the early exploratory and EIA stages. When a decision has been made to utilize a geothermal field including construction of a power plant the project should not need to be subject to repeated processes of EIA, planning and permit applications, as has been the case of some geothermal projects in Iceland.

ER6-2

Using benthic foraminifera as bioindicators of pollution in the SW Barents Sea

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The SW Barents Sea is experiencing an increase in petroleum activities. Exploitation of the Snøhvit gas field has started and production at the Goliat oilfield will start in the near future. These activities may result in contamination of the environment with petroleum industry related pollutants as polycyclic aromatic hydrocarbons (PAH) and heavy metals. The Northern Environmental Waste Management project (EWMA) at the University of Tromsø aims to develop a strategy for waste handling associated with petroleum industry activities in the SW Barents Sea.

As part of EWMA, the effect of enhanced anthropogenic activities in this area on benthic foraminfera and their use as bioindicators of pollution is being studied. At present, contamination levels are of background level (level I of the Ecological Status Classes of the EU's Water Framework Directive, WFD). Still, the pre impact benthic foraminiferal assemblages will serve as a baseline to future biomonitoring of any anthropogenic induced changes of the benthic environment in the SW Barents Sea.

In this study surface sediment samples (0-1 cm) have been collected from sites close to oil- and gas fields in the SW Barents Sea (e.g. Snøhvit) and more distal sites (Tromsøflaket and Ingøydjupet). In addition samples from the polluted Hammerfest harbor were collected. A Rose Bengal ethanol mixture (1 g/l) was added to the samples directly after sampling to stain living foraminifera. After sieving over a 100 µm mesh a minimum of 300 living specimens was picked from the wet sample and identified. In addition the grain size, polycyclic aromatic hydrocarbons (PAH) and heavy metal content of the samples was analyzed.

Since contamination rates in the samples from the SW Barents Sea are of background level (EU's Water Framework Directive, WFD, level I), it is not surprising that differences in benthic foraminiferal assemblages only reflect the natural environmental conditions of the sample sites. Benthic foraminiferal assemblages in samples from the polluted (WFD level II to V; good to bad) Hammerfest harbor reflect the local variability of contaminant levels within the embayment. The surface sediments are barren for foraminifera in the most polluted parts of the harbor (WFD level IV-V). Opportunistic and deformed species were found in the less polluted areas (WDF level II-IV) of the embayment.

Ecological quality status classes, normally used in benthic macrofauna studies (Molvær et al., 1997), were calculated for the benthic foraminiferal assemblages of our samples. However, these are not in correspondence with pollutant levels. Therefore, separate ecological status classes, which can be used for bio-monitoring, based on benthic foraminifera need to be developed for the SW Barents Sea region.

Future work will include analyses of high-resolution sediment cores covering the last 100-150 years. The results will establish pre- and post-industrial records of sedimentary pollutants and benthic foraminiferal communities.

ER6-3

Anthropogenic pollutants in surface sediments of SW Barents Sea

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The petroleum activities are increasing in the SW Barents Sea providing a need for strategy for waste handling. The Northern Environmental Waste Management -project (EWMA) at the University of Tromsø is aiming to develop such a strategy to answer this need. As a part of EWMA the activities at the Department of Geology concentrate on advancing the knowledge on spreading of drill cuttings after the deposition and on the distribution and accumulation of pollutants in bottom sediments. The aim is also to fill major gaps in the knowledge of the current status of sea bottom contamination as well as to predict future pollutant loadings and related environmental consequences in the SW Barents Sea.

The objective is to study the characteristics of the modern bottom sediments in the SW Barents Sea including sediment sources and transport pathways and identification of areas of sediment accumulation. The relation between sediment grain size and pollutants in these accumulation areas are of special interest. In this study we analyzed a selection of sediment surface samples from SW Barents Sea collected at sites close to the oil- and gas fields (e.g. Snøhvit) and more distal sites by the Mareano project and Statoil. Grain-size analysis was performed by sieving (>63µm-1mm) and with Sedigraph (<63µm) in order to determine the proportions of clay and silt. XRD analysis of clay minerals (<2µm) was conducted and the contents of heavy metals, polycyclic aromatic hydrocarbons (PAH) and total organic carbon (TOC) were measured from the samples.

The results from the surface samples show overall low heavy metal contents (Level I of the Ecological Status Classes of the EU's Water Framework Directive). Heavy metal contents show correlation with the finer grain size (silt and clay) and partly with

TOC. The deposition of finer particles, heavy metals and TOC occur in deeper water depth associated with calm bottom water currents. PAH measurements indicate that 2 samples have possible petrogenic origin and 8 samples have possible pyrogenic origin where 8 samples have both petrogenic and pyrogenic origin. Future work will include analyses of high-resolution sediment cores for the last 100-150 years providing pre- and post-industrial records of sedimentary pollutants.

THEME: GEOSCIENCE AND THE SOCIETY: HAZARDS AND ANTHROPOGENIC IMPACT (GA)

GA 1 – Geohazards in the Nordic and Arctic regions

GA1-01

Landslide mapping activities and landslide products of the Norwegian Geological Survey

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Due to the uplift of the Scandinavian basement during the break-up of the North Atlantic Ocean, and multiple glacial cycles carving deeply incised valleys into the mountains, Norway is a country with extreme relief contrasts. Thick deposits of soft and sensitive marine clays and other poorly consolidated sediments today lie on- or near shore due to the isostatic rebound of Scandinavia after Pleistocene glaciations. The wide range of geological conditions and natural triggers results in multiple types of slope movements such as rock falls, rock avalanches, soil and debris slides, debris flows and quick-clay landslides. Due to the position of Norway along the eastern margin of the North Atlantic, predominantly westerly winds and the high relief resulting in orographic precipitation along the mountains coastal areas in Norway receive strong annual precipitations that locally exceed 4000 mm/a. This climatic setting adds to the unfavourable topographical and geological conditions responsible for many types of mass movements so that landslides are frequent phenomena. This goes together with the large spread of the Norwegian population which is living in most areas of Norway and almost all fjords have settlements. Together this exposes the Norwegian population and infrastructures to landslide hazards. Although relatively rare, catastrophic events such as rock avalanches and associated displacement waves in impacted fjords or lakes have claimed hundreds of lives in the past centuries.

The Geological Survey of Norway (NGU) is mapping unfavourable geological conditions which might result in landslide disasters in the whole country. This is done in collaboration with, and financially supported by, the Norwegian Water Resources and Energy Directorate (NVE), who is responsible at government level to assist municipalities in the prevention of disasters posed by landslides, floods and snow avalanches. Products are multiple and include databases on landslide incidents, unstable rock slopes prone to large rock slope failures, country-wide rock fall and debris flow susceptibility maps on a scale 1:50.000, Quaternary maps to characterize unstable deposits as well as near shore and submarine mapping of potentially unstable deposits. The intention of this contribution is both (1) to summarize the unique geological conditions which expose the Norwegian society to landslide hazards, and (2) to show how the mapping activities performed by the Geological Survey of Norway cope with this challenge by providing effective tools for decision making and land use planning.

GA1-02

Impacts of extreme weather events on infrastructure in Norway – the InfraRisk project.

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The 3-year project InfraRisk, funded by the Research Council of Norway, aims at understanding the impact of extreme weather events (EWEs) on the Norwegian transport infrastructure, more specifically roads and railroads, and thereby to contribute to the development of a culture of pro-active behavior with regards to mitigation against climate-induced natural hazards in Norway.

This shall be achieved by meeting the following objectives:

- To gain a more solidified understanding of how changing climate affects the frequency, intensity and distribution patterns of EWEs in Norway
- To identify current knowledge about the impact of EWEs on infrastructure in Norway
- To quantify the vulnerability and societal value of Norwegian infrastructure
- To investigate which mitigation measures that could be implemented in order to more effectively adapt to these types of events
- To develop a methodological framework for assessment of the total risk to infrastructure from the combination of EWEs
- To propose guidelines for pro-active behavior with regard to mitigation actions against climate-induced natural hazards.

The project is divided in four modules: A) Analyses of past and future changes in frequency and intensity of EWEs, B) Infrastructure exposure, vulnerability and mitigation measures, C) Value of infrastructure, risk assessment and decision making processes, and D) Synthesis: consequences, recommendations and outreach.

Five focus areas have been selected along main transport routes in Norway. The areas are selected to represent different topographic regions, different climate zones and to account for demographic differences within Norway

In addition to presenting the project, the presentation will show some of the results achieved within the first project year. In particular we will focus on long-term trends in the occurrence of EWEs in Norway, and what impact these may have on the occurrence of natural hazards such as snow avalanches, debris slides/flows, and rockfall. As precipitation seems to be the most important weather element, particular focus has been placed on estimates of threshold values for debris flows. All these are events that frequently cause interruption of transport routes in Norway, and thereby large economic losses.

GA1-03

Changes in snow-avalanche activity on selected paths in Northern Iceland and Western Norway highlighted by dendrogeomorphologic analyses

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Today 5 high temperature geothermal systems in Iceland are being exploited or explored by drilling to produce electricity. All these fields are located within active volcanic complexes. In Hengill in SW-Iceland 433 MW of electricity are being produced in two power plants at Hellisheiði and Nesjavellir. On the Reykjanes peninsula, 176 MWe are being produced in two power plants at Svartsengi and Reykjanes. In N-Iceland 60 MWe are installed in the Krafla volcanic complex and drilling and testing of new wells are being performed at Þeistareykir where at least 100 MWe are planned to be installed. The effluent from the power plants is re-injected into the ground partly in Krafla, Reykjanes, Svartsengi and Nesjavellir and completely at Hellisheiði. The purpose is twofold, to avoid pollution and to maintain the reservoir pressure.

Natural earthquake activity is common in all these fields and is monitored by the national seismological network of the Icelandic Meteorological Office. In addition local networks have been set up and operated by Iceland GeoSurvey and others, permanently in Krafla and temporary networks at Hellisheiði, Reykjanes and Þeistareykir. The purpose is to monitor earthquakes that might be related to drilling, borehole tests, production or reinjection.

Clear examples of induced seismicity have been found in Krafla, Reykjanes and Hellisheiði. The events occur in swarms that are usually connected to onset of injection, change in injection rate or stimulation activity in boreholes. An earthquake swarm observed at Reykjanes might also have been triggered by sudden pressure drop in the reservoir due to strongly increased production.

Most of these earthquakes are quite small and need a local network close the drilling or injection sites. In Hellisheiði, however, earthquakes with magnitude between 3 and 4 have been measured and felt in the village Hveragerði and the suburbs of Reykjavík in September 2011.

In February 2011 ISOR installed five seismic stations around a drill site at Hellisheiði during drilling of a 2 km deep injection well. Four pressure gauges were also installed in nearby boreholes. Shortly after a circulation loss was observed in the borehole an earthquake swarm was initiated that clearly defined the fault which the water was lost into. The fluid pressure increase caused by the circulation loss was less than 10 bars so obviously the fault was critically stressed prior to the drilling and the fluid loss triggered the earthquakes.

During drilling of the IDDP well in Krafla in 2009 the well penetrated the top of a magma layer close to 2 km depth. A total circulation loss was observed at the top of the magma, in a zone of very high temperature gradient. The circulation loss was followed by a swarm of microearthquakes most of them with magnitude between -0,5 and 0,5 and mainly above 2,2 km depth. The earthquakes started close to the bottom of the well and moved gradually to the side and upwards along an inclined plane. This plane is presumably a permeable fissure that connects the molten rock and the geothermal field and is a potential target for drilling.

Iceland GeoSurevy is a partner in a large European Project, GEISER, led by GFZ-Potsdam. It aims at research into induced seismicity related to geothermal energy production and defining measures to mitigate the effects of induced seismicity. For that purpose data from Iceland and several other places of known induced seismicity are analysed and modelled in the GEISER project.

GA1-04

Recent rock slide and rock avalanche activity in Iceland and its connection to climate change

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Large landforms made by huge mass movements from bedrock are quite common in Iceland. The most common of this type of landslides are rock slides, rock avalanches and large rock mass falls. These landforms are by far most common and largest in the older bedrock formations of Iceland, which date from the Late Tertiary and Early Quaternary. The mechanisms that have caused rock slides and rock avalanches in these areas are still far from being fully understood. The most likely explanation is thought to be an interaction between multiple factors such as; bedrock structure, glacial erosion, tectonic features, hydrology, groundwater level and climatic events, such as periods of extensive precipitation or snow melting. As Iceland is a country of high seismic activity, earthquakes probably play an important role in triggering these mass movements. Very few of these landforms have yet been dated but it is suggested that the rock slides and rock avalanches were most frequent during or just after the deglaciation of Iceland, in Late Weichselian and Early Holocene times, in areas where glacial undercutting left U-shaped valleys with gravitationally unstable slopes, prone to landslide events. At present rock slide and rock avalanche activity in these areas seems to be low and only few small landslides of this type seems to have occurred in the last 1000 years or since the settlement of the country. However, relatively fresh looking landforms of this type are common near the present cirque glaciers in the mountainous areas of Central North Iceland. Possible these date from the onset of the Neoglaciation in Late Holocene times or even the LIA and are in some way connected to recent climatic changes.

In the southern Iceland, in the vicinity of the active, glacier covered central volcanoes as the Eyjafjallajökull glacier, the Mýrdalsjökull glacier and the Vatnajökull glacier, quite a few rock slides and rock avalanches seems to have occurred during the last decades. The bedrock in these areas dates to the Late Quaternary and is composed of different layers of various types of breccias and hyaloclastites erupted sub glacially and lava flows from eruptions during ice free conditions. Being tectonically active the bedrock is cut by numerous faults and fissures. These rock slides and rock avalanches have fallen from steep valley slopes, which have been undercut by advancing outlet glaciers in connection with the general climatic change and expanding of glaciers in the LIA. The outlet glaciers in southern Iceland reached their maximum position around 1890-1900 and have since been retreating. Therefore many of these slopes are no longer supported by the glacier ice and at present unstable and prone to landslide events. Some the recent rock slides and rock avalanches in these areas have though clearly been triggered by intensive rain periods or large earthquakes. More rock slide and rock avalanche activity is expected in these areas as the retreat of outlet glaciers continues in connection with the general global warming.

GA1-05

The rock avalanche on the Morsárjökull outlet glacier, 20th of March 2007 and its effects on the glacier

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On the 20th of March 2007 a large rock avalanche fell on Morsárjökull, one of the outlet glaciers from the southern part of the Vatnajökull ice cap, in south Iceland. This is considered to be one of the largest rock avalanches which have occurred in Iceland during the last decades. It is believed that it fell in two separate stages, the main part fell on the 20th of March and the second and smaller one, on the 17th of April 2007.

The Morsárjökull outlet glacier is about 4 km long and surrounded by up to 1000 m high valley slopes. The outlet glacier is fed by two ice falls which are partly disconnected from the main ice cap of Vatnajökull. The rock avalanche fell on the eastern side of the uppermost part of the Morsárjökull glacier and covered about 1/5 of the glacier surface, an area of about 720,000 m^2. The scar of the rock avalanche is about 330 m high and is located on the north face of the headwall above the uppermost part of the glacier. It is estimated that about 4 million m3 of rock debris fell on the glacier, or about 10 million tons. The accumulation lobe is up to 1.6 km long and its width is 480 m on average. The total area which the lobe covers is about 720.000 m^2 and its mean thickness 5.5 m. The debris mass is coarse grained and boulder rich and blocks over 5 to 8 m in diameter are common on the edges of the lobe. No indication was observed of any deformation of the glacier surface under the debris mass. It is evident that the glacier has retreated considerably during the last century and during the last decade the melting has been very rapid. It is therefore suggested that undercutting of the mountain slope by glacial erosion and the retreat of the glacier are the main contributing factors leading to the rock avalanche. The glacial erosion has destabilized the slope, which is mainly composed of palagonite and dolerite rocks, affected by geothermal alteration. Hence a subsequent fracture formation has weakened the bedrock. However the exact triggering factor is not known. No seismic activity or meteorological signal, which could be interpreted as triggering factors, such as heavy rainfall or intensive snowmelt was recorded prior to the rock avalanche. From 2007 considerable changes have been observed on the surface of the glacier. The ice front has retreated considerably and the debris lobe of the rock avalanche has moved downward along with the glacier ice about 80-90 m per year. The rocky material, by insulating the ice, has reduced its melting, leading to a relative "thickening"of the ice beneath the rock avalanche debris up to 11-15 m per year. After four melting seasons the debris mass was about 44 m above the surrounding ice surface.

GA1-06

Use of cosmogenic nuclide dating in rockslide hazard assessment in Norway

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Systematic mapping of unstable rock slopes is carried out in Norway. Our goal is to characterize those rock slopes which, due to their deformation rates and structural development of failure / slide kinematics, are most likely to fail in the near future. Facing this challenge it became obvious that both (1) the development of the failure process of rock slopes and (2) the temporal distribution of catastrophic failures are poorly understood. (1) During historically reported events in Norway, the opening of cracks has been reported prior to failure. However documented events in the past century were collapses along steep structures with minor previous sliding. Until today 288 potential unstable rock slopes have been defined. Several of them are planar slides, where tens of meters of sliding have occurred along sliding planes which subsequently expose bedrock. In order to get a better understanding of the temporal evolution of failure, we sampled 7 of those sliding planes for cosmogenic nuclide (CN) dating to determine when sliding started and what the long term slip rates are. So far, we have results for two sites, the Skjeringahaugane rockslide in Lusterfjord, Sogne og Fjordane and the Lifjellet rockslide in Troms. Results from the first slide indicate that sliding started approx. 10 ka ago and remains ongoing. Slip rates calculated from cosmogenic exposure ages on several parallel sliding planes have paleo-slip rates of 1-4 mm/yr. The Lifjellet slide has preliminary ages that span from before the Last Glacial Maximum (LGM) to the latest Pleistocene. These ages are harder to interpret, however they do suggest that the assumption that glacial erosion in Norway had reset the CN signal in the entire country is invalid and that rockslides which were active before the LGM are preserved as rockslide features in the landscape. Furthermore (2) in order to assess recurrence times of catastrophic failures of rockslides we dated rock avalanche deposits in selected valleys and fjord areas. Preliminary results indicate that catastrophic failures occurred mainly in the first millennia after deglaciation in the Late Pleistocene / Early Holocene; however, several events also occurred throughout the Holocene. This agrees well with a rock-avalanche stratigraphy from the Storfjord region in Møre og Romsdal which is based upon dated seismic stratigraphy of fjord sediments.

GA1-07

Slope-channel coupling and fluvial sediment transfer in a steep mountain river, Oppdal, Norway

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Global warming and a predicted increased frequency of extreme precipitation events may cause impacts to many river systems. Especially steep rivers in colluvial sediments can be expected to experience increased sediment availability both due to fluvial erosion and to mass wasting processes. Several recent flood events in Norway point to steep tributary rivers and their alluvial fans (often inhabited, or with infrastructure such as main roads and railroads) as hazard areas that can be expected to experience increased future risk.

On this background, we have initiated monitoring of the river Vekve in Oppdal, Norway. Vekve is a steep mountain river, with a catchment of ~33 km^2. This river is part of large hydropower regulation, and the water is diverted at 717 m asl. Above this water intake, a sedimentation dam had to be built in 2007 to avoid sediments clogging the intake. We study the lower ~2 km reach, upstream of the sedimentation dam, where the river has a mean gradient of ~ 6° and runs in consolidated till deposits where several slide scars act as main sediment sources. We have applied terrestrial laser scanning to monitor slide scar development, and have tested novel methods such as PIT-tagging of stones to monitor slope to channel transfer and bedload transport, and shock sensors for bedload transport. In the sedimentation dam, turbidity, discharge and catchment sediment export is monitored. During the measurement periods, we have had both large, mainly precipitation floods (2010 and 2011) as well as normal early summer snowmelt floods (2008 and 2009). The large floods caused high bedload transport and sedimentation, and the sedimentation dam was emptied after each event - providing information on sediment volumes. We will present results from repeated laser scanning of slide scars (2009-2011), bedload monitoring and sediment export from the catchment.

GA1-08

Dynamics of observed extreme winds in Iceland

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Observed extreme winds are studied from approximately 80 automatic weather stations in Iceland.

The study reveals a great spatial variability in the maximum mean winds and wind gusts. They confirm that the greatest extremes at many locations can be attributed to mountain-generated gravity waves and/or a topographic channeling effect in stably stratified flow. The lowest extremes values can also be related to sheltering by mountains as well as rough surface on a smaller spatial scale.

The results agree with the pattern of extremes obtained through dynamic downscaling of atmospheric flow over Iceland. There are however indications, that the dynamic downscaling may underestimate

GA1-09

The marine limit as a basis for mapping of landslide susceptibility in fine-grained, fjord deposits, onshore Norway

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Landslides in sensitive clay or quick clay are serious threats to the Norwegian society and have been responsible for numerous fatalities and loss of property throughout history. The unconsolidated marine clays emerged near or above sea level during glacioisostatic uplift following the Ice Age. Salt was subsequently leached from the soil structure, leaving pockets or layers of sensitive clay or quick clay. Quick clay liquefies completely when disturbed causing large areas to collapse. On-going national hazard and risk mapping programs help to identify zones where large quick-clay landslides could potentially occur. Regional mapping is followed by more detailed investigations of prioritized areas to identify the need for mitigation and protection work. However, there are still significant challenges: several areas have not been mapped yet and one obvious limitation of the existing hazard and risk-maps is that they solely focus on areas where larger landslides could occur. Quick clay is also present outside these zones and smaller-sized landslides could also be fatal. To address these challenges, a project at NGU was started in 2011 to gather information necessary for the development of susceptibility maps for all landslides in marine clays including quick clays. A first, important task is to get a regional overview of the marine limit (ML), the highest level of the sea following the Ice Age. The distribution of fine-grained, marine deposits is then constrained using a digital elevation model (DEM) combined with digital geological maps.

Marine deposits can be hidden under other sediments such as for example fluvial deposits, beach deposits and peat. The possibility for encountering marine deposits in an area is divided into six classes and forms the basis for a rough, first-order, regional landslide susceptibility assessment. Discussion with selected municipalities can help to point out how the results could be communicated. The proposed mapping can also help for prioritizing areas for mapping and can possibly work as a tool for improved documentation for quick clay hazard and risk zoning. Some possibilities for further refinement of the first-order susceptibility maps are presented.

GA1-10

Dynamics of extreme winds over Iceland in a numerical downscaling of current climate

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Seventeen years of flow over Iceland is simulated with the WRF numerical system at a horizontal resolution of 3 km. The flow is forced by the ECMWF reanalysis. The simulation reveals very large horizontal variability in maximum winds. There are clear topographic effects, dominated by gravity waves on the downstream slopes of the resolved mountains. There are also clear signals of topographic channeling. Weak extreme winds in certain regions can also be attributed to topographic sheltering. Consequently, the pattern of wind extremes is very sensitive to the wind direction. As expected, surface friction has a clear impact on the wind extremes, but there are indications that this frictional effect may be overestimated.

G A1-11

Climate Change and Natural Hazards in Svalbard

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The settlements in Svalbard have old days mainly been temporary and related to coal mining. Most accidents happened in the work places in the mines and minor focus has been on safety of infrastructures as housing, rigs and communication. Accidents as slides and avalanches have been problems and in the worst cases buildings have been destroyed and people killed.

As Spitsbergen mainly is a semiarid area with low temperatures and precipitation the probability for natural hazards has been relatively low compared with mainland Norway. A changing climate with higher temperatures, less sea ice and increasing precipitation will change this picture. The active layer above permafrost will be deeper due to temperature change, and more sensitive to slope failure. The snow cover will probably be deeper due to increasing precipitation in the winter and the frequency and size of snow avalanches will increase.

As the infrastructures for mining are located close the mines in narrow valleys or underneath steep mountains an increasing probability for slides and avalanches can increase the risk and cause a higher number of accidents and fatalities in the future. To solve these problems the society has to protect the exposed subjects and take the natural hazard into account in the future location of the settlements.

GA1-12

Westman Islands and the South Coast Transportation and Natural Hazards

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In spite of over 30 eruptions during the last 1100 years, at the Mid South Coast and in the Westman Islands group, this has almost never interupted transportation between the Westman Islands and the mainland. These eruptions are four at Eyjafjallajökull, approximately twentyfour at Katla and at least three in the Westman Islands archipelago. The south shore is a typical continuous sandy beach. As in all such sandy beaches, a few hundred meters off the beach there is a submerged, wave breaking, longshore sand bar. Behind the bar the incoming waves pile up the water, causing longshore feeder current along the beach, dissipated by rip currents, through openings (Icelandic: "hlid"meaning gate) in the sandy bar at certain intervals.

The main river in the region is the Markarfljot River, whose mouth is just opposite the Westman Islands. This river has during the last 1100 years changed from being rather tame into a braided glacial river that shifted from one channel to another, esp in the years 1500 to 1940, sweeping over the whole densely populated delta area having the main outlet to the sea during this period from Holtsos lagoon in the east all the way to the Holsa river or even to the Thjorsa river estuary in the west, a distance of more than 60 km. Barriers constructed from 1930 to 2000 along the lowland part of the Markarfljot river, control the flow down to the coast.

On both sides of the Markarfljot river outlet there were repeated fatal accidents on open boats at sea and at the unsheltered sandy shore. To get away from this unsafe existance, many families moved to the Westman Islands in the 1900´s to enjoy the safety of a partly sheltered natural harbour on the Heimaey Island. They were really environmental fugitives, as their coastal environment on the mainland was becoming too difficult, with frequent sea accidents and common winter floods of the Markarfljot river, damaging arable land and interupting movement of people between the small farms. The safety of Heimaey Island was severely shattered in January 1973 when an eruption lasting 5 months started at the outskirts of the Vestmannaeyjar town, so all inhabitants had to be evacuated for 6 to 12 months. Still the Heimaey harbour and the airfield on the island could operate almost every day during the eruption.

There has been steady transportation between the Westman Islands and the south coast (distance 10 km) since the settlement

just before AD 900, except for the limited period of approximately 1935 to 1980. Around 1935 landings by small boats on the sandy beach stopped almost completely, but around 1980 flights to the islands increased from the small Bakki airfield close to the shore. In 2009/2010 the first sandy beach harbour in Iceland, Landeyjar harbour, was built just 2 km west of the Markarfljot river outlet, opposite the Westman Islands, shortening the sailing time to Heimaey from 3 hours to 30 minutes. However, the operation of the new harbour has been interupted because of greatly increased littoral drift of ash carried by longshore current to the entrance of the harbour. The net average littoral drift for the past decades has been approximately 0.3 M tonnes/y, east or west. In the beginning of the 2010 Eyjafjallajökull eruption, two glacial floods during the first two days, carried nearly 30 million tonnes of ash down the Markarfljot river to the shore just 2 km east of the harbour entrance. Unusually persistent SE-waves have transported a large part of these ash sediments westwards partly blocking the harbour entrance, so constant dredging has been needed whenever weather permits.

GA 2 – Risk assessment and management of geohazards

GA2-1

The SafeLand project; Impacts of global change on landslide hazard and risk in Europe in 21st century

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SafeLand is a Large-scale integrating Collaborative research project funded by the FP7 of the European Commission (www.safeland-fp7.eu). The project team composed of 27 institutions from 13 European countries is coordinated by Norwegian Geotechnical Institute (NGI). SafeLand will develop generic quantitative risk assessment and management tools and strategies for landslides at local, regional, European and societal scales and establish the baseline for the risk associated with landslides in Europe, to improve our ability to forecast landslide hazard and detect hazard and risk zones. The scientific work packages in SafeLand are organized in five Areas:

- Area 1 focuses on improving the knowledge on triggering mechanisms, processes and thresholds, including climate-related and anthropogenic triggers, and on run-out models in landslide hazard assessment;
- Area 2 harmonizes quantitative risk assessment methodologies for different spatial scales, looking into uncertainties, vulnerability, landslide susceptibility, landslide frequency, and identifying hotspots in Europe with higher landslide hazard and risk;
- Area 3 focuses on future climate change scenarios and changes in demography and infrastructure, resulting in the evolution of hazard and risk in Europe at selected hotspots;
- Area 4 addresses the technical and practical issues related to monitoring and early warning for landslides, and identifies the best technologies available both in the context of hazard assessment and in the context of design of early warning systems;
- Area 5 provides a toolbox of risk mitigation strategies and guidelines for choosing the most appropriate risk management strategy.

Identification of landslide hazard and risk hotspots was one of the major tasks in the beginning of the project. For that purpose three different models were developed, all of them using the same input data for entire Europe. Common for the three models was the identification of Italy as the country with the highest exposure to landslide risk. However, the small alpine countries had the highest relative exposure compared to their total land area and population. Overall, 4 to 7 million people in Europe, as well as significant amount of infrastructure are exposed to landslide threat.

In the expectation of a changing climate, the question arises on how the level and spatial pattern of landslide hazard and risk in Europe will develop in the 21st century. To answer this question, several factors must be considered. Not only will the climate change in the next 90 years, but also the demography and land cover in Europe will change significantly. The main objective of the present study was therefore to quantify the landslide hazard and risk in Europe now and in the future and see if there will be significant changes. Changing precipitation pattern, land cover and population were used as input to assess the landslide hazard and risk in the years 2030, 2050, 2070 and 2090. The results were then compared to the present situation in 2010. The effect of climate change varies depending on the type of landslide. In this study the focus was on precipitation-induced landslides, which are a direct consequence of the extreme precipitation events and therefore closely coupled to a change in the frequency of extreme events.

The study showed that climate change and changes in land cover will only cause minor variations in landslide hazard. The risk associated with landslides, however, is expected to change significantly due to changing patterns of population in Europe.

GA2-2

Landslide hazard mapping in Bergen, Norway

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During the fall of 2005, two shallow landslides caused a total of four people to perish in Norway's second largest city, Bergen. Both accidents were triggered by extreme rainfall events, with a diurnal maximum of 156 mm precipitation on September 14th 2005. A rockslide accident in Ålesund in 2008 also contributed to the understanding that landslides may pose a serious hazard in urban areas in Norway.

The Geological Survey of Norway, in cooperation with the municipality of Bergen, started investigations in 2005 to systematically map the landslide hazard in the whole municipality. Many areas have already been mapped by various consultant companies, and the author's currently ongoing master thesis will be a contribution in line with these works in the areas Haukeland and Løvstakken close to Bergen city center. However, this thesis will also focus on testing and implementing methodology that has not been commonly used in the Nordic countries before, but that is regularly being used in e.g. the European Alps.

As in most hazard mapping projects done on a local scale, fieldwork will be the primary method. The focus of the fieldwork will be 1) to identify and characterize the source areas, perhaps using a rock mass classification system and 2) to study geomorphological evidence in the run-out areas with the purpose of creating a landslide inventory and estimating event frequency and run-out lengths.

Vegetation in the study areas will also be investigated. The type and density of the vegetation determines the level of protection it offers against rock falls. Traces of previous rock falls might be recorded in vegetation in the run-out areas, which helps determining the frequency of rock falls in the past. Also, the vegetation cover is an important factor for the stability of soils regarding shallow landslides and debris flows.

A structural analysis might be carried out to determine the kinematics of potential failures in the source areas, using field measurements of discontinuities and a high resolution Digital Elevation Model (DEM).

This DEM will also be used together with field data to model rock fall using the software RockyFor3D. The data from the fieldwork and the modeling will be compiled to make landslide hazard zones for annual event probabilities of 1/100, 1/1000 and 1/5000, according to Norwegian regulations. This map, along with considerations regarding methodology, will be the main product of the master thesis. In addition, a brief risk analysis might also be carried out.

GA2-3

Assessing and managing the risk from landslides in a loess plateau, Heifangtai, Gansu Province, NW China.

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In a joint project between NGI and China Geological Survey (CGS), funded by the Norwegian Ministry of Foreign Affairs, we assess landslide problems in the NW China loess region. The Heifangtai area consists of villages along the Yellow River, and a farming community on a plateau 100m above the river level. The farmers were moved here in the late 1960'ies and a large irrigation project was initiated, pumping water from the river to the plateau. 12-15 years later, the area started to experience significant landslide problems, with many fatalities and large economic losses. The project aims at understanding the landslide processes and suggesting robust mitigation measures.

Managing the water balance in the area is the key problem. However, the local stratigraphy allows different solutions for drainage, being most important near the steep slopes of the plateau. The project includes significant data acquisition over several years, including laser scanning of the whole area, infiltration tests, pumping tests and other in-situ tests in boreholes, in-situ and laboratory geotechnical testing, chemical analyses, hazard and risk mapping, tsunami analyses (from landslides into the Yellow River), etc. The project poses cultural and socio-economic challenges. This is a poor region, and the costs of any large scale mitigation measures to be suggested must be acceptable to both the local and central authorities.

We will present preliminary results of landslide hazard assessment, including stability calculations for the Heifangtai slopes, as well as suggested solutions for mitigation measures to reduce the risk for the villages along the Yellow River.

GA2-4

Avalanche hazard mapping and risk assessment in Iceland

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Snow avalanches have taken more human lives through the centuries in Iceland than any other type of natural hazard except storms at sea and in wilderness areas. During the first centuries after the settlement of Iceland, most avalanche victims were people travelling in the mountains. After urbanization began in the late 19th century, the majority of avalanche victims have been killed in houses or work places.

Catastrophic avalanches that hit two Icelandic villages in 1995 caused 34 fatalities in total. The accidents led to a discussion of what is acceptable in terms of avalanche risk in homes. A new method for risk-based hazard mapping was developed in the following years, and new laws and regulations were enacted. Although the economic loss due to avalanches in Iceland has been significant, it was decided that the loss of human lives should be a dominant factor when considering the acceptability of risk for society. The criterion in the hazard mapping regulation is individual risk, measured as the annual probability of being killed in an avalanche if one lives or works in a building under a hazardous hillside. The building is assumed to be a typical timber or concrete house that is not especially designed or reinforced with regard to avalanche impact.

The Icelandic hazard zoning regulation states that for living houses, a (nominal) risk level of $0.3 \cdot 10^{-4}$ per year is acceptable assuming 100% exposure, and $1 \cdot 10^{-4}$ is acceptable for work places. Assuming 75% exposure for living houses, the avalanche hazard on the acceptable iso-risk line will add about $0.2 \cdot 10^{-4}$ to the annual probability of death for an individual, which amounts to approximately 11% of the death rate of children due to all causes. Thus, it has been formally decided, that it is not acceptable that risk due to avalanches on settlements is one of the main sources of risk in people's lives.

In order to estimate avalanche risk, both hazard potential and vulnerability should be taken into account as well as the exposure of the individual. In the Icelandic risk model, the frequency of avalanches is estimated as well as the run-out distribution of the avalanches. Vulnerability is represented by the probability of being killed if staying in a house that is hit by an avalanche. This was estimated using data from the avalanches of Súðavík and Flateyri, comparing the calculated speed of the avalanche to the survival rate. The exposure is the proportion of the time that a person is expected to spend within the hazard-prone area during the avalanche season.

If acceptable risk, as defined by Icelandic regulation, is to be reached, the return period of avalanches has to be on the order of several thousand years. Since the known avalanche history of each avalanche path does usually not reach far back, it is impossible to base the frequency estimation of long avalanches on local history alone. By combining the avalanche history of many paths with comparable terrain and weather conditions, one may, however, imagine that one path has been observed for a long time rather than many paths for a short time. To make this possible one must be able to tell how far an avalanche that has fallen in a given path would reach in another path. For hazard mapping in Iceland, physical models have been used for transferring avalanches between paths. The latest development of the methodology focuses on the systematic usage of 2D avalanche models for this purpose.

GA2-5

Risk assessment of natural hazards at the Icelandic Meteorological Office – an overview

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Natural hazards are a major threat in Iceland, both for the society and individuals. Following a series of large events in the 1960's and 1970's (earthquakes, sea-ice disrupting fishing and transportation by ships, volcanic eruptions, snow avalanches, severe storms), a need for natural hazard management was evident. After two catastrophic snow avalanches in the Westfjords in 1995 that killed 34 people, the Icelandic government decided that risk assessment should be performed for the avalanche hazard in Iceland, i.e. snow avalanches and landslides. The Icelandic Meteorological Office (IMO) was given the mandate to perform this task. The societal commitments were formalized shortly thereafter by new laws and regulations. The objectives of risk assessment for natural hazards are to minimize human risks and increase the resilience of the society. The assessment of natural hazards in Iceland fits very well into the framework proposed by the World Meteorological Organization (WMO) at the end of the International Decade for Natural Disaster Reduction in 1999 and the terminology as defined by the UN International Strategy for Disaster Reduction (UN-ISDR) initiative. Over the past decade, IMO has worked towards receiving a formal status as the institute responsible for conducting risk assessments for natural hazards in Iceland in general. In the new law for the institute after the merger with the hydrological institute on 1st January 2009, it is stated that IMO shall conduct risk assessment for natural hazards on request from the civil protection agency or other governmental authorities. The first task after the comprehensive avalanche risk assessment, which is still ongoing, is to carry out risk assessment of volcanic hazard in Iceland. The same methodology will be used as for the avalanche work, i.e. the UN-ISDR approach. In the first phase of the project, estimated to by finalized by end of 2014 (i) fundamental information about the threat will be gathered, and (ii) pre-investigations will be made regarding to hazard due to jökulhlaups caused by subglacial eruptions, (iii) large explosive eruptions and (iv) eruptions close to urban areas;

- An appraisal of current knowledge
- Initial assessment of floods related to eruptions
- Initial assessment of explosive eruptions in Iceland
- Initial assessment of a volcanic eruption that may cause extensive damage to property and infrastructure, i.e. eruption in the vicinity of urban areas and international airports in Iceland

This work is of great importance both domestically and internationally, but the last two eruptions in Iceland especially in

Eyjafjallajökull spring 2010 caused a major financial damage in the aviation community. IMO is the Volcano State Observatory, appointed by the International Aviation Organization (ICAO). As such, the institute has a responsibility to provide information pre-, during and post volcanic eruptions. The institute, with this role, will benefit greatly from the work that has now started.

GA2-6

Natural hazard and disaster risk reduction in Iceland regarding volcanic ash, vegetation and soil conservation

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Recent Icelandic eruptions (2010-2011), proved beyond a doubt the value of pre-event planning for natural hazards by the Civil Protection Department. Here I focus on possible pre-disaster mitigation responses for ash-fall and vegetation.

The United Nations International Strategy for Disaster Reduction defines "Disaster risk reduction"as "the concept and practice of reducing disaster risks through systematic efforts to analyze and reduce the causal factors of disasters. Reducing exposure to hazards, lessening vulnerability of people and property, wise management of land and the environment, and improving preparedness for adverse events are all examples of disaster risk reduction"[1].

Risk Identification

Active volcanism is prevalent in Iceland with active regions covering 30% of the land with historical eruption frequency of 20-25 events per 100 years[2]. There is considerable risk for ash deposition events to occur. Ash can destroy/damage vegetation by the initial direct burial or with post-eruptive transport either by water or wind, extending the area of influence far away from the initial deposition area. Ash deposition can also affect hydrology and air quality.

Ecosystem resilience against deposition of aeolian material and volcanic ash fallout depends on various factors e.g.: depth of burial, species capability of regeneration when buried, seasonal timing, water availability, toxicity etc. Vigorous ecosystems with tall vegetation generally have greater endurance capability; the sheltering effect minimizes the secondary wind transport of ash, and hastens the incorporation of ash into the soil. Whereas when ash falls onto areas with little or no vegetation, it is unstable and easily moved repeatedly by wind and water erosion possibly causing further abrasive damage.

Risk reduction

Build-up of healthy ecosystems increases resilience providing better capability of surviving ash fallout. The common range land in the highlands that are now degraded pose as Iceland´s most serious environmental problem. Existing vegetation in common range lands is generally sparse and low growing and is therefore vulnerable to disruption. Ash-fall onto land in such condition can be catastrophic as seen in recent events. Resilience to catastrophic events can be drastically improved by reclamation efforts.

Effective governance through alignment of policies, e.g.: land use planning/zoning, natural resources management, agricultural policies, mitigation action against climate change through revegetation and carbon sequestration, restoration of natural birch forests[3], along with coherent legislation, multi-sectoral coordination with effective knowledge sharing, are important in successful risk management.

Encouragement of sustainable use and appropriate management of fragile ecosystems through better land-use planning and development activities now has an additional aim to reduce risk and vulnerabilities to natural hazards.[4]

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GA2-7

Development of guidelines for the sustainable exploitation of aggregate resources in arsenic rich areas in Finland

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A new EU Life+ -funded project started in September 2011 with the principal aim to develop guidelines and a decision support model for the sustainable exploitation of aggregate resources in areas of naturally high As-concentrations in southern Finland. The project, ASROCKS, is a follow-up to projects such as LIFE+ Environment project RAMAS, 'Risk Assessment and Risk Management Procedure for Arsenic in the Tampere Region' (Loukola-Ruskeeniemi et al. 2008), which demonstrated the presence of the As problem in the Tampere-Häme area. During these studies, arsenic concentrations in ground- and surface waters were studied in a total of six aggregate quarries in the Tampere region. Highest As-concentration was measured in the water of drilled bedrock well: 140 μg/l of As and, in addition, two surface water samples showed elevated concentrations with 37.0 and 27.3 μg/l As (Loukola-Ruskeeniemi et al. 2007). One of the main observations of the projects was the need to establish guidelines and management practices for the sustainable use of aggregates for large scale construction projects, which involve handling of large amounts of soil and bedrock masses. In addition, the environmental permit process of new aggregate production sites is lacking adequate guidance on the risk management of As-rich aggregate resources.

During the current ASROCKS- project, identification of the aggregate production areas and planned large construction sites with potential arsenic hazards will take place and potential transport pathways of arsenic to surface waters and groundwater will be investigated at sites that show elevated concentration of As. The leaching behavior and mobility of As will be studied by standardized column and shaker tests. The environmental risks in the areas with elevated As-concentrations are assessed and guidelines will be provided for the investigation, risk assessment and sustainable exploitation of aggregate resources with elevated As-concentrations. The guidelines should be available both for the industry and the local and environment authorities by the autumn of 2014.

ORAL GA 2

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GA 3 – Offshore, near-shore and coastal geohazards

GA3-1

A multiproxy analysis of the 2004 tsunami deposits of west coast Thailand: comparison with paleo-tsunami sediments

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In December 2004 the Sumatra-Andaman earthquake with a magnitude of 9.3 on the Richter scale occurred off the west coast of Sumatra, Indonesia triggering seismic waves impacting coast lines distant from the epicentre. We have investigated the tsunami deposits along the west coast of Thailand in the areas of Khao Lak, Bang Nyang and in Ban Nam. Sheets of tsunami sand varies in thickness from centimetres to decimetres and only locally does the sand deposits reach over two metres. Trenches were dug perpendicular to the coastline and the sedimentary intervals were mapped and sampled and subsequently analysed using sedimentological, geochemical and palynological techniques. Here we will present the results from this multidisciplinary investigation. The aims are to improve the geological understanding of the principal sediment-depositing mechanisms effective in tsunami surges as a model to identify paleo-tsunami successions. The distinctive features of the tsunami generated deposits from the Khao Lak area are characterized by sediments derived from mixed sources, such as plant fragments and soil fungi from terrestrial settings, and bioclastic sand eroded from shore face deposits. The marine input is of much lower significance than expected, which we interpret as a result of the local onshore and offshore topography. Further, comparisons with paleo-tsunami deposits will be discussed.

GA3-2

Offshore geo-hazards to be kept in mind during exploration and production activities in the Jan Mayen Micro-Continent area.

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The idea to realize a prospecting and exploration program at the Jan Mayen Micro-Continent has been ongoing since the late 1980´s and early 1990´s. The activity picked up again by the initiation of the first and second licensing rounds for oil and gas exploration on the Icelandic Continental Shelf in 2009 and 2011. Numerous papers and studies have been published throughout time to explain the geo-scientific data and the sub-surface setting of the Jan Mayen Micro-Continent. A Strategic Environmental Assessment (SEA) study was published by the Ministry of Industry, Energy and Tourism in 2007 to evaluate possible environmental impacts, divided according to the effects at each stage of the project - prospecting, exploration, production, and decommissioning. The main concerns are the effects of possible impacts on the ecosystem around the Jan Mayen Ridge. Furthermore, it is of importance to review possible hazards due to the project operations themselves, especially with regard to drilling operations. Firstly, such hazards could include difficulties in controlling possible accidents while drilling in deep water conditions, where a large part of the prospective areas lie between 1000 - 2000m water depth. Possible submarine landslides close to the main ridges have to be considered as well; as such occurrences have been observed on seismic and bathymetry data. In addition, shallow free gas or gas hydrates may have effects on drilling safety, i.e. cause blow-outs and seafloor instability. Secondly, the evaluation includes hazards posed by transport activities during the production phase i.e. transport of oil or gas via tanker ships or pipelines, if hydrocarbons were to be found.

GA3-3

The 1978 quick clay landslide at Rissa: subaqueous morphology and slide dynamics

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The 1978 quick clay landslide at Rissa is the largest to have struck Norway during the last century and is world famous because it was filmed. The landslide devastated an area of 0.33 km^2, which included 20 houses and farms. Of the 40 people caught in the landslide, one person died. The landslide was initiated by excavation and stockpiling along the shoreline of Lake Botn and within a few hours 5-6 $x10^6$ m^3 of marine clay liquefied and flowed into the lake. The flow of sediment triggered a flood wave with a recorded maximum surface elevation of 6.8 m. In this study we present the subaqueous morphology of the Rissa landslide deposit using a dataset of high resolution swath bathymetry and seismic data. Such detailed mapping offers a unique possibility to reconstruct the development of the slide and its dynamics.

Results show that the landslide affected nearly 20 % of the lake bottom and that it exhibits a complex morphology including distinct lobes, compression ridges, flow structures and rafted blocks. In the slide initiation area along the shore of the lake, reflection seismic data shows a distinct acoustic reflection associated to the glide plane. Detailed morphological analysis also shows a myriad of pockmarks (up to 75 m in diameter) on the lake bottom. These features appear to be concentrated on the flat seafloor in front of bedrock ridges and testify to high excess pore-pressure in the near-shore sediments. The presence of shallow scars at various locations along the lake also indicates unstable slopes in the soft Holocene sediments.

GA3-4

Offshore Geohazards in the Atlantic Ocean Mapped by High-Resolution P-Cable 3D Seismic Data

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The focus on offshore geohazards has increased the last few years, as they have been the origin for several catastrophic events with devastating consequences. Offshore geohazards represent a risk for both the petroleum industry, the nuclear energy industry and populated near shore areas. Drilling hazards are represented by gas hydrates and shallow gas in particular, with blowouts and ground failure due to phase shift instability as two possible outcomes of misplaced drilling sites. The main hazard for the nuclear energy industry and populated near shore areas are faults and slides causing earthquakes and tsunamis. New technologies and data may help to prevent or foresee disastrous events like the ones we have recently seen in the Gulf of Mexico and on the coast of Japan. Conventional 3D seismic data is sometimes available in high-risk areas, but such data have low resolution and the acquisition is expensive. High-resolution P-Cable 3D seismic data are particularly useful to identify geohazards such as shallow gas, gas hydrates and deformation structures. The P-Cable has been used to acquire high-resolution seismic data on several geohazard sites in the Atlantic Ocean. Shallow gas and gas hydrates are interpreted in most of the eight cubes acquired in the Barents Sea. Similarly, shallow gas, gas hydrates and vertical pipe structures are present in 3D high-resolution data near the head-wall of the Storegga slide on the mid-Norwegian margin. Offshore Montserrat in the Lesser Antilles Volcanic Arc, P-Cable 3D data have been acquired over volcanic debris avalanche deposits showing at least five different deposits. Despite the highly-incoherent nature of these types of deposits the data deliver a wealth of information on emplacement factors such as deposit extent, block sizes, erosion, surface deformation, mobility, and topographic run-up. Being able to get this level of detail in 3D seismic data is a step toward better understanding of offshore geohazards, and documents that 3D high-resolution seismic data are very useful for understanding potential geohazards related to energy production and coastal infrastructure and settlements.

THEME: GEODYNAMICS (GD)

GD

ORAL
GD

GD-01

The 2011 Grímsvötn Eruption Observed with High Rate Geodesy

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High rate geodetic measurements at volcanoes can give displacements at sub second interval, revealing surface deformation associated with magma movements. The Grímsvötn volcano lies beneath the Vatnajökull icecap, Iceland, limiting the near field monitoring efforts to a single nunatak, Mt. Grímsfjall, on the southern caldera rim. A 5 Hz GPS station and an electronic tilt meter are located at the nuntak. The colocation of the GPS and tilt station allow us to relate the observed surface deformation to pressure change in a magma chamber assuming simple Mogi source within elastic half space. During the 21-28 May 2011 Grímsvötn eruption a continuous stream of data, despite the eruption plume and lightning, was transmitted to Reykjavík.

The high rate data from the GPS station at Grímsfjall (GFUM) were analyzed using the Track part of GAMIT/GLOBK. We produced kinematic solutions at 5 Hz and 1 Hz intervals using reference stations in 40-120 km distance of the volcano. To minimize multipath effect we used sidereal filtering and stacked solutions to further improve the signal to noise ratio. The deformation suggests a rapid pressure drop starting about 50 minutes prior to the onset of the eruption when over 20 km high plume formed. The characteristics of the GPS and tilt data time series suggests that the main signal is due to a single source of fixed location and geometry throughout the eruption; a shallow magma chamber. Small deviation in displacement direction prior to the onset of the eruption can be explained by influence from the opening of the feeder dike. The GPS station recorded a total displacement of 57 cm in direction N38.5°W and down, suggesting a source depth of ~1.7 km. Majority of the displacement (95%) took place within the first 24 hours.

GD-02

Plate spreading in the North Volcanic Zone, Iceland, constrained by geodetic GPS observations and finite element numerical modeling

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Iceland is located on the Mid Atlantic Ridge (MAR), the only part above sea level, which gives a unique opportunity for research of spreading induct crustal deformation. The aim of this study crustal deformation in the Northern Volcanic Zone (NVZ), by Global Positioning System (GPS) geodetic measurements, and through finite element modelling (FEM) of deformation taking place at spreading plate boundaries. In the NVZ, the volcanic systems are arranged en-echelon and are not aligned perfectly parallel with the plate boundaries. An overlapping of the volcanic systems causes a slightly asymmetrical deformation in the NVZ. Velocities of GPS sites were calculated in Terrestrial Reference Frame 2005 (ITRF2005) and NUVEL-1A reference frame, and presented relative to stable Eurasian plate. The measured full spreading rate between North American and Eurasian plates was to 21.7 ± 3 mm yr^{-1}, projected on a profile striking N1050E (predicted spreading direction in NUVEL-1A). The full deformation zone was identified to be 90 km wide. A half spreading rate was applied on the half deformation zone to construct a two dimensional (2D) symmetrical models using the commercial FEM package Abaqus/CAE 6.11. General pull-push modeling with different geometry between elastic crust and viscoelastic half-space were tested. Advance modeling of cooling oceanic lithosphere and temperature dependent rheology were also studied. In the cooling oceanic model, varied crustal thickness, isotherm and viscosity for viscoelastic half-space were tested to investigate corresponding surface deformation. In the temperature dependent rheology models, temperature distribution for both thin and thick crust models with creep relation where strain is proportional to stress in 3^{rd} and 3.5^{th} power were tested for both wet and dry mantle rheology. The horizontal components resulting from modeling were evaluated with measured spreading rate. However, horizontal displacement in study area was not perfectly symmetrical. This gives, temperature dependent wet mantle rheology with strain proportional to stress in 3.5^{th} power for both thin and thick crust models with best fitted. The vertical deformation is a mix of a spreading generated signal on the general uplift of central Iceland and it could not be well constructed in the plate spreading model.

GD-03

Long-term monitoring of coupling between seismic activity and groundwater chemistry at Husavik, northern Iceland

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Sampling and ICP-OES analysis of groundwater from a 1.5 km deep borehole at Husavik, northern Iceland has been ongoing since July 2002. This is now the most extensive time series of hydrogeochemical data collected from a single site in a seismically active area. This study has shown strong evidence of coupling between groundwater chemistry and seismic activity, but chemical changes which are not related to seismicity have also been observed. Seismically-coupled hydrogeochemical changes comprise concentration anomalies for transition metals before a M 5.8 earthquake (September 16, 2002), a 10-20% increase in the concentrations of dissolved ions following this earthquake and subsequenct hydrogeochemical recovery over a period which exceeds 2 years. Based on PHREEQCI modelling, hydrogeochemical changes not coupled with seismicity are interpreted as representative of vein infilling processes, whereby fractures are repeatedly clogged by zeolite minerals and ruptured because of transiently elevated fluid pressures. This fracturing - rock sealing - re-fracturing process can cause fractures opened by an earthquake to remain open for periods far exceeding those predicted by experimental studies.

GD-04

Rheology in east Iceland, revealed by InSAR and finite element modeling of the GIA around Vatnajökull ice cap

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The largest ice cap in Europe, Vatnajökull (area of 8100 km^2 and maximum thickness of 900 m), has been retreating since the end of the Little Ice Age in 1890. A significant rebound has been induced in south-east Iceland due to this ongoing response to climate warming. This signal has been studied with GPS measurements over the past few years, revealing an uplift of up to 20-25 mm/yr close to the edges of the ice cap. Here, we use Interferometric Synthetic Aperture Radar (InSAR) measurements to extract the deformation signal induced by the Glacio-Isostatic Adjustment (GIA) around Vatnajökull ice cap. We compare the observations to finite element modeling results to investigate and improve the knowledge on the rheology of the Earth beneath the ice cap.

InSAR is a phase differencing technique with a good spatial coverage, providing in our case more data to retrieve information about the Earth structure and ice model. Deformation observed at the surface is in Line-Of-Sight (LOS) direction, meaning that the signal is mostly showing vertical motion but also contains a horizontal component. 150 InSAR images from both ERS 1/2 (spanning 1992-2002) and Envisat (2004-2009) satellites were processed and LOS velocity plots obtained. The finite element method was then applied through 90 models of the GIA process to infer for the best-fitting Earth structure.

The InSAR data reveal the full extent of the GIA pattern around the ice cap with greater details than observed previously. The LOS velocity plots give uplift rates of ~15 mm/yr for the 1992-2002 period and ~20 mm/yr for the 2004-2009 one. We observe a significant difference in uplift velocities from neighboring outlet glaciers, attributed to a difference in melting rates, which couldn't be detected by other methods. Other processes are also seen, such as glacial surges and volcanic intrusions. Modeling is done with the Abaqus software, assuming two layers (an elastic layer on top of a viscoelastic one). The ice model assumes variable melting rates for Vatnajökull and a constant rate for the other ice caps in Iceland. Each model result is converted to the LOS geometry and compared with the InSAR scenes. The fit is estimated using the chi-square method. First results show that models with a crust thickness between 10 to 30 km and a viscosity of 6 to 10x10^18 Pa s are in best agreement with the data, which is comparable to what was found in previous studies. Further modeling will look into non-linear rheology and crust thickness variation from the ridge axis outwards.

GD-05

Preliminary results from GPS measurements of the Värmland Network (Southern Sweden) between 1997–2011

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In 1989, the Värmland GPS network consisting of 8 stations spaced an average of 60 km apart was setup to monitor the ongoing deformation in and around Lake Vänern due to Glacial Isostatic Adjustment (GIA) process in Fennoscandia. This network covers an area of about 10000 km^2, straddles the Protogine and the Mylonite zones and includes one of the most active seismic zones of Sweden.We use GAMIT/GLOBK software to process the past GPS data, collected in October 1997, the only campaign that was measured with choke ring antenna, the new GPS measurements in October 2010 and the data from measurements scheduled in October 2011 to estimate station velocities. We also integrate our local network with the SWEPOS (Swedish Permanent GPS network) and IGS (International GNSS Service) stations to better constrain the velocity fields in ITRF and Eurasia-fixed reference frames. Since the rates of horizontal movements are very slow (less than 1 mm/year), our measurements in longer time spans (at least in 13 years, between 1997 to 2010, 2011 and planned 2012) better resolve the tectonic signal from the noise. Preliminary results obtained from campaign-mode measurements in 1997 and 2010 agree well with those reported in the latest study by Lidberg et al. (2010) who used the data from permanent GPS stations of the BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonics) project. Strain analysis resulting from the obtained velocities illustrates the overall extensional component trending NW-SE with local variations. Adding more campaigns in 2011 and 2012, will surely increase the reliability of our analysis.The velocity field obtained form this research will add more details to the tectonic picture generated by BIFROST. The results are also relevant to GIA modeling, geodetic vs. seismic strain accumulation, waste isolation and seismic hazards.

Reference:

M. Lidberg et al. 2010, Journal of Geodynamics 50, p. 8-18.

GD-06

The Hydrorift Experiment

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Understanding the behaviour of fluids in the deep upper crust and at the brittle/ductile crust transition is of importance in both academic and industrial fields. Pore fluids are thought to play a major role in the seismogenic cycle, mainly by decreasing friction along major faults.

The HYDRORIFT experiment involves ISOR (Iceland GeoSurvey), the energy company HS Orka and a group of French GEOFLUX scientists in a geophysical experiment on the Reykjanes Peninsula in Iceland. It includes high-resolution TEM/MT resistivity studies, seismic tomography and general analysis of seismic data. The objective is to better stress the significance of the velocity anomalies discovered in the area following an experiment in 2005 (notably beneath Kleifarvatn Lake) and to reach a more accurate physical knowledge of the geometry and time-evolution of the different reservoirs within the active rift zone in Iceland. An array of 30 seismic stations, including three broadband seismometers, was deployed in May 2009 for a six-month period.

During the operation period of the network an intense seismic swarm occurred in the region, located mainly within the network. The swarm gives a good insight into the processes at the plate boundary in the area, such as the stress field and the stress release. Furthermore, prerequisites for detailed tomographic analysis exist. Dense magnetotelluric and transient electromagnetic (MT/TEM) soundings have been made in the area. Comparative analysis of the seismic velocity distribution from seismic tomography and 3D interpretation of resistivity from MT/TEM soundings may shed light on the physical conditions of the rock and the geothermal fluids.

GD-07

The inflation and deflation episodes in the Krísuvík geothermal area

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Krísuvík is a volcanic system with a high-temperature geothermal area located in the central part of the Reykjanes Peninsula, SW Iceland. The area is seismically very active with the largest earthquakes (M 5-6) associated with a system of N-S trending, right-lateral strike-slip faults. In early 2009 GPS measurement at a continuous station KRIV suggested inflation of the Krísuvík geothermal area, which was then confirmed by ENVISAT interferometric synthetic aperture radar (InSAR) data. The uplift episode continued until fall of 2009 when the area began to subside reaching the pre-inflation state in early spring 2010. In April 2010 another uplift episode started. The inflation is ongoing at present with a comparable deformation rate to the pre-deflation one.

The Krísuvík area has been closely monitored in the last year with continuous and campaign GPS measurements and InSAR interferometry. The deformation registered by the GPS stations suggests an inflation source at 4-5 km depth located beneath Sveifluháls area, with uplift rates exceeding 50 mm/yr at stations closest to the inflation center, just north of Seltún geothermal area. TerraSAR-X images (in both ascending and descending orbits) have been acquired during the latest inflation period showing the extent of the uplift. In addition to geodetic data repeated gravity measurements will be used to help constraining the nature of the source and its depth. Precise gravity measurements on numerous sites were performed in June 2010. In March 2011 measurements were conducted along a profile crossing the estimated inflation center. In June/July 2011 majority of the sites in the network were remeasured.

Seismic activity in the Krísuvík area in last two years has been reflecting the ongoing deformation character, more frequent earthquakes were recorded during the inflation periods while fewer during the deflating phase. In late February 2011 a seismic swarm occurred in Krísuvík with eight events of magnitude exceeding 3, many felt in Reykjavík. The largest (M 4.2) occurred on 27 February and was located just west of lake Kleifarvatn. The earthquakes lineate a N-S trending structure and coseismic GPS displacements suggest right lateral rupture on a N-S trending strike-slip fault.

GD-08

Eyjafjallajökull's plumbing system and magma movements during 2009–2010 through relocated earthquakes and GPS measurements

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Eyjafjallajökull volcano, S-Iceland, awoke, after 187 years of dormancy on March 20th 2010 when a small, basaltic, fissure eruption began on the eastern flank, outside the volcano's ice-cap. This three-week-long, effusive eruption was followed by a six-week-long explosive eruption of trachy-andesite that began on April 14th in the ice-filled summit crater and caused local flooding and widespread air-traffic disruption. This eruptive phase was preceded by a 18-year-long period of intermittent swarm activity and crustal uplift, indicating magma intruding into the upper crust and the lower crust. Here we show how relocated earthquakes and GPS-measurements can be used to track magma movements beneath Eyjafjallajökull before and during the 2010 eruptions.

The seismicity shows that the recent unrest period began at 20-25 km depth, near the crust-mantle boundary in March 2009 and was followed by small intrusive activity into the upper crust the following summer. This small intrusion also caused a subtle southward movement of a near cGPS-station on the southern flank. Seismicity, picked up again in December 2009 and early January 2010 a cGPS station on the south flank of the volcano started moving away from the volcano, suggesting inflation.

Deformation observed at cGPS stations in January and February suggests formation of intrusions under the southeastern flank of the volcano. Similarly, the seismic pattern indicates the formation of intrusions beneath the south-eastern flank between February 20th and March 3rd. Also, time series from more distant cGPS stations show a small but distinct change around the 20th of February, with sites moving in toward the volcano, suggesting deep pressure changes.

From March 4th seismic activity migrated eastwards and intensified. Observed synchronous rapid deformation is interpreted as northward and upward migration of the intrusion. When the effusive flank eruption started deformation almost ceased and the volcano remained at an inflated state. However, when the summit eruption began, rapid deformation toward the summit of the volcano and subsidence observed both with GPS and InSAR measurements indicate contraction of a shallow source at 3-4 km depth below the summit. A seismic gap in the magma pathway towards the summit, defined by relocated earthquakes, is also observed at 3-5 km depth just south-south-east of the summit. Deep seismic activity (near the crust-mantle boundary) in early May is interpreted as signs of new deep magma input from the mantle, before the effect of the new material reached the surface and caused increased ash production again.

GD-09

The May 2008 earthquake sequence: Crustal deformation, stress and and strain.

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On May 29, 2008, an earthquake doublet with two Mw6 events struck the western part of the South Iceland seismic zone (SISZ). In addition, earthquakes (up to ML3) illuminated an E-W zone extending about 20 km further westward. The May 2008 main shocks thus appear to have triggered activity on a complex set of structures in a fairly confined region located near the Hengill triple junction, where the SISZ, the Western volcanic zone and the Reykjanes peninsula intersect. The May 2008 sequence is most likely a continuation of the previous earthquake sequence in the SISZ, when two Mw=6.5 earthquakes ruptured two 10-15 km long N-S striking faults, located about 17 km apart within a span of three days in June 2000. Prior to the June 2000 earthquake sequence, intense seismic activity and uplift (up to ~2 cm/yr) took place in the Hengill area during 1994-1998.

Modeling of the co-seismic deformation observed by GPS and InSAR, indicates that most of the slip occurred on two N-S, right lateral strike slip faults. The first event ruptured a fault located in Ingólfsfjall, and a second event was triggered within 3 seconds, on a fault located about 5 km further west. Slip on the western fault appears to have extended somewhat deeper (3-6 km) than the fault that ruptured first (2-4 km). The aftershocks on the second rupture also extend deeper and further North and South than the fault illuminated by aftershocks due to rupture of the first event. A small week-long transient deformation signal was observed at a few continuous and semi-continuous GPS stations, indicating that the co-seismic stress changes caused fluid flow in the epicentral area. Analysis of earthquake focal mechanisms in the epicentral area, allows us to estimate the stress tensor orientation and search for possible temporal changes due to the May 2008 main shocks. A comparison of the stress orientation estimated from focal mechanisms with the orientation of the principal strain rates axis, estimated from the geodetic data, may shed light on how the activity in Hengill (1994-1998) altered the stress field in the Õlfus area, prior to the May 2008 main shocks.

THEME: INTERDISCIPLINARY SESSIONS (IS)

IS 1 – Planetary geoscience (including e.g. Impact craters, Mars etc.)

ORAL IS 1

IS1-1

Post impact sedimentation in the Ritland impact structure, Western Norway

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The crater infill sediments of the Ritland impact structure can be classified as: A) syn-impact B) early-post impact, and C) post impact sediments. The syn- and early-post impact sediments are composed of a minor, basal melt unit succeeded by a relatively thick succession of coarse grained clastics; breccias, conglomeratic and arkosic sandstones. The post impact sediments consist of finer grained clastics representing a rather stable crater situation and succeeded by regionally developed extensive clastic sequences.

The post impact sediments are exposed in the central and at the eastern part of the crater, showing onlapping relations to the upper part of the early-post impact sediments. The post impact sediments consist of a lower unit (~6 m thick) of fine to medium grained sandstones, succeeded by very fine sand and silty-shales in the upper part, overlain by a thick (estimated 180 m) unit of dark grey to black shales. Evidences of bioturbation, possibly *planolites, thalassinoides* has been found within the sandy sediments indicating the establishment of Early Cambrian life within the crater. The transition to black shales indicates that more stable and anoxic conditions started to prevail within the crater.

Higher up along the easternmost crater wall, the early-post impact to post impact transition is marked by three clast-supported breccia beds interbedded with dark grey to black shales. The breccia beds are composed of decimetre sized, sub-angular to sub-rounded clasts of granitic and gneissic origin, with bed thickness ranging from 1-2 m. The matrix consists of a mix of fine to medium grained sand and dark grey to blackish clay. The breccia beds have limited lateral extent (10 to 20 m) and, thin towards the crater centre. Towards bed tops some thin beds (2 cm) consisting of medium to coarse grained sand have been found intercalating with thinly laminated dark grey shales and silty shales. Submarine slides and reworking of sediments were active processes along the crater wall for a long time after impact, occasionally depositing coarser material between the long and quiet periods of clay deposition.

This study will focus on the sedimentological and mineralogical aspects of the transitional sediments (early-post impact to post impact) inferring to their depositional mechanisms, the paleoenvironmental conditions and their possible source areas.

IS1-2

Ejecta distribution and stratigraphy – field evidence from the Ritland impact structure

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The Ritland structure is the remnants of a marine Cambrian impact crater, once deeply buried, and now partly re-exposed due to Cenozoic uplift and erosion. East of the crater, an ejecta layer from the impact is well preserved within a succession of Cambrian shales. A stratigraphic study of the about 10 meters of sediments below the ejecta layer illustrates the regional geological settings at the time just before impact. This interval records the Cambrian transgression, when the wide-stretched peneplanated surface of Precambrian basement was flooded by the epicontinental sea covering large areas of Baltica/Scandinavia. A thin basal conglomerate appears patchy on the peneplain, overlain by less than a meter of silty to fine-grained sandstones, followed by silty, dark shales. Individual beds may be enriched in carbonate cement, and there are some occurrences of stromatolitic fragments in the shales. A shallow, epicontinental sea with a general, low-energy regime is suggested at the time of impact.

The ejecta layer has been studied in several sections, ranging in distance from 3.2 to approximately 5 km from the crater center, where the amount of ejecta material decreases rather abruptly. The main part of the ejecta layer appears as a mix of crystalline rock clasts and shale (5-50%). The ejecta bed distribution appears as an uneven blanket, with a maximum thickness of about 4 m. Below the main layer commonly larger boulders, up to ~ 5 m diameter, are found totally surrounded by shale. At some localities up to a meter thick unit of better sorted sand to gravel is draping the main ejecta bed.

Three main mechanisms of deposition are suggested: 1) Ballistic travel of material, where the boulder-sized clasts had sufficient energy to penetrate into the upper part of the soft, unconsolidated shales. 2) The main part of the ejecta was deposited by a "surge"-like transport of dominantly crystalline debris which were mixed with the seafloor clays/shales. 3) The upper, sandy beds may be the products of post-impact reworking by (tsunami?) waves or density currents.

IS1-3

Geophysical Survey of the Proposed Målingen Marine-Target Crater, Sweden

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Målingen is a 1km wide circular structure situated about 15km to SW of the similar age, 8km wide Lockne impact crater, Sweden. At the time of the Lockne impact the area was covered by a >500m deep sea. Sedimentary breccias occur in the central parts of the

Malingen structure in both outcrop and drill core and show similarities to the resurge deposits at Lockne. The ongoing Geophysical survey will provide data for a geophysical modeling that will aid the geological studies to determine the dimensions and shape of the Målingen structure. In turn, the geophysical/geological models will be used as constrains for numerical simulations to evaluate the potential impact formation of this structure and its relation with the Lockne impact crater. The ongoing geophysical survey comprises gravity and magnetic measurements with portable field equipment (i.e. gravimeter and proton magnetometer). They are complemented with geological mapping, a core drilling to 149m depth at the center of the structure, detailed leveling, and lab/field susceptibility measurements of lithologies in outcrop and drillcore. The gravity data were obtained along two roads crudely oriented N-S and E-W intersecting the apparent center of the structure. The resulting Bouguer anomaly map shows a general gravity low over the interior of the structure as well as a concentric pattern of weak lows outside the apparent topographical rim. The magnetic survey covers the whole structure and extends to a distance of about one diameter outside the apparent rim where the terrain allows it. Similarly to the gravity data there appears a concentric pattern of low magnetic anomalies at some distance outside the topographic rim. The gravity low over the interior of the structure and low magnetic anomalies are consistent with the magnetic and gravity signature of bowl shaped, simple impact craters described in literature. The distribution of the low anomalies from the gravity and magnetic surveys suggest a circular disturbance zone larger than the apparent structure, possibly due to fracturing. The concentric pattern may be a consequence of the putative impact occurring at relatively deep water, thus obtaining a point of explosion at relatively higher level in the target than at an equal sized land-target crater.

IS1-4

Middle Ordovician L-chondritic meteorite shower and clastic sedimentary facies in Baltoscandian carbonate shelf: are these related?

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The disruption of large parent body in the asteroid belt at ~470 Ma resulted in increased paleoflux of L-chondritic meteorites and micrometeorites on Earth by up to two orders of magnitude (Korochantseva et al. 2007). Sedimentary beds enriched with micrometeorites and extraterrestrial chromite have been studied in a narrow stratigraphic interval of the Middle Ordovician Darriwilian Stage in Sweden and China (eg. Schmitz et al. 2008). This dates the meteoritic shower to 466-467 Ma. In Baltoscandia, five of the seventeen well-confirmed meteorite craters are of Ordovician age (Kärdla, Tvären, Hummeln, Lockne, Granby). From these, the Granby and the Hummeln structures in S-Sweden have also Darriwilian age and impactor of the Lockne crater in central Sweden has been confirmed as ordinary L-chondrite (Alwmark & Schmitz 2007) type. In addition, impact origin was recently confirmed for the ca. 466 Ma Osmussaar breccia, covering an area more than 5000 km^2 in NW Estonia (Alwmark et al. 2010). The actual magnitude and possible global effects of the meteoritic bombardment are poorly understood yet, but as the period coincided in time with the Great Ordovician Biodiversification Event, Schmitz et al. (2008) have speculated that the asteroid break-up and the following meteoritic bombardment may have accelerated this largest known radiation of marine life. We analyzed two sedimentation events deposited in East Baltic region under high hydrodynamic conditions close to the meteoritic bombardment interval. The Pakri Fm in NW Estonia and the Volkhov Collector in W Latvia were studied in boreholes and in thin-sections.

The Pakri Fm has early Kunda (Darriwilian) age. This up to 4 m thick limy sandstone belt stretches from NW Estonia to SE Sweden. The Osmussaar breccia occurs in the Pakri Fm and underlying strata. The bed is composed of poorly sorted and often matrix supported sub-angular to well-rounded quartz and bioclastic material in calcite cement. It occurs in between the limestone layers and its five litostratigraphical subdivisions can be correlated throughout the NW Estonia. The Volkhov Collector is up to 1.5 m thick, 100 km long and 50 km wide sandstone belt in W Latvia and below the Baltic Sea. It is composed of poorly sorted and diagenetically altered mixed siliciclastic sediment in between argillaceous limestone layers. This potential hydrocarbon reservoir is is supposed to be late Volkhov age, but the Kunda age can not be excluded by existing micropaleontological data. In Vergale drillcore it can be subdivided into four gradationally upward-fining beds closely resembling the Bouma division of turbitide succession. Such turbitide bed is unique for the whole Paleozoic carbonate succession in the East Baltic.

Because Ordovician carbonates in Baltoscandia are extremely poor in sand-size siliciclastic material and with only minor litofacies changes within the middle and outer ramp in the Baltic basin, we suggest that sudden inflow of terrigeneous material from north or northwesterly direction took place during the deposition of both Pakri Fm and Volkhov Collector. These events may be related to a release of new terrigeneous sediment sources in the Baltoscandian sea from some unknown uplifted structure(s) in the middle-outer ramp as a result of enhance local tectonic activity or of the meteoritic bombardment.

IS1-5

The origin of alteration fluids at the Ries crater, Germany: boron isotopic composition of secondary smectite in suevites

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The Ries impact structure (Germany) provides a good opportunity to study the evolution of post-impact development of impact craters. Clay minerals in the groundmass of the Ries suevites have been recognized for several decades. It is generally accepted that these clays were formed by post-impact aqueous alteration of impact-generated glasses and/or finely comminuted crystalline basement material at temperatures above ambient conditions. Here we present a data of boron isotopic compositions (δ11B) and B concentrations of the secondary smectite clay fraction in surficial and crater-fill suevites from the Ries crater in order to determine the source and history of changing (geothermal) fluids.

Surficial suevites, collected from 4 different outcrops (Amerdingen, Aumühle, Lehberg, Otting) within and around the Ries structure, and drill core material from the Nördlingen 1973 drill core at the suevite sequence 340 m to 525 m interval, were studied.

B-isotope composition of the <2 µm clays were measured using a Cameca 3f secondary ion mass spectrometer (SIMS) at the Arizona State University. B-isotope values were corrected for instrumental mass fractionation (IMF) by comparison with SIMS analyses of a reference material, Silver Hill Illite (Clay Minerals Society Source Clay, IMt-1).

The data show the significant difference between the boron isotopic composition of smectite in surficial and crater filling samples. The surficial suevite samples show very low δ11B values (-24.55‰) compared to crater-fill suevites (-4.07‰), except the deepest sample R09, which also shows a very low boron isotopic values (-21.8‰). After the exchangeable B was removed by NH4Cl exchange treatment, the B isotopic composition of smectite in surficial and crater fill suevites did not change significantly. Similarly to the boron isotopic composition of smectite in suevites, the δ11B composition of the fluids responsible for the alteration calculated from smectite isotopic composition in the surficial suevites (7.5±1.6‰), differs from the alteration fluid composition in crater-fill suevites (17.6±10.8‰); indicating a different origin of the fluids responsible for the alteration of the surficial and crater-fill suevites in the Ries crater. Our results suggest that the alteration in surficial suevites occurred at lower temperatures than the crater-fill suevites and at a lower pH, which is consistent with the smectite precipitation in equilibrium with meteoritic fluids. The boron isotopic composition of smectite in crater-fill suevites, suggests secondary clay formation at higher temperatures and/or at elevated pH (>8), which is possibly related to the effective removal of the available H+ ions in hydrothermal fluid through anion hydrolysis of primary silicates.

IS1-6

Water-Related Geological Events of the Eastern Hellas Rim, Mars

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Hellas is a huge, 2300 km wide impact basin on the southern hemisphere of Mars. Its eastern rim displays effects of numerous geologic events that have sculpted the surface along the run of Martian history. Volcanic events have built edifices and covered wide areas while various erosion forces have carved the rim units.

Our approach has been to study several locations where water and ice have been active and resulted in channels and other formations. The long time scale and complexity of the geologic events within the study area have forced us to approach the water- and ice-related geology by dividing the large study area to sub-areas which may better display few processes that have been most important within each of them.

On the way to establish episodes of the regional geologic history and to find how these episodes relate to the water- and ice-related events, we have found important aspects from within several sub-areas. Studies on the fluvial history of Hesperia Planum, the formation of Reull Vallis and its relation to Morpheus basin, the stratification and erosion of the Promethei Terra, and the origin of the Dao, Niger and Harmakhis Valles have given at least partial insight to such Martian phenomena as paleolake and channel formation, importance of permafrost and ground ice vs. brine storages, formation and effects of on-surface ice accumulations, and presence of icy flows and their relation to the existence of water and ice on and close to the surface. A continued series of such studies will reveal importance of water (and ice) reservoirs in the high-lying areas and if (or how) the Hellas basin acted as a final major water sink - and what all processes and events took place when amounts of water were transported from the storage volumes into the sink. As a by-product, the studies made and the results obtained have already clarified the importance of the changes in the Martian climate and environment.

IS1-7

Alteration of impact melt – implications for our understanding of Noachian of Mars?

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Clay minerals have been detected in relation with meteorite impacts, the possible result of impact glass alteration. In this project we are analyzing both experimentally and numerically impact glass transformations. These results are compared with analysis of melt-rich rocks from several different impact structures of various ages and target lithologies..

The experiments are conducted at hydrothermal temperatures (200 to 250 oC) by 1 to 3 weeks percolation in a titanium batch reactor without flowing or stirring. We are using a saline solution containing 30 mg/l NaCl, close to the composition of normal, marine water. The experiments are aiming at representing the conditions found in the melt bearing rocks within impact craters the first few thousand years after deposition. The first results show the formation of smectite, chlinochlore, Fe-pyrophyllite, saponite, analcime, talc and philippsite. The geochemical compositions of the samples are studied before and after dissolution. Finally the experimental results will be compared to geochemical modeling (PHREEQC).

During the studies we aim at explaining the formation of minerals found as natural alteration products of impact melt; smectite, saponite and other clay minerals. These minerals and associated phyllosilicates have also been indicated to appear on the surface of Mars.

In this study we show the alteration products partly to reflect the composition of both source material (glass/melt rocks) and the percolation water. The natural appearance, both on the Earth and Mars, are also controlled by other processes; e.g. surface weathering and postdepositional diagenesis.

IS1-8

Bicarbonate, olivine, hydrogen and methane

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Dissolution experiments with olivine at three different temperatures (30°C, 50°C and 70°C) and with three different concentrations of bicarbonate were conducted to investigate the possible formation of H2, CH_4 and solid products.

An increased accumulation of both H2 and CH_4 with time and temperature could be observed in the experiments with little or no added bicarbonate, whereas in the experiments with high bicarbonate concentrations, showed no CH_4 but an increased accumulation of H2.

Olivine dissolution is known to be able to form H2, which is capable of catalytically, reducing CO_2 into CH_4 in the so-called aqueous Fischer-Tropsch Type reaction (rxn 1).

4H2 + CO_2 = CH_4 + 2H2O (1)

We hypothize that CH_4 can be formed at low temperatures at reactive catalytic surface sites. The inhibition of CH_4 but not H2 formation in a system with high concentrations of bicarbonate in solution may therefore be caused by a carbonate precipitating on and blocking sites catalyzing CH_4 formation.

Our experiments indicate that formation of CH_4 is possible at very low temperatures and with low concentrations of bicarbonate in solution, which have implications for the research about Martian methane seeps as well as terrestrial, supposedly abiotic methane seeps. The formation of H2 from olivine dissolution at low temperatures indicate the potential for large areas on the early Earth to sustain the life of certain, hydrogen consuming microorganisms at temperatures low enough to also allow the survival of cells.

IS1-9

Biosignatures in secondary minerals in tertiary basalts, Breiðdalur, Eastern Iceland

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Secondary minerals are very abundant in tertiary basalts in Iceland. Zeolites, SiO2-minerals and clay-minerals are the most frequent mineral groups in the research area. Zeolithes are indicators for the regional maximum burial depth of the lava pile. Different zeolithe types form at different pressures and temperatures. This regional metamorphism is interrupted by contact aureoles around central volcanoes. In these aureoles, different mineral associations occur. This are the results of detailed mapping work of Walker G.P.L. in Eastern Iceland, during the 1950ies and 60ies.

The emphasis of this work is the secondary mineral chert, called jaspis in Iceland. It is based on the publication of Hofmann & Farmer (2000). The coloured aggregate of SiO2-minerals forms preferred at the outer margin of the contact aureole of Breiðdalur central volcano. Its colour is caused by contaminations of hematite, goethite and or celadonite. Often, this contaminations are filaments. The origin of some of them is biogenic. In particular examples they are that well preserved that they can be identified as products of Gallionella ferruginea, an iron oxidizing bacterium. Its extracellular precipitates form a typical helical structure. This species could also be found recent in conspicuous red (ferrous iron) pools in swamps of the mapping area. Other filament types can be interpreted as bacterium Leptothrix sp. or as traces of fungal hyphae. The interest of chemo autotrophs grew in the last years. It is not for so long known that subsurface microbes make up a big part of the biomass of the planet earth. Also on the seafloor there are microbial habitats. In some of them they live without light up to temperatures of 100 C (extremophiles). Black smokers on mid ocean ridges are the most famous among them, only discovered in 1977. Until now two other types of submarine habitats have been found: Conic silicate structures with hot springs north of Iceland and an off-axis geothermal field at 20 N, 15 km away from the Atlantic spreading centre, called Lost City.

The existence of such life forms raises more questions about the origin of life. Although there is no planetary body in the solar system where there are temperatures for liquid water at its surface, which is said to be a condition for life it is possible at the subsurface. There could be heat flow from inside the planetary body. Possibly primitive life hosting planetary bodies are Mars, Jupiter's moon Europa and Saturn's moon Titan.

IS 2 – Developments in data aquisition, modelling and visualization

ORAL IS 2

IS2-1

Evaluation of geological specimen composition and structure using X-ray µCT. Part 2: qualitative and quantitative analyses

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X-ray computed (micro)tomography (µCT) is a non-destructive analytical technique that can be used to create digital volumetric three-dimensional (3D) models representing the internal composition and structure of lithified and undisturbed unlithified sediment, and other material, samples. The data that comprises such models can be mined in a variety of ways, thus permitting the quantification of all specimen elements detected and differentiated using the technique. This presentation contains 3D visualisations (volume renderings) of a variety of geological specimens, illustrating what additional information can be acquired using the technique. In addition some quantitative analyses of particular interest to the geological community are outlined. Details of the technique are presented in the associated poster (part 1).

Samples were acquired at various locations within a hydrofracture system and analysed to complement detailed 2D micromorphological analyses (see Phillips et al., this volume). The 3D geometry of the system can be studied by serial thin-sectioning the volume rendering; a process that can be conducted parallel to the real thin-section or at any other angle within the sphere. The models can also be converted into other formats, including polygons and meshes, which are compatible with other software such as finite and discrete element modelling programs.

Specimens taken from within a drumlin emerging from the snout of Múlajökull, Hofsjökull, Iceland, have been scanned to analyse the morphology and orientation of any fissility present as well as any other voids, the void ratio and sediment compositional variations. As voids have a very low density they can be differentiated easily and hence modelled very accurately.

A natural debris-rich basal ice core from an alpine glacier and an artificial equivalent, containing debris-rich, bubble-rich/debris poor and clean ice, have been scanned to investigate both the properties of the two samples and the capabilities of µCT regarding the analysis of such materials. Despite the pronounced contrast between the debris, ice and voids and limited time available in which to scan the samples (at room temperature), it has been possible to achieve very satisfactory results without any damage to the specimens.

A specimen of subglacial diamict acquired downglacier of the Tynagh mineral deposit, Galway, Ireland, contains Pb oxide grains that are particularly X-ray attenuating, the sample therefore potentially compromising any analyses using µCT significantly. The application of advanced scanning and reconstruction methods have demonstrated that such problems can be mitigated or overcome completely, the resultant volume rendering being of a very high quality. The different compositional elements differentiated within the dataset were analysed using advanced software, Blob3D, specifically designed for geological specimen analysis. Data such as individual object volume, shape and orientation can be acquired automatically for all objects, thereby allowing statistically significant analyses to be conducted and such investigations as clast fabric studies to be made completely objective.

µCT offers significant potential for elucidating geological specimen characteristics non-destructively. In addition the technique permits the archiving and dissemination of sample volumetric 3D data and the seamless linking of analytical techniques applied at the hand specimen (mm-cm), micromorphological (µm-mm) and scanning electron microscopy (nm-µm) scales.

IS2-2

Mapping of Quaternary deposits at the Geological Survey of Norway: Digital workflow from field observation to database and hard-copy map

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The Geological Survey of Norway (NGU) is responsible for all geological mapping in Norway. Quaternary geology mapping (including some geomorphology) is performed at scales from 1:20,000 to 1:250,000 and NGU geologists are yearly analyzing thousands of square kilometers of terrain. Until a few years ago mapping was performed using mainly analog tools. One major bottleneck of this approach was secondary digitizing of analog manuscript maps and observations. This was a time- and resource consuming process, but a more severe problem was that spatial and thematic precision was reduced in the different stages of map production.

During the last three years, NGU has moved into a fully digital mapping workflow where geologists are now responsible and actively contributing to the digital data management until the final layout stages of map preparation. The precise workflow differs somewhat between different geological themes, since data models and methodology differ between for example Bedrock- and Quaternary geology.

The GIS backbone at NGU is ESRI ArcGIS. The Quaternary geologists use ArcGIS/ArcPAD to record observations in the field on rugged GPS-equipped laptops (Panasonic Toughbook). Another key component in the workflow is to integrate fieldwork observations from with the spatial context using digital stereo aerial photographs. This is also done in ESRI ArcGIS® using the extension ERDAS Stereo Analyst for ArcGIS®, which allows on-screen digitizing directly into a standardized GIS databases using a high resolution stereo model. All observations are thus digitized with very high spatial precision (GPS error is typically less than 15 m in the field and digital aerial photo error is less than 2 m). When the geologist is finished with field- and 3D data capture, the map database is transferred to GIS engineers that clean up the data, check for topological errors, and prepare it for incorporation into the company's ArcSDE database, and subsequent hard-copy map production. By implementing this fully digital workflow NGU reduces production time and increases mapping precision.

IS2-3

Generating digital surfaces – mapping the sub-Cambrian peneplain in southern Norway

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Palaeo-surface morphology is an important element in the analysis of the geological history. With particular emphasis on palaeo-surfaces of known age and regional significance, morphological analysis can give reliable information on tectonic, isostatic and climatic events. The usefulness of such studies can be greatly enhanced and facilitated by the use of geomorphological mapping in GIS. Thus, a first-order (palaeo)-morphological surface can be digitally constructed using computer software, starting from a limited of field-controlled outcrops and thus rationalizing dramatically the procedure for identifying and checking additional localities in the field.

As applied in the present test study we introduce two alternative methods for digital mapping and analysis of topographic surfaces of moderate morphology, such as erosional surfaces. The surface used as a test case in the present study is the sub-Cambrian peneplain, and the study area is the northern parts of the Hardangervidda. The sub-Cambrian peneplain was selected because of its well established geological characteristics, its clear geological expression defining the border between bedrock and the black Cambrian Alun shale and its associate basal conglomerate, and its well known smooth topography over large areas. Profiles through the sub-Cambrian peneplain was systematically recorded across the study area, with particular focus on regional (first-order) elevation and also identifying second- and third-order irregularities such as faults.

The two methods applied are surface fitting and region growing. The method of surface fit uses least squares to solve the problem of finding the best surface fit to the data, whereas the region growing procedure uses the surface angles and a set of properties (e.g. maximum slope between adjacent pixels) to generate surfaces from single seed GPS-positions. In both methods the analyzed surface was identified by the use of field controlled geological maps. As both methods rely on the present altitude, present surface morphology is crucial for the accuracy of each method. The surface fitting method is applicable in landscape areas characterized by great varieties in topography, whereas the region growing method is most applicable in relatively flat landscape areas. Both methods can be used to identify areas where the surface in question (in this case the sub-Cambrian peneplain), has not yet been confirmed, but is likely to outcrop. In a field study carried out the summer of 2011, several such outcrops were visited, revealing parts of the peneplain of surprising topographic regularity and consistent stratigraphical and lithological characteristics.

IS2-4

Application of SketchUp, ArcScene and GSI3D for 2.5D visualisation and analysis of geophysical data from valley-fill deposits

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Quaternary deposits such as valley-fills can be investigated through the study of geomorphology and sediment exposures if available. These can give a first insight into the general stratigraphic organization of an area. However, subsurface data are necessary to confirm these models and to outline the actual composition and stratigraphic architecture. In addition, such data usually allow for the extension of these models and numerous details can be added. Geophysical data e.g. from seismics, GPR and 2D resistivity combined with drilling are commonly used methods for subsurface investigations. However, the more data available, the more difficult it can be to get an overview of the various types of information to effectively analyse the data and to communicate the interpretations. Various ways for presenting and organizing subsurface data (mainly geophysical) are presented using ESRI's ArcScene, Google SketchUp and GSI3D. A combination of these softwares can quite easily help to provide an overview in a 3D environment of multiple types of data sets. An advantage is that the user level is relatively low and some software components are quite inexpensive. Disadvantages are that large data sets can be time consuming to prepare for visualization and there is a low interactivity between programs. GSI3D provides one step ahead to account for this problem and is also capable of e.g. volume calculations and better modelling capabilities. However, several steps of development are still needed also with regard to further management and storage of data.

IS 3 – Earth history – stratigraphy and palaeontology

ORAL IS 3

IS3-1

Palaeoarchean to upper Ediacaran provenance of the Neoproterozoic Mora Formation in northern Spain

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The Mora Formation comprises Neoproterozoic to possibly earliest Palaeozoic rocks deposited in the Cantabrian Mountains in northern Spain (Cadomia) and has a thickness of c. 4 km. The main lithologies are shales, arenites and wackes, although thin conglomeratic and a few carbonate beds are described. Two exposure areas were sampled: south of Salce (N 42° 50′ 21″, W6° 01′ 05″) and close to Mora (N42° 48′ 21.8″, W5° 49′ 23.6″). Age equivalent rocks from the Iberian Massif, further south, were subject of provenance, palaeoclimatological and palaeontological studies, where Cloudina sp. was found in limestones associated with shallow marine sandstones and shales.

The rocks in northern Spain show epizonal to lower greenschist facies metamorphism and are strongly folded, which produced a strong cleavage in the shales but left the coarser clastic rocks nearly unaffected. The succession is characterised by immature arenites and wackes as well as shales. Sandstone geochemistry points to relatively unrecycled clastic rocks and shales have a partial volcanic arc signature. It is still not clear if this geochemical signature is inherited or relates to syndepositional magmatic activity. Volcanic rocks of Ediacaran age are absent in the region but further northwest, in Galicia, granitic intrusions are exposed in more highly metamorphosed, Late Neoproterozoic, metasedimentary rocks.

Detrital zircons (n=176 < 10% discordance) point to a wide range of ages - starting with Palaeoarchaen ages with abundant Archaean zircons (n=19). Palaeoproterozoic zircons are also frequent (n=21), but Late Palaeoproterozoic grains (younger than 1850 Ma) to Early Mesoproterozoic ages (older than 1300 Ma) are absent. A small group of Late Mesoproterozoic ages could be observed (1100-1000 Ma; n= 8). Most detrital zircons analyzed (71%) produced Neoproterozoic ages; with the youngest grain at 564 Ma, corresponding to the age of Cloudina in equivalent rocks of the Central Iberian Massif.

Rocks older than the Ediacaran Mora Formation are unknown in the Iberian Peninsula, and therefore this detrital zircon population sheds new light on the geological evolution of peri-Gondwanan terranes, by indicating the influence of Archean to Palaeoproterozoic basement in the detrital record of supracrustal Neoproterozoic to Palaeozoic rocks.

IS3-2

What can detrital zircon really tell us about the depositional age and provenance of clastic sediments ? The strange case of the Precambrian Eriksfjord Formation sandstones, southern Greenland

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Zircon is an extremely resistant mineral, known to survive extended cycles of weathering and crustal recycling. Therefore, the use of U-Pb and Lu-Hf isotope data from detrital zircon separated from sediments or sedimentary rocks has become a popular tool in sedimentary correlation and provenance analysis. The approach has been used with apparent success in studies of first-order global processes such as the extraction, growth and preservation of continental crust as well as in regional studies where the purpose is to identify the source of material in a given sedimentary succession, and commonly also to limit the timing of deposition. For zircon to be useful in provenance analysis, different protosource terranes must show specific patterns of age, rock type and Hf isotopic compositions, which are inherited by the detrital zircons. This justifies a qualitative approach to provenance analysis, which has the identification of different sources as its main purpose.

The Eriksfjord Formation sandstones were deposited in the Gardar Rift of southern Greenland in Mesoproterozoic time. Dating of crosscutting intrusions suggests a depositional age around 1300 Ma. The rift structure is developed within Paleoproterozoic rocks of the Ketilidian mobile belt, near its boundary to the Archaean craton of southern Greenland. Detrital zircon from the basal unit of the succession (Majût Sandstone Member) shows a range of ages and initial Hf isotopic composition, compatible with proto sources within the Archaean craton and the Nagsaqtoquidian mobile belt north and east of the craton. Zircon with an isotopic signature that can be attributed to nearby Ketilidian source rocks are notably scarce. This suggests a predominance of distant sources, probably by recycling of older and no longer preserved cover strata. A significant fraction of zircon was dated to ca. 1300 Ma, with epsilon Hf ranging from -5 to -20. Rather than originating from an hitherto unknown igneous body within the Gardar Rift, these are interpreted as Paleoproterozoic to late Archaean zircons that have lost radiogenic lead during diagenesis and post-depositional thermal alteration related to Gardar magmatism. Although the sediments may be assumed to have originated from sources within Greenland, the age and initial Hf isotope distribution of Paleoproterozoic and Archaean zircons mimics that of granitoids from the Fennoscandian Shield. This may be coincidental, because of parallel evolution of the two shield areas, but since the two continents have shared a history in the Mesoproterozoic Rodinia supercontinent, it may also be real, reflecting long-range exchange of detritus.

The example of the Eriksfjord sandstone shows us that detrital zircon age data should not be used to constrain the age of sedimentary deposition unless the post-depositional history is well understood, and that recycling of old sediments, long-range transport and parallel evolution of different continents precludes the unambiguous identification of the primary sources of detritus.

IS3-3

Early Triassic palynostratigraphy of the Barents Sea area, a reflection of environmental instability in the aftermath of the end Permian mass extinction

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The Norwegian Barents Shelf with Svalbard forming its exposed north-western corner reveals an almost complete Triassic sedimentary record when combining outcrops with stratigraphic cores and explorations wells. An ongoing project to establish a formal regional zonal scheme for the entire Triassic succession has shown an interesting palynofloral development for the Early Triassic resulting in a new stratigraphic framework for this part of the succession. Since the distribution of spores and pollen generally follows climatic patterns it can be used as a proxy for paleoclimatic evolution. Changes in spore-pollen assemblages representing a subtle succession of recovery following the globally recognised end Permian extinction, has resulted in a high resolution palynostratigraphic framework of seven composite assemblage zones spanning the five million years of the Early Triassic. Five of these zones are calibrated to the boreal ammonoid zonation.

During one of the most catastrophic events in the history of the Earth, the end Permian extinction event, about 80 % of marine genera disappeared. Based on the palynofloras recorded in the Norwegian Arctic we argue that that many plants survived this event. Despite a marked change from gymnosperm pollen dominated assemblages in the late Permian to a total dominance of spores in the earliest Triassic the present study shows that many species and genera extended into the Triassic and gymnosperms showed a fast recovery. Consistently occurring "typical Permian"species represent characteristic elements of the Griesbachian substage. A discourse has existed as to whether these taxa are in situ or reworked. Based on various criteria including their preservation, consistent record and their gradual fading-out we consider them as *in situ*.

Pronounced changes in the palynofloras associated with distinct shifts in δ13C recorded from around the Permian/Triassic boundary (Hochuli *et al.*, 2010) as well as from around the Smithian-Spathian boundary (Galfetti *et al.*, 2007) indicate a close link between the evolution terrestrial ecosystems, carbon cycle and climate. Spathian assemblages are characterized by increasing abundance and diversity of gymnosperms suggesting stabilisation of terrestrial ecosystems.

Galfetti, T., Hochuli, P., Brayard, A., Bucher, H., Weissert, H. & Vigran, J.O. 2007: Smithian-Spathian boundary event: Evidence for global climatic change in the wake of the end-Permian biotic crisis. *Geology*, 35 (4), 291-294.

Hochuli, P.A., Hermann, E., Vigran, J.O., Bucher, H., & Weissert, H. (2010). Rapid demise and recovery of plant ecosystems across the end-Permian extinction-event, *Global and Planetary Change* 74: 144-155. doi:10.1016/j.gloplacha.2010.10.004

IS3-4

CO_2 and stomatal responses at the Triassic-Jurassic Boundary

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Stomata are pores on plant leaf surfaces through which gas-exchange takes place and are often preserved in fossil material. Stomatal density (SD: Number of stomata/ leaf area in mm^2) generally displays an inverse relationship to carbon dioxide concentration ([CO_2]) in the atmosphere: Plants adjust to fluctuating [CO_2] by reducing their SD during high [CO_2], in order to reduce transpiration, and by increasing SD during low [CO_2], to maintain the necessary carbon uptake for photosynthesis. Therefore SD of fossil plants can be used as a proxy for palaeo-atmospheric [CO_2]. Furthermore, by comparing phylogenetic groups through geological time, it has been shown that during long-term increases in [CO_2], plants have in general compensated for low SD by increasing the size of their stomata. For at least the past 400 million years, stomata have caused an acceleration of the hydrological cycle over the continents through transpiration of water taken up by roots, thus expanding the climate zones favorable to plant life. Stomata thus play a key role in CO_2 driven global change in the past, present and future.

The Triassic-Jurassic boundary (TJB, ~200 million years ago) is marked by one of the "big five"marine faunal mass extinctions and significant floral turnover as well as a major perturbation of the carbon cycle and environmentail upheaval. The events took place quickly, perhaps in just 10-20 K years. Here we present [CO_2] across the boundary, reconstructed based on multiple high-resolution SD records of phylogenetically and ecologically independent taxonomic plant groups. The compiled proxy records indicate that pre-TJB (Rhaetian), the [CO_2] was ~1000 ppm, rising steeply to ~2000-2500 pmm at the TJB, before returning to pre-TJB levels some time after the boundary.

In addition we show that stomatal size (SL) as well as density decreased dramatically at the TJB in contrast to the "optimal stomatal control"theory, which describes uniformity of the mutually inverse relationship between SD and SL. We estimate that this resulted in a 50-60% drop in stomatal and canopy transpiration as calibrated using a leaf gas-exchange model. Decreased transpiration may lead to increased runoff and erosion at the regional and perhaps even global scale, resulting in increased flux of nutrients from land to oceans, leading to eutrophication, anoxia and ultimately loss of biodiversity. We propose that the consequences of stomatal responses to elevated [CO_2] may link terrestrial and marine mass extinction via the hydrological cycle.

IS3-5

Tracing the phytogeographic history of Northern Hemispheric angiosperms using fossils, tectonic evidence, and palaeoclimate

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The modern distribution of many angiosperms is the result of a number of intertwining factors and events that took place in the geological past. Several extant taxa show, for example, an Eastern North American - East Asian disjunct distribution, suggesting that they must have had a more continuous Northern Hemispheric distribution during earlier parts of the Cenozoic. Other plants are presently found only in East Asia and/or Europe, but have a North American fossil record, and vice versa, also suggesting a wider or different distribution than at present. The fossil records of, for example, *Decodon* (Lythraceae), *Fagus* (Fagaceae), *Aristogeitonia* (Picrodendraceae), and *Tetracentron* (Trochodendraceae), show that these taxa had a much wider and/ or different distribution in the early to late Cenozoic than at present.

There are basically three main factors that influence the occurrence and dispersal of plants; 1) climate, 2) dispersal mechanisms, and 3) physical terrestrial or oceanic barriers and biotic factors such as competition with other plants. Earth climate systems prevent warmth-loving plants (at low latitudes) from migrating north (to higher latitudes) unless global climate becomes warmer and temperature equilibrium lines are shifted. The dispersal mechanisms of plants affect both the distance and the speed of dispersal. For example, plants producing large diaspores that are dropped close to the mother plant (dyschory) take longer time in spreading over wide distances as compared to plants producing small wind (anemochory) or bird (zoochory) dispersed diaspores. They are also more unlikely to cross water barriers or high mountains caused by tectonic movements or orogenic events. The formation or closure of inland seas, openings of oceans, the rise and erosion of mountains, and the change in global climate since the Cretaceous, in combination with the dispersal mechanisms of the plants, has resulted in the complex present distribution of angiosperm taxa. When the fossil records of plants, such as the ones mentioned above, are correlated to major geological events and palaeo-ecological factors, it is possible to trace plant dispersal patterns both in time and space.

IS 4 – General contributions to geosicence – Open for session proposals

IS4-1

GeoTreat – the geotourism app for Fennoscandia

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In most of the Nordic countries, the public awareness and knowledge about geology and its implications to modern society is low. An increased awareness is of great importance since geology is a natural component in many aspects of everyday life and of industries, infrastructure and policymaking. When aiming at an increased awareness, geotourism is a channel worth exploring, since tourism is a source that is hard to beat when it comes to experiences making both people and economy to grow. Internationally, geotourism is a growing activity, but the infrastructure of geotourism in the Nordic countries is underdeveloped. The Geological Surveys of Denmark, Finland, Norway and Sweden are therefore developing a mobile phone app for domestic and international visitors with an interest in adding value to their visit. The idea is that other countries will be welcome to add their data to the GeoTreat-app and that the app will have a component of interactivity, making it interesting for use in schools for example.

IS4-2

The Norwegian millstone landscape: new insight from multidisciplinary research

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Throughout the last ten to fifteen years the Norwegian millstone quarries have been investigated and mapped and so far fifteen production sites for hand querns and millstones are put on the map. For the last three years the investigations have been focused even more due to the Millstone project hosted by the Geological Survey of Norway. This paper presents some of the main conclusions from ongoing research performed by geologists, archaeologists, historians and craft development people. The very first rotating hand querns in Norway were produced from a wide range of rock types and were carved from erratic blocks or scree material. But at some point during the 8th or 9th century people began to carve millstones directly from the solid bedrock at Hyllestad. The quarries in Norway vary in size from the production of a few pairs of stones to more than a 100 000 pairs. The stones were produced almost exclusively from mica schist with knobbles of the hard minerals garnet or staurolite. The production of millstones was the beginning of perhaps the most long-lasting and most important stone industry in Norway through the Viking Age until recent. The history of the millstone quarrying ends at the beginning of the 20th century when industrialization eliminated the need for natural stones.

IS4-3

Paleogeopraphy and depositional environment of Grumantbyen Formation (Paleocene), Svalbard

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The Paleocene Grumantbyen Formation on Svalbard is one of the least understood units in the geological record of Svalbard, even though it's well exposed in the landscape, especially in the vicinity of Longyearbyen, the largest settlement on the archipelago. No detailed studies have previously been published on the formation. The aim of the project was to increase the understanding of the depositional environment and the paleogeographic development.

Sedimentary studies on cores from Nordenskiöld Land and Nathorst Land, together with fieldwork in Nordenskiöld Land has been the basis for this study. The Grumantbyen Formation is intensely bioturbated and almost devoid of physical sedimentary structures, thus ichnological analysis has been an important part of the work process.

Of the trace fossils identified, Nereites, Phycosiphon, Planolites, Palaeophycus and Macaronichnus are dominating. The investigated succession, which also comprises the upper part of the underlying Basilika Formation, has been divided into four different facies on the basis of trace fossil appearance and characteristic textural features. The succession comprises three shallowing upwards parasequences that extend through the whole study area. The Grumantbyen Formation appears to have a relatively constant thickness in the north, from 150 -175 m, with a slightly decrease towards the south, to approximately 130 m. The combined thickness of Grumantbyen Formation and Basilika Formation appears to increase in thickness in the same direction. The formation is interpreted to be an outer shelf sand deposit, with a deltaic sediment source in the northeast.

The large thickness combined with absence of major facies shifts in most of the succession indicates that there has been a balance between the rate of sediment supply and the rate of subsidence during deposition. Excepted from this is a potential fall in relative sea-level and subsequent erosion recorded in the upper part of the formation expressed by an abrubt shift in facies from distal marine to shoreface environment.

IS4-4

Relay evolution in carbonate rocks: implications for localizing point sourced conduits for vertical and lateral fluid flow

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A fully breached relay zone was investigated to gain insights into relay growth and breakage in tight carbonate rocks. Associated fracture patterns were mapped in detail to gain a qualitative understanding of damage zone evolution and fracture-related fluid conduits associated with fault overlap zones. Internally, the breached relay zone is characterized by dilatant brittle deformation in mechanically strong limestone in the upper part of the ramp, and down-dip shear along extensional detachments in stratigraphically lower and mechanically weak shale layers at the base. The linking damage zone is characterized by multi-directional fracture patterns, including fracture corridors at high angles to the main fault system. The causal relationship between fault growth and the complex fracture patterns lies in modification of the local stress fields of overlapping/linking fault segments. Increasingly complex fracture patterns may be expected during progressive evolution and linkage of fault segments. The observed fracture patterns, in concert with complex juxtaposition relations generated by dipping relay beds, indicate that fault linkage points in carbonate rocks represent localized conduits for cross-fault as well as vertical along-fault fluid flow. This has wide-ranging implications for fluid transport in the brittle crust. Examples of the importance of fault linkage zones include their roles as (1) foci for geothermal activity and ore deposits, (2) focal points for structurally controlled diagenetic alteration (e.g. dolomitization), (3) hydrocarbon migration pathways, (4) conduits for injection- and hydrocarbon fluids during production, and (4) zones where seal integrity in petroleum traps may be compromised.

IS4-5

A revised Michel Levy interference color chart based on first principles calculations

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Students are commonly confused when first introduced to the phenomena of interference colors and determination of birefringence. Today most optical microscopes are only equipped with $_2$ lambda and 1 lambda plates and hence rely on different versions of the Michel Levy interference color charts. This is often a big challenge, partly because of the pour representation of the observed colors on the reference charts.

The aim of this study as to produce a birefringence color chart that presents the interference colors as they are observed in the microscope by using the original light interference equations to produce the spectral colors and then transform them into human vision and device colors that can be viewed on a computer screen.

ORAL
IS 4

The chart is based on the original equation of light interference in anisotropic crystals and is represented as human vision by transformation to first the CIE1931 XYZ color standard and then to AdobeRGB. The chart gives a realistic representation the colors observed in a petrographic microscope. An alternative birefringence color chart developed by the author in dialogue with Professor M. Raith, University of Bonn is also presented. This chart enables the direct reading of birefringence form thickness of sample and observed interference color directly below the observed color.

Both charts have been applied this semester in optical mineralogy at the Universities in Bonn and at the Department of Geology and Mineral Resources Engineering, NTNU, Norway. The main impression is that the charts improved the understanding and interpretation of interference colors, which is an important aspect in the identification of common silicate minerals.

IS4-6

The fault architecture and damage zone characteristics of normal, inverted faults of the Northumberland Basin, northeast England

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Fluid flow in faults has lately gained much attention due to its impact on production in hydrocarbon fields and its potential influence on the sealing capacity of cap rock. In the modeling of such systems detailed understanding of fault architecture is crucial.

The present study, conducted in the Northumberland Basin of northeastern England comprises four extensional fault systems with a normal offset ranging from 10 to 200 meters. The faults affect Carboniferous coal-bearing sediments. The four studied localities are situated northeast of Newcastle where faults are well displayed in three dimensions along cliff sections and the beach. Three of the faults occur in a sequence of alternating shale, siltstone, sandstone and coal-beds, whereas the fourth also cuts a limestone unit.

The data used include aerial photographs, LiDAR scans and field data analyzed by traditional statistical methods (fault architecture, fracture frequency diagrams, orientation data and thin sections). The field study included the following steps:

1) The outcrops were studied by the use of aerial photography to determine the traces of the most important faults,

2) the master faults were studied in outcrops and the general pattern of displacement and the fault architectures were established,

3) fracture frequency diagrams covering footwall, hanging wall and fault cores were generated,

4) and the relation between fault core lenses and high strain zones (fault rocks and fault smear products) was determined.

The fracture frequency diagrams indicate more intense deformation on the hanging wall side than on the footwall side. However, most deformation was accommodated in the fault core. Fault-related folds and drag-structures are evident, and various contractional structures are observed, especially in fine-grained rocks and coal.

The steep geometry of the faults is ascribed to reactivation and/or mechanical inhomogeneities related to lithological contrasts. The fault core thickness is related to the amount of displacement, and is proportional to the amount of lens-shaped rock bodies within the core. The lenses are thicker relative their length axes than examples previously reported in the literature. We conclude that the individual fault systems exercise great control on lens dimensions.

Complex fault geometries are evident both in macro an micro scale and indicate several stages of deformation, compatible with 1) syn-sedimentary / soft-sediment normal faulting, 2) post-consolidation normal faulting 3) tectonic inversion. The complex geometry associated with the multistage structuring is likely to influence fluid flow across and along the studied fault zones. Whether the fault systems are sealing and how they affect fluid flow is strongly influenced by the lithology, since sandstone and limestone produce drag structures and confined lenses, whereas shale contributes to smear along fault planes.

IS4-7

EMODNET GEOLOGY – Data on seafloor geology and substrates for pan-European marine assessments

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The marine departments of the geological surveys of Europe (through the Association of European Geological Surveys - Euro GeoSurveys) have taken an initiative and launched EMODNET -Geology project to compile and harmonize their information from the Baltic Sea, Greater North Sea and Celtic Sea (http://www.emodnet-geology.eu/). The project yields information on seafloor geology, sea-bed substrates, geological boundaries and faults among others. The EMODNET -Geology (2009-2012) is one of the European Marine Observation and Data Network projects and it is funded by EU Commission. The project has 14 partners and NERC/BGS is the project coordinator.

We will present the EMODNET sea-bed substrate map at a scale of 1:1 million with confidence assessment. The project partners have identified various local and regional substrate maps and have merged those to form a full-coverage sea-bed substrate map for the whole study area. An index map identifies initial data layers and provides information on metadata: variation in remote observation, interpretation and ground-truthing methods. Where necessary, the existing substrate classifications were harmonized into a shared classification scheme taking to account the integration with hydrographic, chemical and biological studies. This EMODNET reclassification scheme consists of four substrate classes defined on the basis of the modified Folk triangle (mud to sandy mud; sand to muddy sand; coarse sediment; mixed sediment) and three additional substrate classes (boulder, diamicton, rock).

The sea-bed substrate map (GIS) is available through One-Geology -Europe portal. However, the focus of the EMODNET -Geology is not only to deliver digital information on substrate distribution, but also to highlight data gaps and deficiencies. In addition, the experiences and remarks from this project can be utilized when mapping new marine areas, e.g. Arctic seas.

IS4-8

Holocene saline water inflow changes into the Baltic Sea, ecosystem responses and future scenarios – BONUS+ INFLOW project

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Global climate change, growing population and increased activities in marine and coastal areas have threatened the marine environment worldwide. This deteriorating is valid also for the Baltic Sea, the European inland sea. Effective and sustainable marine management and more reliable predictions of the future Baltic Sea depend on improved understanding of the natural variability of the Baltic Sea ecosystem and its response to climate and human induced forcing.

The INFLOW project has used integrated sediment multi-proxy studies and modelling to reconstruct past changes in the Baltic Sea ecosystem (e.g. in saline water inflow strength, temperature, redox and benthic fauna activity over the past 6000 years, concentrating on time period that covers two natural climate extremes of Little Ice Age and Medieval Climate Anomaly); to identify the forcing mechanisms of those environmental changes; and to provide scenarios of impact of climate change on the Baltic Sea ecosystem at the end of the 21st century.

New results of natural past changes in the Baltic Sea ecosystem, received in the INFLOW project, provide a discouraging forecast for the future of the sea. Integrated modeling and sediment proxy studies reveal increased sea surface temperatures and extended seafloor anoxia (in deep basins) also during earlier natural warm climate phases such as the Medieval Climate Anomaly. The INFLOW project has shown that there is strong natural variability at millennial to multi-decadal timescale which will have some impact on the future Baltic.

Modeling and sediment proxy results suggest that under future IPCC scenario of a global warming there is likely no improvement of bottom water conditions. Thus, the already taken measures towards a better Baltic Sea are insufficient to guarantee a healthier future for the Baltic Sea. Therefore nutrients loads, among other, need to be reduced in the future too in order to minimize the effect of sea surface temperature changes.

INFLOW (2009-2011) (http://projects.gtk.fi/inflow/index.html) is one of the BONUS Research Programme (http://www.bonusportal.org/) projects that generate new knowledge in support of decision-making in the Baltic Sea region. It is funded by national funding agencies (e.g. Academy of Finland) and the EU Commission. Geological Survey of Finland (GTK) coordinates the INFLOW project that has 9 partners in 7 countries of the Baltic Sea Region: Finland, Norway, Russia, Poland, Germany, Denmark, and Sweden.

THEME: A TRIBUTE TO SIGURÐUR ÞÓRARINSSON (SÞ)

SÞ 1 – Volcanic eruptions in historical records

SÞ1-1

Volcanic eruptions in prehistory – the Laacher See case study

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Around 12.920 BP the Laacher See volcano erupted catastrophically (Schmincke et al., 1999). With an eruption column an estimated 40 km high, this eruption sent tephra across a wide swath of Europe, from Italy in the south to the Baltic Sea region in the north (van den Bogaard and Schmincke, 1985; van den Bogaard et al., 1990). This paper explores how this eruption affected contemporaneous human societies by investigating a multitude of empirical strands (Riede, 2008). Remarkably, the Laacher See eruption appears to have led to the emergence of the first indigenous Scandinavian Stone Age culture. This culture, the so-called Bromme culture, differs from its neighbours by range of characteristics (spatial circumscription, hunting weaponry, and flint technology - Riede, 2009), and its origin and fate require explanation. Formulating hypotheses about possible links between the eruption, its tephra fallout and plant, animal and human communities requires - as Professor Thorarinsson pioneered - that different disciplines are welded together. I explore some of these hypotheses and the empirical investigations of the archaeological and palaeo-environmental records that have been used to test them (see also Riede and Bazely, 2009; Riede et al., in press; Riede and Wheeler, 2009.

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SÞ1-2

Short accounts of large events

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In a letter written in Eyjafjördur, North Iceland on March 11, 1477 the present state of affairs is described as follows: 'Gathered were the clerks and laymen from between Varðgjá and Glerá, and they spoke of those wonders, singular occurrences and menaces which were then current in the form of fires, the falling of sand and darkness caused by ash and terrifying thunderings. Owing to these wonders animals were deprived of their sustenance although there was no snow on the ground' (translation by Thorarinsson, 1958). This is the only known reference to the predominantly explosive, basaltic eruption on the 65 km long Veidivötn fissure in South-central Iceland. It produced ~10 km^3 of tephra and is one of the largest recorded eruptions of its kind. The AD 1477 Veiðivötn tephra was carried towards northeast and east and the 1 cm isopach covers almost half of Iceland. It is the thickest historical tephra layer in Northeast Iceland, where it was initially referred to as 'layer a'.

The descriptions of the Hekla eruption in AD 1104, found in four contemporary annals, were even shorter. They simply state: 'The first coming up of fire in Mount Hekla' and the longest one is only 7 words in the original text. Some of the annals refer to the following winter as 'sandfall winter'. The tephra fall from that eruption, equivalent to ~2 km^3 of white silicic tephra, also covered about half of Iceland and caused farms to be abandoned.

Accounts of volcanic activity and related events appear in one of the first books written in Icelandic, Landnámabók (the Book of Settlement). These descriptions are short and to the point: e.g. 'the coming up of fire' (volcanic eruption) and 'an earth-fire' (lava flow) but also indicate drastic environmental changes. In less than 70 words they indicate the timing and type of activity, areas affected and the aftermath of the largest volcanic eruption experienced to date by the Icelandic people, the AD 934-40 Eldgjá eruption. It took place on a 75 km-long, partly ice-covered volcanic fissure that expelled ~4.5 km^3 of basaltic tephra blanketing ~20.000 km^2 in South Iceland and 18.2 km^3 of lava that covered 780 km^2, thereof about 400 km^2 in the lowlands, forcing the settlers to relocate. Jökulhlaups accompanied the eruption and flooded the area known today as Mýrdalssandur, their deposits filling in a small fjord. The Eldgjá eruption also released ~220 Mt of SO2 into the atmosphere and thus is the worst volcanic pollution event from a flood lava eruption in the last 11 centuries. The effects were felt across the northern hemisphere and must have been particularly harsh in Iceland.

The Eldgjá eruption may have terminated the migration of people to Iceland. It is hardly a coincidence that the Settlement Period, which according to the Book of Settlement lasted about 60 years, came to an end in the 930ies, at the time when a major disaster had occurred. It was a bad publicity for Iceland and best forgotten.

SÞ1-3

Perception of volcanic eruptions in Iceland

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Iceland is a hot spot situated in the middle of the North Atlantic and one of the most active volcanic regions on Earth. On average a volcanic event occurs every 5 years. This display of nature has, however, only been observed by man for 11 centuries or since settlement in the late 9th Century AD. The settlers did not have to wait long to be introduced to the ferocity of Icelandic volcanism, because within the first century at least six eruptions had taken place, including the Great 934-940 Eldgjá flood lava eruption (~20 km^3 of lava and tephra), which is the largest event of its type in the last 2000 years. Since then every generation of Icelanders has been exposed to volcanic eruptions and their consequences over the ~1140 years of habitation. Therefore, volcanism has been a significant force in shaping Icelandic society, to such an extent that volcanic eruptions are imprinted into the cultural landscape. The relatively short and well documented history of Iceland and its volcanism in historical time provides the ideal platform for assessing the societal perception towards volcanic eruptions and changes therein with time. Analysis of these records gives the impression that Icelanders looked upon volcanic eruptions as a natural phenomenon and had acquired basic understanding of such events very early on, as can be inferred from reply attributed to heathen priest Snorri during the parliamentary debate on Christianization of Iceland in the year 1000 AD: "At what were the gods enraged when the lava which we are now standing on formed...". Irrespective of the accuracy of this account, the fact that it links older lava flows with past eruptions illustrates that general understanding of such events existed at the time when 'Kristni Saga' was written in the mid 13th Century. Another aspects of the 10th -13th Century cultural landscape is revealed by this account: authoritarian figures in society promoted pragmatic views towards natural events, but at the same time a portion of the population was disposed to connect such events to the supernatural. Although these two opposing perspectives have co-existed throughout Iceland's history, the pragmatic perception recurs and prevails.

So, why did this pragmatic view develop and persist in Iceland? I suggest that this view originated and endured out of social and cultural necessity. No part of Iceland was exempt from the effects of volcanic eruptions, although the nature and magnitude of the impacts was variable between regions. The impact was also non-discriminatory - it affected people from all levels of the society and brought hardship and devastation to estates of prominence as well as farms and crofts. Attributing volcanic eruptions and their effects to punishment by the supernatural was self-defeating; it would undermine integrity of the material and spiritual authority and thus destabilizes the establishment.

SÞ1-4

Late Holocene terrestrial ecosystem change in West Iceland.

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Soils and lake sediments preserve important records of long term ecosystem change. Lakes contain a strong record of catchment soil and erosion via the inputs of minerogenic and chemical erosional products, while soil profiles store records from the local area. In this way lakes and wetland Histosols act as sinks for eolian deposits and record soil erosion of both local and regional character. Another important variable for the study of soil erosion and soil formation is vegetation, which can be studied using the analyses of pollen and other fossilised plant material. For Iceland, preserved tephra layers of known origin and age in sediment profiles may form chronological framework to assess terrestrial ecosystem change.

Iceland provides a rare opportunity to assess impact of human activity on soil erosion and ecosystem change. Before the Norse settlement around AD 874 there is no evidence of human settlement or mammalian herbivores in Iceland. This event is made stratigraphically identifiable by the Landnám tephra from AD 871. As a result it is possible to identify purely environmental archives from before this time in the Holocene, during which climates have been similar, warmer or cooler than today, while anthropogenic impact can be studied from sediments overlying this tephra.

In this study we discuss the terrestrial ecosystem change in West Iceland over the last 4000 years through records from the lake Breiðavatn and from a Histosol at Hólakot near the lake. The chronology is reconstructed through tephra layers including the 871 AD tephra, and 14C. We use indicators, such as changes in the rates of sediment and soil accumulation, Carbon (C), Nitrogen (N), C:N, bulk density, soil water content, pH, and vegetation change to reconstruct past instances and patterns of land degradation and erosion. We compare this data with a 3000 year long record of chironomid-inferred temperatures that were reconstructed from the lake Breiðavatn, while a previous study of plant macrofossils is available for Hólakot. Of specific interest was the impact of natural forces on the terrestrial ecosystem before arrivals of the humans and the impacts of the initial settlement.

The study benefitted from support by the University of Iceland Research Fund, Rannis Grant No. 080655021, Snorrastofa Medieval Centre, and Targeted Investment in Excellence, Climate, Water and Carbon Project, Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH, USA.

SÞ1-5

The Askja 1875 eruption: World's first map of an ash plume and properties of the ash from samples collected in Norway in 1875

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The 29-30th March 1875 there was a major ash fall across Norway and Sweden that soon was identified to stem from the eruption of the volcano Askja on Iceland. This led the Norwegian meteorologist Henrik Mohn onstruct a map of the ash plume and the time of ash fall at each site with the purpose to understand movement of air masses (Mangerud, 2011). According to Sigurdur Thorarinsson (1981a, 1981b) this is the very first map published of an ash plume. An extensive account on the eruption and its tephra is recently given by Carey et al. (2010).

The Askja 1875 ash is potentially a very useful age level in stratigraphical studies in connection with sea-level changes, retreat of glaciers, pollution studies, etc. because precise dating is difficult for the last couple of centuries. The ash was indeed found at a number of sites in Christer Persson´s (1966, 1967, 1971) pioneer studies of ash beds in Holocene sequences in Scandinavia, and is recently found far north (Pilcher et al., 2005) of the plume originally shown by Mohn.

In this presentation we will outline the history of the ash fall in Norway and Sweden and how Henrik Mohn utilized this data along with other available information to construct his map. We will also present new grain size and chemical data on ash samples collected in Norway in the year 1875.

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SÞ1-6

The Grímsvötn 2011 eruption – scientific and social views

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On May 21 2011 an eruption began in the ice covered central volcano of Grímsvötn on the Eastern Volcanic Zone in Iceland. It went on for seven days and was officially declared over on the 28th of May. This eruption produced an order of magnitude more of freshly fallen tephra during the seven days of eruption than during its past eruptions. An increase in earthquake activity was observed several months before the eruption. An hour before the eruption started the earthquakes became more frequent and volcanic tremor increased. The onset of the eruption is set between 18 and 19 hours GMT. The volcanic plume rose up to more than 20 km during the first hours and tephra was deposited on inhabited areas south of the volcano, more than 50 km from the eruption site. Due to weather conditions it was impossible to reach the eruption sites during the first days of eruption making tephra observations important for gaining better understanding on the course of events during the eruption but the volcanic deposits show that the activity switched repeatedly between phreatomagmatic and magmatic activity.

People living in the area between Mýrdalsjökull and Vatnajökull have seen quite a lot of volcanic eruptions through the ages but the area can be affected by eruptions in e.g. Katla, Grímsvötn, Bárdarbunga and Eyjafjallajökull. This is one of the reasons for the nickname, Eldsveitirnar, for the area, or "the fire districts". As the Grímsvötn eruptions in 1998 and 2004 were rather small and did not affect people living in this area, located 60-70 km away from the volcanic sites, they were not frightened by the news they heard at 19 hours GMT the 21 of May 2011. They went on with their daily lives, farmers continued to attend to their livestock, some of them changed their routine a bit and went to fetch their cameras to take photographs of the beautiful volcanic plume rising over Vatnajökull. Nobody expected that the night and following days would bring intense tephra fall obstructing daylight in one of the brightest spring months. Old tales known by the inhabitants of the area were brought to live and people understood that it was no exaggeration that people went out during the middle of the day during the Katla 1918 eruption and did not see their hands. People could hardly find their way to their barns, sometimes less than 100 meters away from their front door, a walk taken several times per day every day of the year. In this presentation we shall compare the contemporary accounts from people experiencing the Grímsvötn 2011 eruption and its tephra fall to other accounts such as the ones given by people 93 years ago during the Katla 1918 eruption. The comparison reveals a remarkable similarity even though technological advances have tremendously changed people's way of living.

SÞ 2 – Eruption types and styles in Iceland and long distnace plume transport

SÞ2-1

What caused the Grímsvötn 2011 eruption to penetrate into the stratosphere?

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The last eruption of Grímsvötn began on 21 May and its duration was shorter than a week. Its eruption column rose higher than 20 km during the first hours and therefore penetrated into the stratosphere. Such forceful eruption has not been documented before at Grímsvötn volcano although the tephra record suggests several large explosive eruption during Postglacial time.

Since the beginning of the 20th century Grímsvötn has erupted 10 times. All eruptions are phreatomagmatic due to the presence of glacial melt water at the eruption sites. The basaltic tephra produced is of uniform composition, evolved qz-normative tholeiite, with less than 10% plagioclase, clinopyroxene and rare olivine crystals. Only high-precision measurements of trace element concentrations reveal slight compositional variability. A steady increase of Th concentration is observed in the Grímsvötn products since the eruption of Laki 1783-84. This suggests tapping of evolving magma in a chamber without input of more primitive deep-derived magma. This pattern of a semi-closed magma chamber is disrupted in the 21st century and the 2004 eruption produced tephra with both the highest and average Th concentration. Therefore, the intensity of the 2011 eruption could result either 1) from an eruption of more evolved magma with higher gas concentration than before or 2) from a fresh basaltic recharge of the plumbing system beneath Grímsvötn.

New analysis of the 2011 tephra collected at three different locations during the first hours of tephra fall and a composite sample of tephra from the first three days have indistinguishable major element and Th concentrations. The major element composition is the same as before whereas Th concentration is lower than expected from the temporal evolution since the Laki eruption. Sulphur concentrations are relatively low in the groundmass glass indicating high degree of degassing ($S = 821 \pm 22$ppm in 2004 tephra but 509 ± 21 ppm in the 2011 tephra). Important degassing also is indicated by the presence of abundant microlites. Small but significant variations in glass compositions indicate several liquid-line-of-descent, possibly at somewhat different pressure, with MgO and K2O concentrations ranging from 4.6-5.7% and 0.46 to 0.60%, respectively. Plagioclase-melt geothermometer suggest an eruption temperature of 1100 ± 4 °C with less than 10 ° difference between different basalt glasses. Trace-element ratios and Sr- and Nd-isotope composition are indistinguishable from earlier products of Grímsvötn volcano.

These results suggest the following scenario: the magma plumbing system beneath Grímsvötn has been recently recharged with a gas-rich (S and CO_2) basaltic melt. The basaltic recharge brought in a volume of fresh magma that degassed over a considerable depth range and remobilized magma pockets at different depths with somewhat variable compositions. This resulted in mingled basaltic magma with higher gas content than before and the sub-phreatoplinian character of the last Grímsvötn eruption.

SÞ2-2

Assessing simple models of volcanic plumes using observations from the summit eruption of Eyjafjallajökull in 2010

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A volcanic eruption plume enters into an atmosphere that has a pre-existing structure to it, in terms of temperature, moisture content, stratification, wind and wind shear. How high the plume rises depends predominantly on the strength of the eruption. However, through dynamic interactions with the rising plume, the ambient atmosphere also exerts an influence on how high into the atmosphere plume material can be lofted and how far afield it is distributed.

Idealized models of volcanic plumes consider three dynamically distinct regions, the gas thrust region, where the dynamics is dominated by the exit velocity at the vent, the buoyancy driven convective region and the umbrella cloud where vertical motion is small.

During the 2010 summit eruption at Eyjafjallajökull, several cameras where located with a view of the volcano. The time resolution of the images was 5 seconds and the vertical resolution was 7m. Based on this data, and on video recordings made by a TV crew we have analyzed variations in the speed of the updraft in the plume, the horizontal wind profile above the vent, and changes in the size of individual thermals as they rise in the atmosphere.

We compare the results from the analysis with results obtained using simplified models of volcanic plumes. The results tend to agree with the simplified models, in that the boyancy driven phase seems to be well resolved by the data. However, resolving the shallow gas thrust region is more of a challenge.

SÞ2-3

Energy fluxes in volcanic eruptions

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The energy carried to the surface of the earth in a volcanic eruption is dominantly the heat of the erupted material. This energy is released in a variety of ways. In an effusive eruption on land the heat is mostly advected from the lava by interaction with the atmosphere, while in a subaqueous setting the energy is transferred to the surrounding water. For a plinian magmatic eruptions it is commonly assumed that most of the energy is lost to the atmosphere through the eruption plume. In the case of a phreatomagmatic eruption some energy is also lost to a surrounding water body, by heating and boiling, and in the case of a partly subglacial eruption, a substantial part may be lost to ice melting. For these types of eruptions energy partitioning may therefore be highly variable. However, provided that good constraints can be placed on some of the principal terms in the energy budget, the energy available to drive the eruption plume, can be estimated. We have carried out such an analysis for the eruption of Grímsvötn in November 2004. It lasted for six days and produced only basaltic tephra. About half of the erupted material was deposited at the eruption site, within a 500-700 m wide and 150-200 m deep ice cauldron formed in the eruption. The remaining half formed a well defined tephra fan towards north and northeast. Through repeated pre- and post-eruption surveying of glacier geometry the volume of ice melted in the eruption could be measured. Detailed measurements of key parameters such as volume and mass of erupted material were carried out and a total deposit grain size distribution could be determined on the basis of extensive sieving of both proximal and distal parts of the deposit. The heat capacity of the tephra and energy used for generation of new surface (fragmentation energy) was determined through laboratory measurements. On the basis of these data, the total mass of erupted material was determined as about 6-1010 kg, and the total thermal energy of the eruption was found to be 7- 1016 J. Moreover, the partitioning of the total energy into energy lost to: a) ice melting, b) meltwater heating, c) residual heat in volcanic pile, d) kinetic energy and e) total fragmentation energy could be determined. The results indicate that about a third of the energy was used for ice melting, that about a tenth was expended for meltwater heating and remained as heat in the crater, and that energy expended for fragmenting the magma amounted to a few percent. The remaining energy, about half of the total, was available for driving the sustained 6-10 km high eruption plume during the 33 hour long main phase of the eruption.

SÞ2-4

Resuspension of ash from the Grímsvötn volcanic eruption

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On 13 September 2011, large quantities of ash from the Grímsvötn eruption were resuspended into the atmosphere and transported over SE-Iceland.

From airborne observations of the dust stroke, satellite imagery, observations of visibility and analysis of previous plumes, the rate of suspension is estimated to be of the order of 1000 kg/s which is roughly one tenth of a typical Bodele dust storm.

As in the Bodele depression, the dust is suspended due to topographically generated strong winds. However, unlike the Bodele dust storms, which are associated with relatively large scale channeling of the winds, the present windstorm has a smaller spatial extension and is associated with gravity waves on the downslopes of Vatnajökull glacier. Furthermore, after the first winter snows on Vatnajökull, thesource of most of the resuspended ash is permanently cut off, while the Bodele dust storms are in fact most active during winter with a continous supply of source material

Numerical simulations of the flow confirm that the surface friction velocity below the gravity wave has values close to 1 m/s. Elsewhere, the values are much less, and below the critical threshold for extreme suspension of dust. Downstream of the wave, there is a hydraulic jump, followed by a well mixed boundary layer of roughly 2 km depth.

SÞ 3 – Tephrochronology – on land, in ice, lakes and sea

SÞ3-1

Framework for the tephra stratigraphy and chronology in western Iceland for the last 12ka

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In the last 12 ka explosive eruptions in Iceland have produced numerous widespread tephra fall deposits with typical recurrence intervals in the range of 5-10 years. This elevated eruption frequency coupled with high sediment accumulation (up to 5m/1000yrs) makes lake sediments in Iceland ideal for constructing high-resolution Holocene tephra chronologies. Such chronologies are important for studies on history, nature and evolution of explosive volcanism in Iceland and for timing of climate modifying events.

A component of the VAST (Volcanism in the Arctic SysTems) program was to establish comprehensive records of Holocene tephra layers in south, central and western Iceland. The pilot cores are from four lakes featuring continuous sediment records back to ~11-12 ka BP. Two of the lakes are situated in the southern lowlands between the West Volcanic Zone (WVZ) and East Volcanic Zone (EVZ), the third, Hvítárvatn, is on the flank of the WVZ in central Iceland and the four is located ~80 km northwest of the WVZ. Correlation of these archives is based on chemical fingerprinting of local and regional marker layers and is underpinned by well characterized key marker layers within the Holocene succession in Iceland.

The Holocene chronology for western Iceland has been established by physical and chemical characterization of >450 tephra layers identified in our pilot cores. Correlations indicate that these archives contain a record of ~160 explosive eruptions spanning the last 12 ka. More than 90% of the tephra layers originated from volcanic systems in the EVZ. Majority of the layers (~70%) is from either the Katla or Hekla-Vatnafjöll volcanic systems and about 20% are from the more distal Grímsvötn or the Bárðarbunga-Veiðivötn systems in the EVZ.

Such an extended record on explosive eruptions in Iceland inevitably provides new insight into the history and nature of the volcanism and some of the new and interesting results obtained so far include the following:

- Tephra production in Iceland is be dominated by eruptions at central volcanoes within the EVZ, where basaltic explosive volcanism is enhanced by the glaciers that cover the Katla, Grímsvötn and Bárðarbunga central volcanoes.
- Tephra layers from Katla are fairly evenly dispersed throughout the 12 ka period and the record is dominated by tephra layers of transitional basalt and dacite composition, but also features a few mid to early Holocene silicic tephra of Vedde-like composition.
- The Hekla-Vatnafjöll volcanic system produced 10-15 basaltic tephra layers in the period from ~10.5-11 ka BP, which are characterized by composition identical to the I-THOL-2. Four additional basaltic Hekla tephra layers are present in the period 7-10 ka and the oldest Hekla layer of intermediate to silicic composition in our archives is between 8-9 ka.
- A ~500 year-long period, from ~10.4-9.9 ka BP, of intense basaltic explosive eruptions took place at the Grímsvötn volcanic system, producing at least 5 widespread tephra layers of composition identical to that of the Saksunarvatn tephra.

These results will undoubtedly have an influence on how we view and interpret the late glacial and Holocene far-distal tephrochronological record in the North Atlantic region.

SÞ3-2

Late glacial and Holocene tephra stratigraphy on the North Icelandic shelf

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A detailed tephra stratigraphical and tephrochronological study in high-resolution marine sediments on the North Icelandic shelf has reveled over 100 tephra layers from the Late glacial and the Holocene. The most detailed study has been performed on core MD99-2275 but seven other coring sites have been investigated with the purpose of locating tephra layers. The high-resolution tephra stratigraphy of core MD99-2275 has been correlated to terrestrial tephra stratigraphy resulting in the correlation of 44 tephra layers. Of these 40 tephra layers 21 are tephra markers that have been dated terrestrially with 14C, with documentary records and/or ice core chronologies. These include two newly identified Hekla tephra markers, the Hekla Õ and the Hekla DH (Gudmundsdóttir et al., 2011). Core MD99-2275 provides high-resolution marine sediment chronology based on comprehensive tephra stratigraphy that has the potential to provide a detailed and accurate reference section for dating and correlating purposes in the region and the possibility to serve as a master core/stratotype in the northern North Atlantic - Nordic Seas region.

The marine tephra tephra stratigraphy on the North Icelandic shelf can not only be used for dating and correlation purposes but can also give an idea of eruption frequency and eruption history of Icelandic volcanoes using tephra layer frequency. Because the marine sediments on the shelf go further back in time than most soil sections in Iceland they are particularly valuable for obtaining information on eruption history and frequency of Icelandic volcanic systems beyond 8000 cal. yrs. BP where information in terrestrial soil sections is poor and incomplete.

Gudmundsdóttir, E.R., Larsen, G., Eiríksson, J., 2011: Two new Icelandic tephra markers: The Hekla-Õ tephra layer,~6060 cal. yr BP and Hekla-DH tephra layer, ~6650 cal. yr BP - Land-Sea correlation of Mid-Holocene markers. The Holocene. Vol. 26, 4 p. 629. DOI: 10.1177/0959683610391313

SÞ3-3

Mid- and Late Holocene tephrastratigraphy in a high resolution marine archive from the Eastern Norwegian Sea (Ormen Lange)

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Laboratory data show that water in nominally anhydrous mantle minerals will significantly reduce the viscosity of the mantle. Dehydration upon melting of the mantle can therefore result in a sharp viscosity contrast, referred to as de-hydration stiffening. Beneath a mid-oceanic ridge or in a mantle plume a high viscosity layer (HVL) will form above the depth of the dry solidus. For typical MORB source water contents (125±75 ppm) a viscosity contrast of a factor of 500±300 has been suggested. Thus far, the effects or the magnitude of dehydration stiffening have not been observed outside the laboratory. As the GIA process is to first order dependent on the viscosity structure of the mantle, the existence of such a viscosity contrast can be accessed in situ. Iceland, located on top of a mantle plume and cut through by the Mid-Atlantic ridge, is currently undergoing GIA. It is estimated that the largest glacier, Vatnajökull, has lost 435 km^3 of ice between 1890-2004, causing the land to uplift with vertical velocities in excess of 20 mm/yr close to the glacier. This offers a unique opportunity to study the effect dehydration stiffening beneath Iceland. We set up a 3D model of present day GIA on Iceland including the 5 largest Icelandic glaciers. To constrain the model predictions we use the vertical surface velocities estimated from two nation wide GPS campaigns in 1993 and 2004, as well as continuous GPS station data. For this data set we find that the GIA model is sensitive to viscosity contrasts in the mantle down to at least 200 km. We first test a conceptual model of the viscosity structure in the mantle consisting of a lower viscosity plume conduit embedded in the mantle beneath a higher viscosity layer, HVL, directly beneath the lithosphere. The best fit to the GPS data is achieved for a background mantle viscosity between 8-12 x 10^{18} Pa s and a viscosity contrast of a factor of 1-3 between the background mantle and the HVL, while larger viscosity contrast demands a mantle viscosity lower than 8 x 10^{18} Pa s. For our next set of models we use a self-consistent effective viscosity field from dynamic modeling of the plume-ridge interaction using a non-linear rheology. An initially wet mantle and a moderate dehydration upon melting yields a reasonable fit to the observed GPS data. However, even if the viscosity contrast between the HVL and the background mantle locally can reach a factor of 40, the mean viscosity contrast is of a factor of 10. Our conceptual model does not yield an acceptable fit to the observed data for large viscosity contrasts unless the viscosity of the mantle is extremely low. Alternatively, if the rheology of the mantle is nonlinear and the system evolves under a state of constant viscous dissipation, the expected viscosity contrast is of the order of 10 which is compatible with our findings.

SÞ3-4

How much of the 'European' tephrochronological framework is North American?

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Ultra-distal ash (micro-tephra) isochrons have been detected at a Holocene ombrotrophic peat bog on Newfoundland Island, eastern Canada, deriving from North American volcanic sources in Alaska and the Cascades [1]. A number of these isochrons are well-documented and can be correlated over distances ranging from extensive proximal deposits to low-concentration ultra-distal deposits in the Greenland ice-cores. Such geographic ranges demonstrate the capacity of micro-tephra glass shards for far-travelled atmospheric transport.

Examination of published geochemical datasets from a number of European tephrostratigraphic studies may suggest further range extensions for some of these North American isochrons, with reports of Holocene 'Icelandic' micro-tephra layers, or mixed populations of low concentration, which do not conform to the known geochemical behaviour of Icelandic volcanic centres [*2, 3, 4*]. Many of these may yet be correlated with Icelandic sources after further study. However, several are shown in this study to have major oxide geochemical signatures which are indistinguishable from documented North American eruptions, while others have signatures suggesting affinities with North American source areas.

It is speculated that a number of North American eruptions, such as the Mazama Ash (7627±150 GISP2 yr BP) and White River Ash (~1147 cal. yr BP), were of sufficient magnitude (VEI 6-7) to propel ash so high into the stratosphere that it would remain aloft for sufficient time to cross the North Atlantic, possibly aided by westerly jet stream winds. Such ultra-Plinian events would also produce sufficient material to be detectable as useful isochrons in sequences at such distances. Many parts of Europe (e.g. upland areas of the British Isles and Norway) are ideally situated to receive and preserve such ultra-distal deposits. It is expected that trace element analysis (e.g. LA-ICP-MS) of these micro-tephras should provide the level of differentiation required in this study to definitively correlate between North American or Icelandic source areas.

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ORAL SÞ 3

SÞ3-5

The Hoftorfa tephra: a 6th Century tephra layer from Eyjafjallajökull

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Eyjafjallajökull tephra was brought to worldwide attention and put under detailed scientific scrutiny with the eruptions of 2010. Previous historical eruptions have been studied in some detail also, but until recently few details have been known about prehistoric explosive activity. Tephrochronological investigations have shown that explosive activity from the central crater of Eyjafjallajökull in the mid-6th century AD produced a distinctive tephra deposit, the Hoftorfa tephra (also previously known as Layer H or E500). This paper describes this tephra layer, it's distribution and volume, based on over 100 profiles from south Iceland.

The Eyjafjallajökull Hoftorfa eruption produced a pale white to yellow, silicic tephra that is thickest on the northern flanks of the volcano. The tephra deposit generally has a matrix of medium to fine grained ash supporting coarse grained ash to lapilli and in some locations bedding and grading are apparent. The extent of the tephra is similar to the Eyjafjallajökull 1821-3 eruption though it is somewhat greater in volume and is considerably thicker on the northern flanks. It is significantly smaller in volume and area than the 2010 Eyjafjallajökull tephra. Hoftorfa (the bedrock outcrop anchoring the north east margin of the great terminal moraine of Gígjökull) is proposed as the type site for this tephra layer being close to its thickest point and easily accessible for further study, following Dugmore (1987; 45).

Deposits have only been found within 20 km of the crater, but being highly visually distinctive, the Eyjafjallajökull Hoftorfa tephra layer still forms a very useful key marker horizon in the late prehistoric geological record, covering at least 600 km^2 including the forelands of 8 major outlet glaciers from two separate icecaps. Despite being of a limited volume and visible extent this tephra is important because its identification extends the record of known activity in the central crater of Eyjafjallajökull from the 17th century AD to the 6th century AD. It shows that the style of activity observed in 1821-3 also occurred some 1300 years previously; moreover, the same stratigraphic sections that have been used to identify this tephra also show that no similar events have taken place in the last c.7000 years.

SÞ3-6

The Classical Surtarbrandsgil Locality, Brjánslækur, W. Iceland – A Mineralogical and Chemical Study

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Interbasalt sediments commonly occur within the Tertiary lavas in Iceland. The sediments mainly consist of hyaloclastite and tephra, but also fluvial and eolian debris. In the oldest Early to middle Miocene interbasalt sections laterite weathering remnants and coal beds are preserved.

The interbasalt sediments exposed in the Surtarbrandsgil at Brjánslækur were first described by Eggert Olafsson (1772). During his travels through Iceland (1752-1757), he discovered in the sedimentary sequence layers of lignitic coal (surtarbrand) with plant fossils. This became the first reported observation of plant fossils in the Arctic region. Later O.Heer (1868) identified the fossil plant remnants to 14 species Brjánslækur fossils in 14 different species including Sequoia sternbergi, Betula prisca, Alnus kefersteinii, Ulmus diptera, Quercus olafseni, Liriodendron procaccinii, Vitis islandica, Juglans bilinica.. Since then the Brjánslækur Surtarbrandsgil has been visited by a number of paleoontologists, and detailed studies have been undertaken . Datings of the lavas at the base and the top of the sediment sequence give ages of 11.9 m.y. and 9.1 m.y., respectively, confirming. the sediments to be of Middle Miocene age.

In spite of that the locality and its plant fossils have been known for more than 250 years, little attention has been paid to studies of the sediments themselves.

This paper presents textural, mineralogical and chemical (major and trace element) data for 27 sediment samples and 2 samples of basalt lavas, from a vertical section in the Surtarbrandsgil at Brjánslækur. The sediments consist of hyaloclastite and tephra, lignite, sand, and clayey silt. The section was sampled in 1978 as part of a research project on Late Tertiary interbasalt sediments financed by the Nordic Volcanological Institute with the aim to study the lateritic weathering in Late Tertiary. As the samples from Brjánslækur were not the best suited for that study, they have not until now been investigated in detail with respect to original composition, post depositional weathering and burial alterations.

The uppermost basalt lava is alkaline. The upper part of the sediments have a very similar composition as the overlying lava. The sediments probably derive from weathering of a similar original basalt, but are leached in the alkalies and earth-alkali metals and enriched in aluminium, iron and titanium. The mineral composition varies greatly in the sediments depending on their type, grain size and weathering rate.

SÞ3-7

Deposition in the UK of Tephra from Recent Icelandic Eruptions.

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Both recent Icelandic eruptions deposited tephra in the UK, despite different compositions, styles and weather conditions. The Grímsvötn 2011 eruption had a larger plume (20 km vs 10 km) and a shorter duration (7 days vs 43 days) than Eyjafjallajökull 2010, but wind conditions meant that tephra was only transported to the UK during a very narrow time window.

Analysis of samples from rain gauges found that tephra from both explosive phases (14-17th April, 5-7 May) of the Eyjafjallajökull eruption was deposited at all latitudes within the UK, with the majority coming during the first phase. The modal grainsize was 25 microns, but highly-vesicular grains up to 100 microns were also present. The highest mass-loadings (up to 7.5 x 10^5 shards per square metre) were in the northwest. It is unclear whether these grains were deposited by rain, or in a dry state. Air quality monitoring equipment did not detect any increase in PM10 particulate matter in the UK associated with the eruption.

The distribution in the UK of Grímsvötn tephra was measured by a nationwide public sampling effort coordinated by the British Geological Survey. Tephra was collected on sticky tape, which is cheap, but it is difficult to confidently identify tephra unless the mass-loading is significant. The results show that most deposition took place during rainfall, 48-70 hours after the onset of eruption, and was restricted to Scotland and further north. Air quality monitoring data showed a single pulse of tephra passing over the country during this period. Analysis of rainwater samples is ongoing, and is expected to extend the range over which tephra deposition can be confirmed and to allow estimation of mass-loading.

SÞ3-8

Towards a complete Holocene tephrochronology for the Faroe Islands

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The position of the Faroe Islands between Iceland and the European mainland is ideal for receiving tephra from volcanic eruptions on Iceland. Historical records show that fallout on the islands have occurred in connection with eruptions of Katla in the 17th and 18th centuries AD and from Hekla during the eruption in 1845. Tephra fall was also observed during the eruption of Eyjafjallajökull in 2010. Three widespread tephra horizons have been known since the 1960s from lake sediment and peat sequences on the Faroe Islands (e.g. Dugmore and Newton, 1998), the early Holocene Saksunarvatn tephra (c. 10.3 ka BP) and the mid Holocene Hekla-4 (c. 4.2 ka BP) and Hekla-S/Kebister tephras (c. 3.7 ka BP). Recent additions to the tephrochronology network of the Faroe Islands include the early Holocene Hässeldalen, Askja-S and Høvdarhagi tephras (Lind & Wastegård, in press), the Suðuroy tephra (c. 8.0 ka BP; Wastegård, 2002), the Mjáuvøtn tephra (c. 6.8 ka BP; Olsen et al., 2010b), Hekla-3, Hekla-1 and the basaltic phase of the Landnám tephra (c. 870s AD) (e.g. Wastegård, 2002; Olsen et al, 2010a), Also several silicic layers from Katla (”SILK layers”) have been found (Wastegård, 2002; Lind & Wastegård, in press). In total more than 15 silicic and 5 basaltic layers have been found on the Faroe Islands, but since only a few sites have been investigated in detail, it is likely that many more tephra horizons remain to be discovered. The almost complete lack of basaltic tephra within peat bogs on Faroe Islands is striking even though many documentary records report tephra fallout from basaltic eruptions. Silicic tephra is thought to be generally more stable than basaltic tephra, which could be affected by chemical alteration or even complete dissolution in an acid environment, such as blanket peat (Pollard et al., 2003).

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SÞ 4 – Volcanic pollution: its environmental and atmospheric effects

SÞ4-1

The rapid release of condensed volcanic salts and nutrients and the subsequent effect on aqueous environments

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Volcanic ash particles are known to act as sites for active adsorption of condensing volcanic aerosols in volcanic plumes. These metal salts, acids, and nutrients remain attached to tephra surfaces until subjected to contact with a water body, be it glacial, in the atmosphere, or upon deposition into an aqueous environment. These easily soluble surface coatings are referred to as ash-leachates. Often this release of elements leads to an increase in the bioavailability of key nutrients, which may fertilize or hamper primary productivity depending on the volume of ash-leachates released and the buffering capacity of the affected water body. However, a number of studies that used flow-through experiments on unhydrated volcanic ash samples from a variety of volcanoes have shown that ash-leachate speciation is extremely variable between different volcanic regimes, individual volcanoes, and even within an eruption. Even within a largely monolithic geological setting such as Iceland, there are significant differences in ash-leachate volume and speciation between the eruptions of Hekla in 2000, Eyjafjallajökull in 2010 and Grimsvötn in 2011. Understanding these differences is integral to understanding the risk to ecosystems affected by volcanic ash deposition in the aftermath of an eruption.

Here we focus on the limited yet expanding dataset of eruptions from Iceland and other volcanoes worldwide, evaluating the variations in elemental release and the causes of those differences. We also detail recent experiments looking at a potential fertilization or toxicity of aqueous bodies, using marine coccolithophore cultures exposed to various concentrations of ash-leachates in reacted seawater bioassay experiments. These initial findings suggest that at low ash depositions there is the potential for phytoplankton fertilization as demonstrated by enhanced growth rates. However, at higher ash deposition scenarios the growth is significantly impeded, with a large variance in this toxicity threshold depending on the chemistry of the ash-leachates used. These findings both highlight the need to better understand the effect of ash-leachate release and speciation from volcanic eruptions, and the potential for volcanoes to influence the climate through the enhancement or retardation of primary productivity in affected areas.

SÞ4-2

The Ash that Closed Europe's Airspace in 2010

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On 14 April 2010, when meltwater from the Eyjafjallajökull glacier mixed with hot magma, an explosive phreato-magmatic eruption sent unusually fine-grained ash into the jet stream. It quickly dispersed over Europe. Previous airplane encounters with ash had caused sand blasted windows and particles melted inside jet engines, causing them to fail. Therefore, air traffic was grounded for several days. Concerns also arose about health risks from fallout, because ash can transport acids as well as toxic compounds. Studies on ash are usually made on material collected far from the source, where it could have mixed with other atmospheric particles, or after exposure to water as rain or fog, which would alter surface composition. In this study, a unique set of dry ash samples was collected during the explosive eruption and compared with fresh ash with the same bulk composition from a later more typical magmatic event, when meltwater did not have access to the magma[1].

Up to 70 mass % of the phreato-magmatic ash particles, collected 60 km from the source, was <60 μm in diameter, 22% was <10 μm and 11% was ≤ 4.4 μm. The finest grain size was found in the centre of the "collapsed" plume. The magmatic ash was coarser and its surface area was an order of magnitude smaller than for the explosive ash. The relative concentration of surface salts down to 10 nm depth was significantly lower on the explosive ash than the magmatic ash, because less volatile compounds were available to condense on the surfaces when water and steam were present. Instead, they dissolved in the meltwater and were transported as solutes in the ensuing floodwaters. The surface salts dissolved rapidly when exposed to experimental and natural waters, releasing pollutants and nutrients. Some of the salts further enhanced bulk dissolution of the ash.

The particles of phreato-magmatic ash that reached Europe in the jet stream were especially sharp and hard, therefore abrasive, over their entire size range, from submillimeter to tens of nanometers. Edges remained sharp, even after 2 weeks of abrasion in stirred water suspensions. From the composition of the particles, we could predict that they would soften and melt at the temperatures typical of a jet engine (1500 to 2000 °C).

[1] Gislason S.R. et al. (2011), PNAS, 108, 7307-7312

ORAL
SÞ 4

SÞ4-3

Surface properties of the Grímsvötn 2011 volcanic ash

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In the evening of the 21st of May, 2011, the Grímsvötn volcano, located in South-East Iceland, began its strongest eruption in more than 100 years. The eruption continued until the morning of the 28th of May, 2011 and released more ash within the first 24 hours than Eyjafjallajökull did during its entire 2010 eruption. The plume from Grímsvötn rose to 20 km and spread over the North Atlantic, causing the cancellation of several hundred flights. Heavy ash-fall affected the local farms south of Grímsvötn, destroying agricultural crops, contaminating surface waters and causing hardship to livestock. The purpose of this study was to define the surface properties of the ash and to measure the release rate of various elements when the ash interacts with water. Some of these elements are harmful to the environment while others are nutrients.

The ash samples were collected May 22nd, 2011, from 16:05 to 19:30, 51 km to 115 km south and south-west of the eruption site. During sampling, the relative humidity ranged from 40% to 80%, the weather was calm and there was no rain. The ash represents the first 24 hours of the eruption. The thickness of the ash-cover ranged from less than 1 mm to about 15 mm. The ash is fine grained, the largest grains are 200 µm in diameter, 50-65% of the mass is fine ash (<60 µm), and 7-10% is at the inhalation risk, ≤ 10µm in diameter. The BET surface area of the samples is 0.5 m^2/g. Scanning electron microscopy (SEM) shows that the ash particles range in diameter from approximately 200 µm to a few tens of nanometers, and often with smaller particles attached to larger grains. X-ray photoelectron spectroscopy (XPS) was used to investigate the chemical composition of the top 10 nm layers of the dry ash. The most dominant elements are O, Si, Al, Mg, Ca, S, Na and Fe. Nanopure water (pH 5.9) was pumped through Teflon columns filled with ash of known surface area to measure the release rate of 70 elements and pH, as a function of time. At first, the release rates were dominated by dissolution of surface salts, and after hours or days, by the bulk dissolution of the volcanic ash. Within the first 10 minutes, the concentrations of most measured elements decreased by more than an order of magnitude. Initially, the most dominant elements released were S, Na, Ca, Mg and Cl, but after 12 hours, the most dominant element released was Si. The first water exiting the ash-filled column had a pH of 7.25 and the pH gradually increased until it reached 9.66 at about 160 minutes. Over the next 30 days, the pH slowly decreased to the pH of nanopure water.

SÞ4-4

Gas release from Grímsvötn eruption in May 2011

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The subglacial Grímsvötn volcano erupts more frequently than any other volcanic system in Iceland. The last eruption began on 21 May 2011 and produced a highly ash-rich plume which was sustained for several days. We undertook a week-long fieldtrip to measure gas emissions at the eruptive vent ~5 days after the highly explosive phase finished. Gas phase species (SO2, H2S, CO_2, H2 and H2O) were measured using a system of electrochemical sensors (MultiGAS) at the eruptive vent, and also at long-lived fumaroles on the summit of Vestri-Svíahnúkur nunatak. This was the first time that such data were collected at Grímsvötn. Here we discuss variations in the gas composition between sites, with particular emphasis on the concentration of glacier-sourced H2O relative to CO_2 and sulphur-species.

SÞ4-5

Excess mortality in Europe following a future Laki-style Icelandic eruption

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The eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011 not only alerted European governments to the risks posed by volcanic ash but also to those that could arise from 'low-probability, high-impact' sulfur-dominated volcanic events such as the A.D. 1783-1784 Laki eruption.

Historical records show that the A.D. 1783-1784 Laki eruption in Iceland caused severe environmental stress and posed a health hazard far beyond the borders of Iceland. Given the reasonable likelihood of such an event recurring, it is important to assess the scale on which a future eruption could impact society. We quantify the potential health effects caused by an increase in air pollution during a future Laki-style eruption using an advanced global aerosol model (GLOMAP) together with concentration-response functions derived from modern epidemiological studies.

The concentration of particulate matter with diameters smaller than 2.5 micrometers ($PM^2.5$) is predicted to double across central, western and northern Europe during the first three months of the eruption. Over land areas of Europe, the current World Health Organization 24-hour air quality guideline for $PM^2.5$ is exceeded on an additional 36 days on average (range 13-63 days) over the course of the eruption.

Based on the changes in particulate air pollution we estimate that between 139,000 and 144,000 additional cardiopulmonary fatalities could occur in Europe depending on the meteorological conditions. Such a volcanic air pollution event would therefore be a severe health hazard, increasing excess mortality in Europe on a scale that likely exceeds excess mortality due to seasonal influenza.

SÞ4-6

Impacts of the 2010 Eyjafjallajökull eruptions on the local communities

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South Iceland experienced two different volcanic eruptions in the same area between March and May 2010. The first one located in the flank along a fissure at Fimmvörðuháls in between the Mýrdalsjökull and Eyjafjallajökull icecaps started on March 20. This initial phase produced spectacular fire-fountain activity and lava flows and as such, attracted domestic and international tourists that flocked to observe the volcano. As soon as the Fimmvörðuháls flank eruption was declared over on 13 April a second one, the sub-glacial eruption, in Eyjafjallajökull began. This explosive eruption, which commenced on 14 April, resulted in glacial outburst floods, lahars, and considerable ash fall to the south and east. The ash reached high altitudes in the atmosphere causing unprecedented disruption to international aviation. Locally, the eruption also produced lightning, gas emissions, lava flows and heavy sound blasts that were heard especially to the south and east of the volcano. Some residents in the farming communities suffered badly, it was dark during mid day, people had respiratory problems and had to stay indoors and use masks and safety glasses if they vent outdoors to tend to their animals. Farmers were worried about the wellbeing of their sheep, cattle and horses, and also about the future recovery of the grazing land and cultivated land that was covered with ash and sediment from the flooding. While the Fimmvörðuháls eruption had positive economic impact in Iceland, the sub-glacial Eyjafjallajökull did not. Many communities dealt with ash fall during the weeks that followed and the continual redistribution of ash that frequently exceeded the maximum limits set by public health authorities for dust quantity, and repeated lahars for many months after the eruption had subsided. Based on a survey conducted in August 2010 and 2011 with residents living within close proximity of Eyjafjallajökull, we discuss the societal and economic impacts of these eruptions on these communities.

The research was funded by the Icelandic Road Administration

ORAL
SÞ 4

THEME: UNDERSTANDING VOLCANOES (UV)

UV 1 – Volcanoes in Iceland

ORAL
UV 1

UV1-1

Post glacial activity and magma output rates on the Askja volcanic system

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Postglacial activity on the Askja volcanic system, north Iceland is dominated by basaltic volcanism. New dating and mapping of the postglacial lavas indicates that the total volume of magma erupted in the last 10 ka is at least 45 ±5 km^3. Tephrochronological dating of Askja's postglacial lavas indicates that over 70% of the postglacial magmatic output occurred before the deposition of the Hekla 4 tephra at 4.2 ka BP. Improved tephrochronological dating of lava flows, particularly on the southern lava fan, demonstrates that the Askja volcanic system has been more active in the past 1500 years than has previously thought. It also indicates that eruptive activity on the volcanic system to the north of Askja central volcano has declined since 3600 years BP. This implies that the focus of activity in late postglacial time has shifted to vents and fissures in the vicinity of the central volcano. Over the last 1000 years fissures on the western and southern edges of the Askja caldera have been the most active parts of the volcanic system.

The current tephrochronological resolution in the Askja region is adequate for the last 4.2 ka, but is non-existent for the rest of the postglacial period. Seven marker tephra layers that are useful for dating purposes have been identified and the oldest of these is the 4.2 ka Hekla 4 tephra. Consequently, tephrochronology cannot resolve the ages of eruptions from the mid to early postglacial period. These limitations prevent reconstruction of changes in the magma output rates at Askja during postglacial times. If we assume that Askja became ice-free at 10 ka BP, then calculated eruption rates for the Askja volcanic system appear to have remained relatively constant over the postglacial period at 6 km^3/ka. The exception is the period 3 - 1 ka BP when the average output rates dropped to ~0.3 km^3/ka. This apparent dip in activity closely mirrors results from the WVZ, which experienced a period of low productivity between 3.5 and 1.5 ka BP. Interestingly, the highest eruption rates calculated for the Askja region are in the post-1875 period or 7.8 km^3/ka. The largest single eruption in this age bracket is the Nýjahraun lava, with a volume of ~0.35 km^3, while the remaining volume comprises the eruptions that occurred in the vicinity of the Askja caldera in the early 20th century. This demonstrates the importance of taking multiple, small-volume eruptions into account when estimating magma output rates on the Askja volcanic system.

UV1-2

The Hekla 2000 tephra deposit: Grain-size characteristics and eruptive parameters

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The highly active volcano Hekla last erupted in 2000 and current crustal deformation indicates that the next eruption may be soon. Hekla eruptions usually begin with a short subPlinian to Plinian explosive phase. The associated volcanic plume can cause disruption to air-traffic while tephra fall can affect the environment and infrastructure nearby. The total grain size distribution (TGSD) of tephra and the erupted mass and volume are important input parameters for models used for forecasting dispersal and ash concentration in the volcanic plume, as well as hazard and risk evaluation. This paper presents new calculations of eruptive parameters for the Hekla 2000 eruption, new tephra grain size data and TGSDs.

Haraldsson (2000) and Höskuldsson et al. (2007) calculated Hekla 2000 tephra volumes but with considerably different results. New calculations, based on mass loading data (Haraldsson, 2000) and reassessment of the isomass map, result in an erupted mass value between 7.8 x 10^9kg and 2.3 x 10^{10}kg, depending on the method used. The associated volume lies between 1.1 and 3.3 x $10^7$$m^3$, corresponding to a dense rock equivalent volume of 2.9 to 8.5 x $10^6$$m^3$ and VEI 3.

The eruption deposited tephra with a main dispersal axis to the north and a minor dispersal axis to the south. Tephra was sampled by Icelandic scientists and members of the public within days to weeks of deposition. Granulometric analysis was performed on 31 samples using hand sieving and laser diffraction. This data was used to construct TGSDs using weighted mean and Voronoi Tessellation methods.

Median diameter decreases with distance from the vent from medium-grained lapilli (15.24mm) in the proximal zone, falling sharply over 30km to coarse-grained ash (1.85mm) and then gradually fining to 102μm on Grímsey (294km distance). Proximal to medial distributions are generally weakly bimodal, whereas peripheral samples and most samples more than 60 km from the vent are unimodal or very weakly bimodal. Spatial variations in mode and fine ash concentration are interesting. The majority of the samples have 2% or less fine ash (<63μm). However, concentration of fine ash is distinctly higher in two domains; 8 to 12 wt% of fine ash is found within 20km west of the vent, and 4 to 8% fine ash is found from 80 to 190km north of the vent. The bimodality and fine ash concentration variations can be attributed to different transport pathways, deposition from different eruptive phases, aggregation of fines, multiple fragmentation mechanisms and reworking; the nature and contribution of these will be discussed. Sorting values improve with distance from the vent, ranging from 2.04 to 0.70 along the dispersal axis and reflecting effective fractionation of the coarser clast populations by transport and deposition.

All TGSDs determined for Hekla 2000, using these analyses, are bimodal, but different TGSDs emphasise the bimodality and the proportion of fine-grained ash more than others. The TGSD has a significant impact on dispersal model results and it is therefore important to understand the impact of different techniques and sampling patterns for local and international hazard assessment.

UV1-3

Real-time procsessing of harmonic tremor from digital seismograps in the SILsystem – five volcanic eruptions in 15 years.

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During the eruption of Gjálp in October 1996, work was started on the design and implementation of software to process, analyze and display harmonic tremor signals present in data recorded by he digital seismograph stations in the SIL system.

The software has been in operation since late in 1996.SIL stations record three components at 100 samples per second and up to 24 bit resolution. At the time, communication technology and price precluded the transmission and archiving of all waveform data. Each station includes a dedicated computer running a Unix/Linux operating system.

Each component is passed through three parallel digital bandpass filters in real time. The frequency bands

used are 0.5 to 1 Hz, 1 to 2 Hz and 2 to 4 Hz. The filterd signal levels are averaged for one minute and transmitted to the processing center. The filters are implemented in the time domain and are recursive and minimum phase. This results in a highly compressed overview of activity on all the seismographs in the system that can then be displayed on a single monitor.

During this period, five confirmed volcanic eruptions have taken place in Iceland: Hekla in 2000, Eyjafjallajökull in 2010 and three eruptions in Grimsvotn, in 1988, 2004 and 2011.Two suspected subglacial eruptions took place in Katla, in 1999 and 2011.

Data from all those events will be shown. In four of the eruptions, the digital tremor provided a clear indication of imminent eruption. This was not the case for the first phase of the Eyjafjallajökull eruption in 2010, which was a small subaerial basaltic fissure eruption in the Fimmvörðuháls region. Similar tremor levels, as those that accompanied the onset of the eruption, had been observed in preceding weeks, possibly related to magma movement and intrusions. During this phase, the level of activity at the craters remained relatively constant, and variations in tremor intensity were often correlated with conditions at the edge of the lava flow, where the advancing lava frequently caused melting and boiling of snow and ice. The remaining phases of the Eyjafjallajökull eruption, after the eruption moved to the summit, were subglacial and were accompanied by much higher tremor intensity. This is also true of the eruptions in Hekla and Grímsvötn.

In the aftermath of the glacial floods, short bursts of tremors have frequently been observed. Those are probably caused by boiling events, triggered by the sudden drop in pressure in hydrothermal systems. A flood that took place in Katla on July 9, 2011 was accompanied by unusually strong tremor levels, suggesting that either a very small subglacial eruption or shallow intrusive activity took place.

UV1-4

Sulphur release from subglacial basalt eruptions in Iceland

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The basalt volcanism in Iceland is distinguished by unusually high proportions of explosive eruptions (e.g. Thordarson and Larsen, 2007). In historical time (i.e. last 1140 years), explosive basalt eruptions account for ~80% of recorded events (= 205) and ~30% of the total erupted magma volume (= 69 km^3). They occur as fissure-fed phreatomagmatic and submarine eruption, although vast majority (>90%) has taken place at the ice-covered Katla, Grimsvotn and Bardabunga central volcanoes on the Katla, Grimsvotn, Bardarbunga-Veidivotn volcanic systems on the Eastern Volcanic Zone - the three most active volcanic systems in Iceland. The Grimsvotn central volcano has the highest eruption frequency, with 7 to 10 eruptions per hundred years in historical time, followed by the Katla and Bardabunga volcanoes, each with ~2 eruptions per century. The size of individual eruptions is relatively small, where typical magma volume in the range of 0.01-1 km^3 and the magma composition ranges from mildly alkalic (Katla volcanic system) to tholeiitic (Grimsvotn and Bardabunga-Veidivotn volcanic systems). The pre-eruption sulfur content of these magmas has determined by measurements of melt inclusions trapped in phenocrysts and give pre-eruption mean values of 1470±185 ppm for typical Bardabunga compositions, 1660±240 ppm for Grimsvotn and 2200±165 ppm for Katla magmas (e.g. Thordarson et al., 2003). Similarly, the post-eruption mean sulfur values in degassed magmatic tephra are 450±90 ppm (Bardabunga-Veidivotn), 490±80 ppm (Grimsvotn) and 460±125 ppm (Katla). However, the tephra produced by subglacial and subaerial phreatomagmatic eruptions has much more variable S contents, ranging from 255-1490 ppm for Bardabunga-Veidivotn, 460-1350 ppm for Grimsvotn 545-1890 ppm for Katla. These variable sulfur values are attributed to arresting of degassing as the magma is quenched upon contact with external water in the shallow levels of the volcano conduit. It is noteworthy that in each case, the sulfur concentrations in the phreatomagmatic tephra span the compositional gap between magmatic tephra and melt inclusions. Furthermore, the measured sulfur values exhibit a near Gaussian distribution imply that the amount of sulfur released into the atmosphere by subglacial and phreatomagmatic eruptions is only one half of what is released in comparable magmatic basalt eruptions.

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UV1-5

Simulation of the eruption of a volatile-rich magma column

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The composition and dynamics of volcanic jets and plumes are constrained by the form and composition of the erupting column and its interaction with the country rock on the way to the surface. Simulations of a mixed, volatile-rich magma column erupting through layered media have been performed with the adaptive-mesh multi-material finite-volume code Sage. A downward return flow is observed around the periphery of the plume, contributing to the abrasion and erosion of the country rock. Penetration at the tip is enhanced as the volatile component (supercritical water in this case) separates from the bulk flow. Entrainment of wall material occurs within an annular cylinder of diameter determined at the pinch region. When the column emerges at the surface, the dynamics of the jet that is formed depends on these subsurface developments We explore effects of differences in the volatile richness of the mixture and of the characteristics of the country rock.

UV 3 – Volcanism in the North Atlantic

UV3-01

Ongoing Challenges on North Atlantic Rift-, Ridge- and Continental Margin-Volcanism

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The igneous history of the Atlantic starts around 200 Myrs ago with the emplacement of probably the most extensive large igneous province, the Central Atlantic Magmatic Province during initial continental rifting and fragmentation of the largest and most recent supercontinent Pangea. Two additional large igneous provinces set off the rift-to-drift transition in the present North Atlantic region. Cretaceous mafic igneous rock formations forming the High Arctic Large Igneous Province are outcropping all over Svalbard, Franz Josef Land, and are found in sedimentary basins in the North-Western Barents Sea. Igneous rocks on the conjugate volcanic rifted margins of the North East Atlantic form the Paleogene North Atlantic Igneous Province. As a result, large igneous province formation seems to play a systematic role during fragmentation of supercontinents. The ongoing discussions to better understand the rift-to-drift transition, concentrate on the structural differences between magma starved and volcanic rifted margins. However the majority of the continental rifted margins are defined as volcanic, as a result only a better petrological, geochemical characterization of the transition from alkaline rift related magmas to a purely mid-ocean ridges-like tholeiitic volcanism is able to eliminate presently proposed theoretical geodynamic models for volcanic rifted margin formation and continental breakup. During the post rift stage seafloor spreading at mid-ocean ridges dominates volumetrically the North Atlantic volcanism. The North Atlantic mid-ocean ridge magmatic activity is one of the largest and most active decompression melting systems on Earth. While active mid-ocean ridges are the present location of voluminous volcanism, extinct ridges like the Aegir Ridge have once been the locus of maximal extension but are now considered volcanically inactive. We have a relatively good understanding of the active ridges, due to the geologically rapid straight forward tectonic processes at ridges. Diving on active ridge axis provides observations of features that where not there just a year before, and sampling of such young volcanics enlightened different petrogenetic processes responsible for the melting, fractionation, ascent and eruption of Mid-ocean Ridge basalts. The North Atlantic natural laboratory provides us with the extinct ridges with an additional chance to comprehend the overall volcanic activity of a mid-ocean ridge from its embryonic state until extinction. In depth petrological studies of entire volcanic rock successions from extinct ridges are the key for this challenge. We can assume that variations of the North Atlantic mid-ocean ridge system are the outcome of differences in the fundamental parameters such as spreading rate and ambient mantle temperature. In contrast ongoing volcanism in the North Atlantic on the Azores, Canaries, Iceland and Jan Mayen is much more complex. Different geodynamic models have been suggested in the literature to explain the excessive melt production rates at these locations,

ranging from multiple thermal mantle plumes to mantle heterogeneities.

The presentation consists of a volcanic history of the North Atlantic region from pre-drift to its present state, milestones in our understanding of the North Atlantic and a coherent general model for supercontinent fragmentation and ocean crust evolution.

UV3-02

The temporal transition between mantle sources at the end of flood volcanism in the Faroes: the elemental and isotopic development in the Enni Formation at Sandoy

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New elemental and isotopic data are presented from the lava succession at Sandoy representing the uppermost part of the early Eocene Faroe continental flood basalts. The flow by flow evolution at Sandoy is characterized and compared to the succession at the neighboring island of Streymoy. The data confirm that the top 100 m of the sequence is constituted completely by High-Ti3 lavas that are equivalent to the Rømer Fjord Formation lavas in East Greenland, both of which are thought to be sourced by the IE1 (Iceland Enriched 1) plume component. Below this there is a gradual change in compositions to High-Ti2 compositions, believed to be sourced by the IE2 (Iceland Enriched 2) plume component, as displayed by e.g. Zr/Nb and Pb isotope ratios. The transitional lavas are sampled in the Skorarnar profile. They are the most evolved high-Ti lavas analysed and have 206Pb/204Pb values in between the High-Ti2 and 3 groups. In Pb-isotopes they form a small trend interpreted to be caused by assimilation of a distinct crustal component with higher 208Pb/204Pb and lower 207Pb/204Pb than the basalts. The transition from High-Ti2 to High-Ti3 magmas reflects the dynamics of the Iceland plume components in the mantleduring the fase of rapid lithospheric thinning, and detailed stratigraphical information impose some constraints on modelling of rates.

The upper part of the lava sequence on the southern part of Streymoy is dominated by low-Ti lavas, but the few high-Ti lavas show that this section is part of the High-Ti2 interval. The only occurrence of High-Ti2 or 3 on the northern Faroe Islands is a High-Ti2 lava from Fugloy suggesting that this profile can be correlated in time with the Sandoy and southern Streymoy profiles. The low-Ti lavas that occur interlayered with the high-Ti lavas are among the most evolved low-Ti lavas from the Faroes and they are relatively crustally contaminated. They probably represent the waning stages of melting in the low-Ti source.The similarities and differences of the upper part of the continental flood basalts in East Greenland and uppermost Enni Formation basalts in relation to the introduction of the IE1 plume component will be discussed at the meeting.

UV3-03

The evolution of the Icelandic hotspot subsequent to the CFB volcanism in East Greenland and the Faroes: a geochemical and petrological investigation of the tuffs in the Eocene Fur Formation, Denmark

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We present new isotope and element geochemical data from the Danish volcanic ash layers in the early Eocene Fur Formation from the area around Mors in Northern Jutland. Most tuffs are deposited after the completion of the continental flood basalt volcanism in East Greenland and the Faroe Islands. The ash layers are believed to have formed mainly by phreato-Plinian eruptions and from an environment that marks the transition from continental volcanism to submarine. More than 180 ash layers are believed to have been erupted over a period of 0.5 - 1.5 Ma, comparable to the interval of the Paleogene flood basalt volcanism. The upper 120 tuffs are tholeiitic basalts with geochemical close affinity to the flood basalts.

Ash layers representing the stratigraphic column have been chosen for geochemical analysis of Pb by high precision TIMS and trace elements by ICP-MS. Basaltic samples for geochemical analysis have been extracted from the lower part of the ash layers, where grain sizes are coarsest and not affected by bioturbation.

Initial investigations concern elimination of the effects from secondary alteration and identification of vertical and lateral within layer variation. Significant within layer variation of Pb isotopic composition in ash layer +31 is believed to reflect the eruption of a zoned magma, whereas difference between units of double layer +30 likely reflect eruption of two magmas.

The isotopic variation except for that caused by contamination reflects changes in the mantle source, and very radiogenic Pb in +31 indicates a source dominated by the IE2-type mantle of the Iceland plume.

Further Pb-data on the ash layers will be presented at the meeting.

UV3-04

Seismic Volcanostratigraphy and Sub-Basalt Structure on the Mid-Norway Margin

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Continental breakup between NW Europe and Greenland in the Paleogene was associated with massive basaltic volcanism. On the Norwegian margin, the igneous rocks are deeply buried underneath the seafloor. However, their distribution is well-defined by geophysical data, and igneous rocks have been sampled by both scientific and petroleum wells during the past three decades. Extensive, multi-layered sheet intrusions are present in the Vøring and Møre basins. Deep sills are dominantly layer parallel, whereas saucer-shaped sills dominate at shallower levels. In contrast, magma emplaced in very shallow, unconsolidated sediments display flow-like morphologies. Thousands of kilometer-sized hydrothermal vent complexes are associated with the sills. Voluminous extrusive volcanic complexes are present along the outer margin, forming prominent marginal highs and major escarpments. New and reprocessed seismic reflection data allow for detailed seismic volcanostratigraphic interpretation of the breakup complex and sub-basalt sequences along both the Møre and Vøring margins. Five main volcanic seismic facies units have been mapped on the new data: Inner Flows, Lava Delta, Landward Flows, Seaward Dipping Reflections (SDRs), and Outer High. Two distinct levels of Inner Flows have been identified in the Møre Basin, the uppermost correlating with the Top Paleocene horizon whereas the lowermost is at a mid-Paleocene level. The base of the Inner Flows is difficult to identify, and few sub-basalt reflections are present. However, integrated seismic-gravity-magnetic modeling suggests that the flows are thin (10's to 100's of meters). The Inner Flows continue underneath both the Vøring and Møre marginal highs. Here, the base of the volcanic complex is easier to interpret, and well-defined sub-basalt reflections are present. The sub-basalt sequences have not been drilled, but most likely represent Cretaceous and Jurassic sedimentary rocks locally intruded by magmatic sills. Regionally extensive Lava Delta facies units overlie the Inner Flows along both the Vøring and Møre marginal highs. Three levels of Lava Deltas are locally identified along the Vøring Transform Margin. Landward Flows and SDRs are identified above and seaward of the Lava Deltas. On the marginal high, the volcanic complex is typically 1-5 km thick on the central part of the Vøring and Møre margins. However, the complex is substantially thinner, and locally absent, within the Jan Mayen Corridor. Volcanic seismic sequence analysis reveals a dynamic breakup-related volcanic system with seven main stages: (1) mid-Paleocene intrusive and extrusive volcanism in a shallow basin; (2) massive intrusive volcanism at the Paleocene-Eocene boundary associated with the formation of hydrothermal vent complexes; (3) emergent volcanism forming a tri-part lava delta (Inner Flows; Lava Delta; Landward Flows) in a coastal environment; (4) infilling of a major rift basin forming sub-aerial SDRs; (5) subsidence of the breakup axis and shallow marine eruptions forming the Outer Highs; (6) voluminous deep marine eruptions, locally forming outer SDRs in a marine environment; and (7) normal seafloor spreading volcanism.

UV3-05

Early Oligocene alkaline volcanism related to the formation of the Jan Mayen Microcontinent

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Based on geophysical data, the Jan Mayen Ridge is believed to represent an off-rifted fragment of East Greenland continental lithosphere. Since the early Miocene the Jan Mayen Ridge has drifted 400 km into the North Atlantic as a result of seafloor spreading along the Kolbeinsey Ridge. Rocks dredged from the southern escarpment of the Jan Mayen Fracture Zone provide new information about the tectonomagmatic evolution of the Jan Mayen Ridge. Volcaniclastic rocks, which range from volcanic breccias to volcaniclastic sandstones, were recently recovered from escarpments just east of Jan Mayen. An early Oligocene age of these rocks is shown by: 1) $^{87}Sr/^{86}Sr$ ages of around 32 Ma for shell fragments; 2) an average $^{238}U/^{206}Pb$ age of 32.7 +/- 1.1 Ma for a population of angular zircons in the volcaniclastic sandstones; and 3) a $^{40}Ar/^{39}Ar$ plateau age of around 31 Ma for a volcanic fragment in one of the breccias.

Like the recent volcanic rocks on Jan Mayen, these early Oligocene volcanics belong to the trachybasaltic suite. The alkaline eruptive complex of Jan Mayen appears accordingly to be underlain by volcanic strata that have similar affinity, but that are 30 million years older. The volcaniclastic sandstones of this Oligocene sequence contain detrital zircon populations with age distributions consistent with an East Greenland source region. This early Oligocene magmatic event appears therefore to represent a phase of alkaline break-up magmatism related to the off-rifting of the Jan Mayen microcontinent from Greenland.

The new data shows that the alkaline volcanism in the Jan Mayen area may be traced 30 my back in time, and documents that Jan Mayen Fracture Zone system has been the locus of repeated alkaline volcanism.

UV3-06

Lead Isotope and Trace Element Results for Basaltic Rocks Dredged from the Extinct Aegir Ridge and the Jan Mayen Fracture Zone

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The extinct Aegir Ridge appears as a major gap or "hole' in the North Atlantic large igneous province, created by the Iceland hotspot. The Aegir Ridge created anomalously thick crust (8-11 km) during the first 2-4 Myr spreading, followed by a decrease in magma production and crustal thickness of 3.5-6 km (51.4-25

Ma). Possible explanations are, the lithospheric structure of the newly rifting Kolbeinsey Ridge and Jan Mayen micro-continent diverted mantle flow from the hotspot away from Aegir Ridge, and/or plume flux was low at that time. We report trace element and Pb isotope results for basalts dredged from the Jan Mayen FZ and Aegir Ridge flanks ~69-64 °N.

Dredges returned Mn crust, erratic cobbles, hyaloclastite, and basalt diabase. The diabase rocks are irregular shaped and appear to have been broken from the scarp target rather than having the rounded shape of an erratic cobble. Ten relatively fresh samples were selected, based upon petrographic examination and X-ray diffraction results, for geochemistry and Pb, Nd, Sr, and Hf isotopes. Trace elements reveal distinct chemical groups, including very-depleted melts with very high Zr/Nb ratios (60.7) at one end, and melts of highly enriched characteristics on the other (2.7). The very-depleted compositions show significant LREE depletion relative to HREE [Ce/Yb]N=0.3, while the highly enriched compositions show LREE enrichment [Ce/Yb]N=2.2. Th/Nb ratios vary between 0.07-0.49, indicating variable Th enrichment. Trace element systematics indicate that between group elemental variations can't be solely explained by fractional crystallization and/or partial melting, the observed variations are largely source-related. Trace element systematics are consistent with a mixed MORB/OIB/SCLM mantle source, where relatively enriched samples resemble Faeroe Island lavas, and depleted ones are akin to Kolbeinsey Ridge lavas. Jan Mayen FZ rocks have initial (40 Ma) 206Pb/204Pb: 207Pb/204Pb: 208Pb/204Pb =18.2-18.57:15.47-15.54:37.83-38.46 and Aegir Ridge 16.59-18.75:15.16-15.53:37:36.62-38.51. Jan Mayen FZ, and Aegir Ridge samples with 206Pb/204Pb > 18.2 have higher 207Pb/204Pb and 208Pb/204Pb than the Iceland Neovolcanic lavas and are similar to the Iceland Tertiary and anomalous Õræfajökull basalts. Aegir Ridge basalts with 206Pb/204Pb <17.5 plot below the NHRL in the 206Pb/204Pb vs 207Pb/204Pb and above it in the 206Pb/204Pb vs 208Pb/204Pb diagrams, a characteristic of the British Tertiary Province lavas formed during the early stages of opening of the North Atlantic.

We can't be certain that the dredged samples represent primary Aegir Ridge material, or if they were derived from elsewhere along the Iceland-Faeroe Ridge (e.g., Faeroes), and transported to the dredge locations. If these rocks were erupted at the Ageir Ridge, the data show that at this time the ambient N-Atlantic upper mantle was relatively uncontaminated by the Iceland Plume, but significantly polluted by continental material, presumably during the early opening of the N-Atlantic Ocean Basin.

UV3-07

The Tertiary Rum Volcanic Centre, NW-Scotland: origin, evolution and death of a large central volcano

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The island of Rum, one of Scotland's Inner Hebrides, is well-known for its spectacular exposures of Palaeogene layered intrusions and felsic volcanic rocks. The Centre is enclosed within a 12 km elliptical ring fault (the 'Main Ring Fault', MRF), with remnants of the early felsic stage of volcanic activity (Stage 1), cross-cut by basic and ultrabasic intrusions that comprise the famous Layered Ultrabasic Suite (Stage 2). During Stage 1, central uplift on the arcuate MRF system was accompanied by felsic and mixed felsic/mafic magmatism and the subsequent formation of a caldera, which filled with felsic ash flows and breccias. The volcanic activity commenced with the eruption of thick intra-caldera rhyodacite ash-flow ignimbrites, fed from shallow-level intrusions located in proximity to the Main Ring Fault. The Western Granite also intruded at that point. Many of the felsic rocks of Stage 1 are of crustal origin with isotope signatures similar to that of the underlying Lewisian gneiss. Stage 2 commenced with the intrusion of basaltic cone-sheets followed by the emplacement of the Layered Suite that comprises feldspathic peridotites, troctolites and gabbros. In eastern and western Rum, these mafic and ultramafic rocks form prominent, gently-dipping layers. Central Rum comprises a N-S belt of igneous breccias, which is regarded the feeder system for the entire Layered Suite.

A major volcanic edifice was likely built over Rum during Stage 2, but subsequent erosion rapidly set in. In NW Rum, the Western Granite is overlain by basaltic lavas and fluviatile conglomerates of the Canna Lava Formation. Inter-lava conglomerates contain clasts of rhyodacite, microgranite, troctolite and gabbro derived from the Rum Centre. Clasts derived from Rum have also been identified in conglomerates in lavas in SW Skye. The Rum Central Complex must have been extinct and dissected before the main activity of the Skye Central Complex began. To constrain the lifetime of the Rum volcano, twenty plagioclase phenocrysts of the early Stage 1 rhyodacites were analyzed using single crystal 40Ar/39Ar laser dating. The resulting mean apparent age is 60.83 ± 0.27Ma (MSWD = 3.65). On an age versus probability plot the feldspars do not, however, show a simple Gaussian distribution, but a major peak at 60.33 ± 0.21Ma and two smaller shoulders at approximately 61.4Ma and 63Ma. The age peak at 60.33 Ma is interpreted to represent the intrusion and eruption age of the rhyodacites. This new age constraint overlaps with that for the ultrabasic intrusion (60.53 ± 0.04 Ma), implying the latter was already forming at depth and supplying the necessary heat for crustal melting during the early felsic activity. Quickly thereafter the ultrabasic magmas migrated upwards to shallow structural levels and intruded into the volcano's earlier deposits. Extremely rapid sub-aerial erosion of the Rum centre followed, which is marked by the Canna Lava

ORAL UV 3

Formation (59.98 ± 0.24 Ma) that rests on the Western Granite. Our new data highlight an extremely short lifespan for the Rum centre, with the entire magmatic evolution occurring in probably as little as 0.8M years.

UV3-08

Atypical depleted mantle components at Mohns Ridge and along the Mid-Atlantic Ridge near the Azores.

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Lu-Hf and Sm-Nd isotopic systems have proven useful to track ancient mantle depletion signal in basalts. Compared to other radiogenic isotopes systems, their specificity is to produce, during mantle melting events, parent-daughter ratios that are higher in the residue than in the melt, and which therefore will develop a radiogenic signature with time. Since these two isotopic systems have similar geochemical behavior during magmatic processes (Patchett and Tatsumoto, 1980), a time-integrated evolution is expected to produce a strong correlation between εNd and εHf in mantle-derived samples. However, in the particular case of mid-oceanic ridges samples, it has long been documented that Hf and Nd isotope compositions can be decoupled (e.g. Debaille et al., 2006). Since these early studies, good correlations have been found along ridge regions such as Mohns Ridge (Blichert-Toft et al., 2005), southern MAR (Agranier et al., 2005) or the entire Pacific-Antarctic Ridge (Hamelin et al., 2011).

We present new Hf, Nd, Pb and Sr isotopes and trace elements data for basalts from the Lucky Strike segment of the Mid-Atlantic Ridge, as well as published data from Mohns ridge area (Blichert-Toft et al., 2005). In a Hf-Nd isotopes diagram, these two regions define an atypical correlation, significantly different from the global mantle array with anomalously high εHf for a given εNd. In order to explain the atypical Hf-Nd correlations identified, we discuss two different hypotheses: (i) a kinetic process during the current melting event (Blichert-Toft et al., 2005) and (ii) an anomalous mantle source created by an ancient melting event with residual garnet (Salters and Hart, 1989; Salters and Zindler, 1995). Based on our new sampling for Lucky Strike basalts, we show that the unusual Hf isotopes signatures in basalts are best explained by re-melting of a refractory component in the mantle rather than a disequilibrium melting effect. This observation provides constraints on the structure of the Mid-Atlantic ridge upper mantle around the Azores and along Mohns ridge.

UV3-09

Eocene volcanism in Virginia: The North American ‘passive’ rifted margin being not so passive.

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Published K-Ar ages suggest an Eocene age magmatic activity around Monterey, VA, so that not all igneous rocks in Virginia are rift-to-drift related and Jurassic in age. We systematically sampled and studied these rocks geochemically and used the Ar-Ar dating technique to define a more precise age for these youngest igneous rocks in the eastern United States. These younger igneous bodies have traditionally been interpreted as intrusive bodies, representing old plumbing systems of eroded volcanic centres. This hypothesis is based on studies of aphanitic to porphyritic and occasionally vesicular hard rocks from quarries and road cuts. Pyroclastic deposits have mainly been neglected during theses earlier studies. However additional petrographic studies of volcanic sediments are able to shed light not only on the volcanic nature of these pyroclastic rocks but also on eruption mechanisms and magma crust interactions. Our petrographic studies indicate that these volcanic sediments contain different clasts of igneous and sedimentary country rocks (sandstones and limestones of different formations), fresh glass shards and crystals of predominantly pyroxene, hornblende and micas. A previously unmapped, massive, m-thick andesitic pyroclastic deposit has been studied in detail to shed light on the formation of theses volcanic sediments. Field relations and observations (e.g. denser rock fragments are enriched in the lower part of the sequence and bedding is largely parallel to the present topography) are consistent with a massive welded ignimbrite. As a result, surface erosion after the eruption must be less significant than previously believed and some rocks are clearly volcanic in nature.

These observations in addition to the presence of hot springs and the ongoing seismicity (e.g. the August 23, 2011 Magnitude 5.8 earthquake 8 km SSW from Mineral, VA) illustrate that a ”passive”rifted margin is not as passive as widely believed. Presently we are in the state of comparing our observations and results with different potential geodynamic models to define the most plausible model for the volcanic restart at this ”passive”rifted margin.

UV3-10

A late Devonian to late Jurassic volcanic triplet in the Embla oil field, the North Sea: constraints from geochemical signatures in altered volcanic rocks

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The Embla oil field is perched on the north flank of the Mid North Sea High in the Norwegian part of the North Sea. The Palaeozoic hydrocarbon reservoir rocks include, and are overlain by extensively clay and carbonate altered, fractured volcanic rocks. These are encountered at three stratigraphic levels: a) the late Devonian level includes 373 ± 3 Ma alkali rhyolites and mafic rocks, b) mafic extrusives are encountered at the late Carboniferous - early Permian level, and c) at the late Jurassic level. The HFSE signatures in the rocks appear to be largely preserved, and are used to interpret the significance of the igneous activity. We propose that alkaline felsic and transitional mafic volcanism in the late Devonian reflects a proto-Central Graben rift. The volcanic rocks at the intermediate level are alkaline and distinctly different from 299 ± 1 Ma basalts in the nearby Flora oil field. We propose that the alkaline rocks represent the local expression of the ca. 315-300 Ma alkaline / lamprophyric precursor to the ca. 300 Ma magmatic flare up in NW Europe. The youngest volcanism is sub-alkaline, and palynology indicates that it is slightly younger than the main Callovian magmatic pulse associated with the North Sea Dome, but coeval with volcanism in the region surrounding the central North Sea. A mafic dyke in the late Devonian section of the reservoir yields an alkaline signature. It is interpreted as a feeder dyke to the late Carboniferous - early Permian extrusive rocks.

UV3-11

The mantle source of Eyjafjallajökull volcano

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Basalts originate from the mantle and are therefore the best probe into the mantle composition and melting processes. After and during partial mantle melting, the melt is extracted and accumulated before the primitive basalt ascends towards the surface. Several processes contribute to the final basaltic composition of the intruded or erupted magma, such as melt extraction processes, mixing of basaltic melts, exsolution of sulphur melt, fractional crystallisation and crustal contamination, blurring the mantle signature of the final basaltic magma. Most recent basalts in Iceland have evolved in a magma reservoir and/or high-level magma chamber before eruption where further compositional transformation occurs. An eruption of a relatively primitive basalt, therefore, allow improved understanding of the mantle source and the earliest processes affecting the basalt composition.

The Mars-April 2010 eruption on the flank of Eyjafjallajökull at Fimmvörðuháls produced a basaltic lava field and scoria. The composition is mildly alkaline basalt very close in major-element composition to that of the early phase of the Surtsey eruption 1963-67, confirming the well-known trend of increased basalt alkalinity towards the south along the propagating rift segment in south Iceland. The basalt contains euhedral phenocrysts of olivine (ol), plagioclase (pl) and clinopyroxene (cpx) frequently as glomerocrysts. Their composition range from Fo71-87, An73-86 and Mg-number 70-76 in cpx, respectively, whereas more evolved composition and oscillatory zonation is observed in those forming glomerocrysts (Fo57-68, An76-68, Cpx Mg-number 79-65). The glass composition show slight but significant variations (MgO: 4.55-4.67%; TiO_2: 4.55-5.38%; K_2O: 0.98-1.27%). These observations strongly suggest mingling between more than one basaltic composition shortly before the eruption.

Melt inclusions (MI) in Fo-rich olivines record, in principle, primary magma composition before differentiation during magma ascent. Only the free-standing ol phenocrysts contain Cr-rich spinel inclusions and these have been separated for melt inclusion studies. The MI compositions exhibit significant variations with MgO and K_2O ranging from 5.2 to 7.2 wt% and 0.36 to 1.04 wt%, respectively. Primitive-mantle normalised trace-element spectra show that the Fimmvörðuháls MIs are enveloped by Katla basalts at higher concentrations and Surtsey basalts with lower concentrations; all displaying similar trace-element patterns. A possible mixing relationship between Katla, Surtsey and Fimmvörðuháls basalts is also suggested by a very good linear correlation (R^2=0.99) in incompatible trace element variation diagram (e.g. La vs Ce) that do not pass through the origin. Therefore, the MI compositional range suggests a binary mixing of two basaltic end-members followed by fractional crystallization processes. The sources of these end-members appear identical to those of Katla and Surtsey basalts, with a dominant role of the Katla parental basalt in the mixture.

Whole-rock analysis of Sr, Nd and Pb isotope ratios in the Fimmvörðuháls basalt yield ratios in between those of Surtsey and Katla basalts. This confirms the inferences from the trace element constraints and suggests either binary mixing of Surtsey and Katla parental magma beneath Eyjafjallajökull or partial melting of a mantle source having intermediate characteristics to those further south and east. The trace element pattern reveals a mantle source characterized by a recycled oceanic crust.

UV3-12

Volcanological studies of the Neogene Hólmar and Grjótá olivine basalt lava groups in eastern Iceland

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Hólmar and Grjótá are two stratigraphically distinct olivine basalt lava groups within the westward-dipping Neogene flood basalts of eastern Iceland. The Hólmar group, separated from the overlying Grjótá group by only a few tholeiite flows, can be traced over 45 km north-south, thickest at Norðfjörður with >20 lava flows (>280 m) and less than 10 flows (~30 m) where thinnest.

The group encircles and partly covers the Reyðarfjörður central volcano and attains an approximate minimum volume of 60 km^3. Scoria deposits were identified within the Hólmar group, scattered around the Reyðarfjörður central volcano. The Grjótá group is thickest at Reyðarfjörður, with ~30 lava flows (~200 m) thinning down dip to ~10 flows (~40 m), and has an estimated minimum volume of 100 km^3. Two thick olivine dolerite sills cut the Hólmar group within the Reyðarfjörður central volcano, and could be part of the plumbing system that fed the Grjótá group. The total volume for both groups might exceed well over twice the estimated minimum considering that they are not fully exhumed and in part lost to erosion. The structure and morphology of both groups are near identical. The structure is highly compound, with lobes stacked horizontally and vertically, varying from 1-15 m thick and 2-200 m long with the exception that the Grjótá group includes a series of thicker (15-20 m) and more extensive (> 1 km long) lava flows. The lavas within the groups are often directly emplaced or welded together, but also found interbedded with thin redbeds and occasionally thicker tuff deposits. Filled lava tubes with a general trend perpendicular to the N-S trending regional dike swarm are commonly observed. Occasionally, tree molds can be identified between flow units. The internal structure follows the characteristics for lava lobe morphology in general, with an upper vesicular crust forming half to one third of the total thickness, a massive core with abundant vesicle cylinders and a thin lower vesicular crust. Flow tops are of pahoehoe type, seldom with scoriaceous rubble or clinker. Inflation structures as tumuli and inflation clefts were identified in few lobes but were absent in others. General surface and internal features of the studied olivine basalt groups, suggest that the lavas flowed with low viscosity from vents, likely along fissures, feeding lobes that developed internal insulated pathways. These lava lobes advanced out of the vents controlled by the pre-existing topography, many inflating to invert the lobate topography of the underlying flows. The parasitic nature of the scoria cones and the location of the olivine dolerite sills suggest that the magmatic system feeding these groups pertains to or intersects the Reyðarfjörður volcanic center. It is also evident that the large and dense spatial distribution of these groups, including numerous thick lava units, suggests voluminous volcanic episodes tapping seemingly uniform sources.

UV 4 – Magma plumbing system

UV4-01

Volcanic plumbing systems in Iceland; inferences from geodetic observations

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Repeated geodetic measurements reveal how active volcanoes deform at the surface, and data inversion facilitates inferences about the related volume changes and probable geometry of underlying deformation sources. Under favourable conditions a combination of the two space geodetic methods, CGPS and InSAR, is optimal for mapping the full extent of not only spatial but also temporal complexities in the deformation field during a volcanic unrest episode.

The typical pattern of surface deformation observed prior to, spanning and following eruptions of Iceland's frequently active volcanoes, relates to melt accumulation, drainage and renewed replenishment from crustal magma chambers.

An example of this is the Hekla volcano in southern Iceland. Hekla's eruption cycle was 1-2 eruptions per century, until it apparently terminated in an explosive eruption in 1947. The next eruption followed in 1970, and Hekla has erupted roughly every 10 years since then (1980/81, 1991, 2000). A strong correlation exists between the length of the inter-eruptive period and the SiO2 content of the eruptive products (initial SiO2 content ~55-70%), suggesting the existence of a magma chamber of considerable size at depth.

Surface deformation measurements reveal a composite pattern of deformation for Hekla volcano and its immediate surroundings. A roughly circular area 20 km in diameter (centered at the summit) subsides continuously during inter-eruptive periods. The subsidence peaks on the most recent lava flows, primarily due to cooling and compaction of the erupted material, although subsidence is not confined to areas covered by recent lava flows. A subtle, but continuous, uplift signal (~5 mm/yr) circumscribes the region of local subsidence. This uplift region has a diameter of ~40 km (centered at the summit). A model of the Hekla plumbing system will be presented, based on FEM models reproducing the complicated surface deformation field recorded at Hekla.

The relatively simple plumbing system at Hekla stands in strong contrast to the complex deformation trends observed at the moderately active Eyjafjallajökull volcano, which closed European airspace for days during it's 2010 ash-producing eruption. Over the last 18 years, Eyjafjallajökull has been experiencing intermittent unrest, where several episodes of elevated seismic energy release have been associated with crustal deformation. GPS and InSAR observations are available throughout the period, with a strongly enhanced data quality and quantity during the most recent unrest episode spanning 2009-2010. A set of inverse models calculated from the entire set of pre-eruptive, and co-eruptive surface deformation data has revealed a complexity of the subsurface magma plumbing, consisting of a network of sills and melt pockets at 4-7 km depth, as opposed to a single crustal magma chamber.

UV4-02

Deformation cycle of the Grímsvötn sub-glacial volcano, Iceland, measured by GPS

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The subglacial Grímsvötn volcano in Vatnajökull ice cap erupted in 1998, 2004, and 2011. We present results of Global Positioning System (GPS) geodetic measurements since 1997 conducted at one site on the volcano's caldera rim, which protrudes through the ice cap. The volcano contains a complex of three calderas (<12 km^2 each). The observed displacement can be attributed to several processes: i) transport of magma in and out of a shallow chamber under the center of a caldera complex (inflation, deflation, accompanied by in- and outward horizontal displacements), ii) isostatic uplift due to gradual thinning of the ice cap, iii) annual variation in snow load, iv) crustal plate movements. Annual GPS measurements started after the 1998 eruption and a continuous GPS-monitoring station has been operative shortly before the 2004 eruption. During inflation periods the vertical displacement is a joint result of a glacial isostatic adjustment due to thinning of the glacier and inflow of magma to a shallow magma chamber, while the horizontal displacement component is predominately attributed to magma pressure changes. The horizontal displacement of the GPS-site on the caldera rim is directed outward during inflation and inward (directly opposite) accompanying the eruptions. This pattern has been repeated for each eruption cycle, pointing to location of one and the same magma chamber in the center of the caldera complex. Erupting vents in 1998, 2004 and 2011 were located at the foot of the southern Grímsvötn caldera rim. The earthquake pattern was similar prior to the two most recent eruptions: a slow increase in number of events during the years before the eruptions and practically none following the eruptions. The continuous GPS data after the eruption in 2011 suggest a fast pressure recovery of the shallow magma chamber similar to that following the 1998 and 2004 eruptions, although the 2011 eruption is the best observed. The regularity of the crustal deformation and the earthquake pattern prior to the past two eruptions led to both successful long- and short-term predictions and warning of the events. Grímsvötn volcano has shown to be in a state of continuous magma accumulation at shallow depths that results in eruptions when the strength of the crust is overcome by the magma pressure.

UV4-03

Grímsvötn 2011 Explosive Eruption, Iceland: Relation between Magma Chamber Pressure Drop inferred from High Rate Geodesy and Plume Strength from Radar Observations

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We demonstrate a clear relation between the vigor of an explosive eruption and inferred pressure change in a magma chamber feeding the eruption, based on near-field records of continuous GPS and ground tilt observations. The explosive mostly phreatomagmatic VEI4 eruption of the subglacial Grímsvötn volcano in Iceland, 21-28 May 2011, produced an initial plume reaching a height of about 20 km. Magma feeding the eruption drained from a shallow magma chamber under the Grímsvötn caldera. A continuous GPS site on the caldera rim sampling data at 5 Hz has allowed the reconstruction of the pressure drop history in this magma chamber. The pressure dropped at a fast rate about an hour prior to the eruption while a feeder dike formed. Throughout the eruption the pressure continued to drop, but decayed exponentially. These observations are compared to measurements of plume heights, based on C-band radar located 257 km from the volcano and a mobile X-band weather radar placed at 75 km distance from the volcano after the eruption began. The radar further away has height resolution steps of 5 km at the location of Grímsvötn above 10 km elevation, and the one closer has resolution steps of 2-3 km. The measurements reveal plume heights often above 15 km between 19:21 on 21 May and 17:35 on 22 May (local time same as GMT). Peak elevation values of about 20-25 km for about 30 minute intervals were observed a few times between 21:25 on 21 May and 06:40 on 22 May. The initial strong plume was followed by pulsating but generally declining activity. After 04:55 on 23 May the measurements indicate a fluctuating plume mainly below 10 km. In order to generate a continuous curve of plume elevation we average all available plume elevation information for each hour. The resulting plume height is then related to magma flow rate using an

empirical formula from Mastin et al. (2009). Integrating these flow rates yields an estimate of accumulated volume of eruptive products calculated as dense rock equivalent (DRE). Despite large uncertainties on the inferred magma flow rate, the shape of the curve of inferred accumulated DRE and the pressure drop are similar. For this eruption, we see a clear link between the strength of an eruption plume and pressure change in the feeding magma chamber, measured by high rate ground deformation studies. Hence we can conclude that magma flow inferred from plume height correlates with the pressure change, which demonstrates the potential of real time high rate geodesy to foresee both onset and evolution of explosive eruptions and their plumes. The inferred volume change of the underlying magma chamber, modeled as a Mogi source, is about 5-8 times smaller than the suggested DRE volume from the integration of plume heights, which we relate to the effects of magma compressibility.

UV4-04

Resonating eruptive flow rate during the Grímsvötn 2011 volcanic eruption

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The Grímsvötn volcano in Iceland erupted 21-28 May 2011 at a similar place (64°23.9’N, 17°23.1’W, about 1450 m a.s.l.) under the SW caldera rim as the last eruption in November 2004. The eruption started at or just before 19:00 UTC on 21 May. During the first night the plume reached 20-25 km altitude over a 10 hour period, after which the strength of the eruption appeared to decrease exponentially.

Two weather radars monitored the plume during the eruption; a fixed C-band radar in Keflavík and a mobile X-band radar at Kirkjubæjarklaustur, 257 and 75 km from the volcano, respectively. The plume height of the radar time-series was used to calculate the mean eruptive flow rate. The calculations indicate that about 90% of the total mass erupted during the first 21 hours. The estimates of eruptive flow rate show very strong regular oscillations with periods of about 5 hours. During the first 12 hours the 1 hour mean dense rock equivalent flow rate oscillated between about 1000 and 8000 m^3/s (2 and 20 million kg/s).

During the eruption, over 16 000 lightning strikes were recorded near Grímsvötn by the ATDnet (Arrival Time Difference) network of the UK Met Office. Peculiar variations in the rate of lightning occurrence became evident during real-time monitoring of the ATDnet lightning data during the first night of the eruption. The calculated flow rate oscillations agree well with the observed lightning oscillations, both in phase and relative amplitude. The same oscillations can also be seen in tiltmeter data from Grímsfjall, about 6 km East of the vent. In hindsight, there also appear to have been some regular long period oscillations in lightning rate and plume height during the Grímsvötn 2004 eruption.

We can only speculate on the causes of the apparent volcanic resonance. (a) The magma chamber and feeding dykes of the volcano might act like a Helmholtz cavity resonator. However, the observed period is considerably longer than one might expect. (b) The oscillations might reflect an interaction between quenching of the feeding dykes to the surface and boiling of the geothermal fluids in the geothermal system above the magma chamber. (c) A small shallow magma chamber might be emptied in a few hours and a larger deeper source might take similar time to refill the shallow magma chamber. Possibly, such a two chamber system might resonate with the observed period.

UV4-05

Inferring volcanic plumbing systems from ground deformation: what we learn from laboratory experiments

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Active volcanoes experience ground deformation as a response to the dynamics of underground magmatic systems. The analysis of ground deformation patterns may provide important constraints on the dynamics and shape of the underlying volcanic plumbing systems. Nevertheless, these analyses usually take into account simplistic shapes (sphere, dykes, sills) and the results cannot be verified as the modelled systems are buried. In this contribution, I present new results from experimental models of magma intrusion, in which both the evolution of ground deformation during intrusion and the shape of the underlying intrusion are monitored. The models consisted of a molten vegetable oil, simulating low viscosity magma, injected into cohesive fine-grained silica flour, simulating the brittle upper crust; oil injection resulted is sheet intrusions (dykes, sills and cone sheets). The initial topography in the models was flat. While the oil was intruding, the surface of the models slightly lifted up to form a smooth relief, which was mapped through time. After an initial symmetrical development, the uplifted area developed asymmetrically; at the end of the experiments, the oil always erupted at the steepest edge of the uplifted area. After the experiment, the oil solidified, the intrusion was excavated and the shape of its top surface mapped. The comparison between the uplifted zone and the underlying intrusions showed that (1) the complex shapes of the uplifted areas reflected the complex shapes of the underlying intrusions, (2) the time evolution of the uplifted zone was correlated with the evolution of the underlying intrusion, and (3) the early asymmetrical evolution of the uplifted areas can be used to predict the location of the eruption of the oil. The experimental results also suggest that complex intrusion shapes (inclined sheet, cone sheet, complex sill) may have to be considered more systematically in analyses of ground deformation patterns on volcanoes.

UV4-06

Early Cretaceous magmatism on Svalbard – a review of geochemistry, generation, geometry and implications for CO_2 sequestration

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Igneous intrusions of the Early to mid-Cretaceous Diabasodden suite (Harland and Kelly 1997) are found over large parts of the Arctic Svalbard archipelago, reflecting activity within a Large Igneous Province (LIP, summary in Maher, 2001). These bodies, typically composed of dolerites, regionally intrude the Permian to Jurassic siliciclastic sedimentary succession. Published geochemical data indicate a consistent basaltic composition from a wide geographic region. Time-equivalent volcanic deposits occur at Kong Karls Land in the north-east of the archipelago. Published K-Ar ages (Birkenmajer et al., 2010; Burov et al., 1977; Firshov and Livshits, 1967; Gayer, 1966) range from approximately 149 Ma to 85 Ma, with an average around 125 Ma. Recent dating, using the more reliable U-Pb dating of zircons as well as Ar-Ar dating, by Polteau et al. (2011) suggests magmatism at approximately 125 Ma.

In the study area of Inner Isfjorden, these dolerite sills and dykes intersect the Late Triassic-Early Jurassic Kapp Toscana Group; an approximately 300 m thick shallow-marine to paralic, siliciclastic succession currently being evaluated for the purpose of CO_2 sequestration (http://CO_2-ccs.unis.no). One of the 4 boreholes drilled in the vicinity of the Longyearbyen settlement (Dh4) encountered dolerite sills up to 2 m thick in the lower half of this formation. Furthermore, seismic data show high-amplitude reflectors approximately 50-100 m beneath the borehole's base. Based on correlation with outcrop data, as well as regional onshore and offshore seismic data sets, these high-amplitude reflectors are interpreted as dolerite sills.

Initial fieldwork results indicate high fracture frequencies (up to 16 fractures/metre) within the dolerite sills and dykes. This includes both primary cooling joints and later Tertiary transpression-related slickensided fractures, revealing an intrinsic permeability. On the other hand, within and around the intrusions a pervasive network of calcite cemented fractures, some with evidence of recurring fracturing and sealing testify to recurrent sealing of fractures by calcite precipitation from circulating fluids. These observations, coupled with possible localized contact metamorphism and metasomatism of the nearby host rock, suggest that the dolerites may act as barriers for later fluid flow.

Our preliminary results suggest that the Cretaceous igneous intrusions of Spitsbergen can be represented by a complex network of sills, some of which may be saucer-shaped. The presence of dolerite intrusions will significantly affect reservoir behavior in a number of ways:

1) Baffling of fluid flow. Flow can be retarded or redirected by unfractured, weakly fractured or fractured rock with sealed fractures.
2) Compartmentalization. The reservoir may be compartmentalized by the igneous intrusions, especially discordant dykes, leading to differential pressure compartments in the reservoir section.
3) Focusing of fluid flow. More intense fracture systems around dykes and sills formed during the intrusion and may have resulted in additional permeability pathways in their vicinity (e.g. Matter et al 2006). Increased hydrothermal activity and subsequent cementation of the fractures may nonetheless prevent these to be exploited for fluid flow.
4) Enhanced long-term CO_2 storability due to enhanced mineral trapping potential through the formation of carbonate minerals (e.g. Matter et al 2007).

UV4-07

Constraints from short-lived U-series nuclides on the magma dynamics leading to the 2010 Eyjafjallajökull eruption

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Magma mixing frequently triggers volcanic eruptions. The process is readily identified if the end-members are of contrasting composition, such as in the 2010 Eyjafjallajökull eruption when evolved basalt was injected into a silicic magma reservoir. The first erupted benmoreite contains three types of glass; basaltic, intermediate and silicic in composition. This glass heterogeneity implies a timescale of only a few hours between basalt injection, mingling and explosive eruption. This concurs with the duration of seismic epicenter migration from 10 km depth to 3 km on 13 April, a few hours before the onset of the explosive eruption. However, a much longer time was needed for the mafic magma to enter the silicic reservoir. Inflation of the volcano began at the end of 2009, most likely indicating influx of magma from depth. This presumably basaltic recharge did not reach the silicic reservoir but bypassed it and erupted at Fimmvörðuháls on 20 March. What hindered the basalt from entering the silicic reservoir is less clear.

Radioactive disequilibria between ^{210}Pb-^{226}Ra and ^{210}Po-^{210}Pb in the ^{238}U decay chain have been measured in different products of the Eyjafjallajökull eruption. These disequlibria are much affected by degassing of ^{222}Rn and ^{210}Po. The flank basalts confirm complete degassing of ^{210}Po upon eruption, whereas the first explosively erupted benmoreites from 15 and 17 April both have excess ^{210}Pb over ^{226}Ra and ^{210}Po relative to ^{210}Pb. These unique observations strongly indicate a transfer of a gas phase enriched in radon and polonium most likely from deep basalt into the half-molten silicic magma reservoir. I f the residing silicic magma was a degassed residual magma after the 1821-23 or older eruptions, then the incoming gas phase would be partially re-dissolved as volatiles in the silicic melt. Additional gas phase would build up pressure in the silicic reservoir before eruption. In that case, both the mass ratio of degassing basaltic magma over gas accumulating silicic magma, and the time of basalt degassing can be estimated. Assuming that all radon and polonium is degassed from the basaltic magma, the ($^{210}Pb/^{226}Ra$) and ($^{210}Po/^{210}Pb$) values of the benmoreite, corrected for post-eruptive decay, yield a degassed/accumulating magma ratio of 12. Moreover, the

ORAL UV 4

degassing duration would be approximately 100 days. The initiation of basalt degassing therefore coincides with the beginning of Eyjafjallajökull inflation as measured by the continuous GPS station at the farm Þorvaldseyri.

The injected CO_2 and S-rich basalt must therefore have been emplaced close enough to the silicic reservoir for efficient gas transfer between the contrasting magma types more than three months before the explosive eruption at the top crater. The degassing of that basalt caused its fractional crystallisation and production of an evolved FeTi-basalt. The latent heat of crystallisation could have contributed to the melting of the silicic reservoir's carapace, thus generating a pass way for evolved basaltic intrusion and the resulting magma mingling.

UV4-08

New U-series isotope data from the Andean backarc stress the OIB-character of the Payún Matrú volcanic complex

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The chemical composition of backarc magmas provide evidence for mantle sources that have been variably enriched in H2O and elements such as Ba, Th, U and Pb. These elements are believed to be transported into the mantle wedge from the subducting slab by aqueous fluids and/or sediment melts from the subducted, altered, basaltic crust, serpentinized mantle and sedimentary rocks. $^{238}U/^{230}Th$ disequilibria data remain a powerful tool to evaluate the role of a recent fluid input from subducting slabs into the magma source of a backarc system. Subduction related volcanic rocks are often characterized by ($^{230}Th/^{238}U$) < 1 (parenthesis indicating activity ratio), reflecting addition of (more fluid-mobile) U relative to (more fluid-immobile) Th in the melt source region. In contrast, mid-ocean ridge basalts (MORB) and ocean island basalts (OIB) are usually characterized by ($^{230}Th/^{238}U$) > 1, reflecting partial melting under influence of residual garnet and/or high-pressure clinopyroxene. Thus, criteria of ($^{230}Th/^{238}U$) < 1 or > 1 may help to critically distinguish between sources and modes of melt formation.

We present U-series disequilibria analyses from Holocene lavas in order to identify the influence, transport and timing of addition of aqueous fluids from the subducting slab into the magma source for two volcanoes in the Payenia backarc province, Argentina. Lavas from the Infernillo volcano (35ºS) are porphyritic basalts to andesites. Trace element ratios such as high Th/Ta, Ba/La > 20 and La/Ta > 25 indicate an arc signature for their mantle source. Lavas from the Payún Matrú (36ºS) volcano have a chemical signature more resembling ocean island basalts with e.g. relatively low Ba and high Nb at a given Zr content.

The new U-series disequilibria analyses from the Andean backarc system support the OIB-character of the Payún Matru volcano, and the more fluid influenced arc-like character of the Infernillo volcano. All samples are very fresh and estimated from field relations to be younger than 10 ka so no correction is required for posteruptive decay of ^{230}Th (half-life 75,200 yr). For all samples the ($^{234}U/^{238}U$) ratios are within 1% of secular equilibrium, supporting evidence for the samples being free of alteration effects. The Infernillo samples plot beneath the equiline with 5-10% excess of ^{238}U. This feature is characteristic of arcs and is best ascribed to the presence of slab-derived fluids in the mantle source beneath Infernillo. The excess of ^{238}U also requires that the fluid addition occurred within the last 300 ka. In contrast data from the Payún Matru volcano show 5-10% excess of ^{230}Th, and plot within the ocean island basalt field as defined by literature data. In the case of OIB, partial melting is the main process fractionating Th/U and thus producing the $^{230}Th/^{238}U$ disequilibria.

UV4-09

The magmatic evolution of lavas from Maipo, SVZ, Andes: on the relative roles of AFC and source contribution from continental crust to the magmas

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The Maipo rock series is subalkaline and encompass basaltic andesite, andesite, shoshonite, and latite that represent a magmatic evolution of around 50 % fractional crystallisation. Among volcanic rocks from the SVZ the Maipo rocks are among the most potassic and comparable only to other high-K calc-alkaline rocks from the Northern SVZ. They are less subalkaline than any other suite in the SVZ, relatively low in Fe (Fe2O3 up to ca. 7 wt%) and range to rather primitive compositions with Mg# = 60. In terms of REEs the source is indicated to be a depleted mantle enriched in LREEs. Tb/YbN = 1.4 - 1.6 indicates very limited amounts of garnet in the source and that the low degree melts segregated at depths of 70-80 km. The most mantle-incompatible elements except Nb and Ta, and Pb are enriched 100 x PM. The most primitive rocks have negative anomalies of Ba, Nb, Ta, P, Eu and Ti in trace element patterns. The enrichment of Rb and Th respective to Nb is an indication of a component of crustal rocks that could be sediments rather than enrichment by fluids.

The rocks that construct the 2000 m stratocone of Maipo constitute at least two liquid lines of descent. Decreasing MgO, CaO, and CaO/Al2O3 is evidence of the importance of clinopyroxene fractionation, and together with decreasing Sr, Eu/Eu*, Sr/Sr*, Ba/Rb and Ba/Th gabbro fractionation is indicated. This shows that the present feldspar dominated phenocryst assemblage is a result of a brief residence in a shallow magma chamber subsequent to a deeper seated magmatic evolution. Also Fe-Ti oxides fractionated over the entire range, as recorded by FeO and TiO2. Positive correlation between Tb/Yb and Sr and negative between Yb and Sr invalidate garnet fractionation in the deep crust as previously suggested (Drew et al., 2010). Rather, amphibole or titanite are possible fractionating phases as perhaps also indicated by a doubling of Rb/La.

Possible crustal contamination is veiled in the arc signature of the parental magmas. Although Nd and Pb isotopic compositions are almost constant, AFC may be indicated by an increase in

87Sr/86Sr with magmatic evolution. The negative anomaly for P and low Ba/Rb in all rocks suggest that an important source component is of evolved (magmatic) composition; and positive Sr/Sr* in primitive rocks with Eu/Eu* = 0.8-0.9 indicate that the source is feldspar cumulative. A continental crustal component in the parental melts is indicated by high 87Sr/86Sr = 0.7049 and low 143Nd/144Nd = 0.51259 even in the most primitive samples compared to the southern SVZ rocks. The relative role of continental crustal material as assimilant and source rock is discussed at the meeting.

UV4-10

Zircon records mafic recharge-induced reheating and remobilization of crystal mush at the Austurhorn Intrusive Complex

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The Austurhorn Intrusive Complex (AIC) is a small silicic center located along the coast of SE Iceland. The exposed portion of the pluton intrudes primarily basaltic lavas of the Álftafjördur and Lón mid-Miocene central volcanoes, and comprises granophyre, gabbro, and an associated mafic-felsic composite zone (MFCZ) in which evidence for open system behavior, including chamber replenishment by basaltic and felsic magmas indicated by the mingling/mixing of magmas, is observed (Blake, 1966; Mattson *et al.*, 1986). The structure of the intrusion and geochemistry of the mafic and felsic rocks at AIC suggest it developed as a shallow pluton forming part of a central volcano within a short-lived immature axial extensional environment (Furman *et al.*, 1992a).

Evidence for mafic magmatic replenishment is ubiquitous within the MFCZ. Clasts, enclaves, pillows, and sheets of mafic rock constitute up to 50% of the exposure. Zones of fine-grained high-Si granophyre (~77 wt.% SiO2) within less felsic granophyre host (~70 wt.% SiO2) are exposed within the complex. Quartz and feldspar make up 98-99% of the high-Si granophyre. We interpret these zones to be the result of melting, remobilization, and segregation of high-Si melt from nearly-solidified felsic material, likely due to reheating by mafic magma replenishment.

Zircons extracted from intermediate to felsic MFCZ rocks retain evidence, as cores that we interpret to be antecrystic, for thermal and chemical fluctuations that mark repeated mafic-felsic magma interactions throughout the history of the complex. U-Pb dating of zircons from mafic to felsic rocks reveals a significant episode of mafic replenishment within the MFCZ. The ages we obtained can be grouped into two coherent age populations: 6.45 ± 0.04 Ma (MSWD = 1.3) and 5.99 ± 0.06 Ma (MSWD = 1.17). The older population is dominantly composed of zircons from intermediate to felsic rocks, with a few analyses coming from gabbro. Thus, we interpret the older age (6.45 Ma) to represent the emplacement of the MFCZ. Zircons from the gabbro alone yield a mean age of 5.99 ± 0.1 Ma, and the younger population includes most gabbro zircons as well as one third of zircons from intermediate to felsic rocks. We therefore interpret the younger age (5.99 Ma) as a major episode of mafic replenishment into the MFCZ. The mean age of zircons in intermediate to felsic samples differs from the mean age of zircons in gabbro by 0.46 m.y. This timescale is consistent with a model in which the longevity of a magmatic system is prolonged by the repeated input of younger and hotter mafic magmas into the system (*cf.* Claiborne *et al.*, 2010). The MFCZ was probably nearly and possibly entirely solid at the time of gabbro intrusion. Based on field evidence, which suggests magmatic interactions between the gabbro and felsic rocks with which it is associated, and the presence of younger zircon in felsic rocks, we infer that this event reheated and reactivated the resident felsic material within the MFCZ magma reservoir with attendant growth of a second generation of zircon during intrusion.

UV4-11

Efficiency of differentiation in the Skaergaard magma chamber

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Although it is largely agreed that crystallization occurs inwardly in crystal mushes along the margins of magma chambers, the efficiency and mechanisms of differentiation are not well constrained. The fractionation paradigm hinges on mass exchange between the crystal mush and the main magma reservoir resulting in coarse-grained, refractory (cumulate) rocks of primary crystals, and complementary enrichment of incompatible elements in the main reservoir of magma. Diffusion, convection, liquid immiscibility and compaction have been proposed as mechanisms driving this mass exchange. Here we examine the efficiency of differentiation in basaltic crystal mushes in different regions of the Skaergaard magma chamber. The contents of incompatible elements such as phosphorus and calculated residual porosities are high in the lowermost cumulate rocks of the floor (47-30%) and decrease upsection, persisting at low values in the uppermost two-thirds of the floor rock stratigraphy (~5% residual porosity). The residual porosity is intermediate at the walls (~15%) and highest and more variable at the roof (10-100%). This is best explained by compaction and expulsion of interstitial liquid from the accumulating crystal mush at the floor and the inefficiency of these processes elsewhere in the intrusion. In addition, the roof data imply upwards infiltration of interstitial liquid. Remarkably uniform residual porosity of ~15% for cumulates formed along the walls suggest that their preservation is related to the rheological properties of the mush, i.e. at ≤ 15% porosity the mush is rigid enough to adhere to the wall, while at higher porosity it is easily swept away. We conclude that the efficiency of compaction and differentiation can be extremely variable along the margins of magma chambers. This should be taken into account in models of magma chamber evolution.

ORAL
UV 4

UV4-12

The influence of crustal composition on magmatic differentiation across five major crustal terranes: the British-Irish Palaeocene Igneous Province revisited

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The British-Irish Palaeocene Igneous Province (BPIP) is an ideal testing ground for the influence of crustal composition on ascending magmas. Four major tectono-stratigraphic terranes are traversed on a transect from Skye and Rum in the North, to Carlingford and the Mourne Mts. in the South. These crustal terranes are bounded by major discontinuities; the Moine Thrust, the Highland Boundary Fault, the Southern Uplands Fault and the Iapetus Suture, and are isotopically extremely diverse. This led to the suggestion that ascending mantle-derived magmas may be variably contaminated depending on the terrane through which they have passed [1, 2], but no comprehensive study or model has yet been presented. We have analysed a large suite of new samples (> 300) for Sr, Nd and Pb isotopes in a spectrum of mafic to felsic igneous rocks from the central complexes of Rum (Hebridean Terrane), Ardnamurchan and Mull (Northern Highlands), Arran (Grampian and Midland Valley Terranes), Slieve Gullion and Carlingford (Southern Uplands Terrane). Using published data together with new data on crustal lithologies from surface exposures and xenoliths, our results suggest that the local crust has indeed had a significant influence on the majority of magma compositions at the six centres investigated and a correlation between crustal terrane and the isotopic composition of BPIP rocks (crustal provincialism) exists. The mantle Sr-isotope ratio (at 60Ma), suggested to be 0.7023-0.7032 [3, 4], is generally lower than our basaltic samples from throughout the province (0.7028 to 0.7111). Felsic rocks yield a range that shows yet further elevation (0.7066 - 0.7226), while crustal rocks span from 0.7065 to 0.7379. Styles of contamination differ not only between centres, but also within individual centres. Our data imply that only very primitive, and generally rare, high MgO rocks are unequivocally suitable for the extraction of sensible information on primary magmatic sources. In turn, as previously suggested for individual centres [5, 6], mafic rocks frequently display lower crustal influences, while felsic rocks regularly record a more complex, multi-stage evolution, reflecting the cumulative effects of contamination events in deep and shallow crustal reservoirs.

UV4-13

Igneous and ore-forming events at the roots of a giant magmatic plumbing system: the Seiland Igneous Province (SIP)

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SIP covers an area of 5500 km^2 in N. Norway. 50 % of the volume comprises mafic layered or homogenous plg+px+Fe-Ti±ol gabbros. 25 % of the area consist of ultramafic intrusions, mostly peridotite and subsidiary pyroxenite and hornblendite and the final 25 % is dominated by calc-alkaline and alkaline plutons, respectively.

Ultramafic plutons intersect gabbros and calc-alkaline plutons. Recent zircon U/Pb geochronology imply that SIP formed at 560-570 Ma, with mafic- and ultramafic rocks emplaced in <4 Ma (Roberts et al., Geol. Mag, 2007).

Geothermobarometry of contact metamorphic mineral assemblages, implies minimum depth of 20-30 kilometres. Accordingly, the Seiland province arguably provides a unique cross section through the deep-seated parts of a large magmatic plumbing system.

Sulphide Cu-Ni-(PGE) deposits are intimately associated with the ultramafic rock suite. One deposit is known from Stjernøy where sulphide dissiminations occur at the floor of a peridotitic pluton, another deposit occur at the floor of the Reinfjord ultramafic layered complex in the far West of SIP and the third deposit comprises vertical sulphide dykes in the interior of a hornblendite on the Øksfjord peninsula. Currently, only the Reinfjord deposit is studied in detail. Previous studies (Søyland Hansen, 1971, unpub. MSc thesis, NTNU) and our preliminary work document dissiminated Cu-Ni sulphides in a 10-20 m's thick and two km's long deposit at the lower contacts of the Reinfjord intrusion. Hansen and NGU reports 0.15 wt% for both Ni and Cu. The sulphide assemblage is pentlandite, chalcopyrite, pyrrhotite and minor pyrite. Most of the pentlandite is bravoitised, hence c. 50 % of the Ni at the surface is lost to weathering. Most Ni occurs in isolated pentlandite grains whereas pyrrhotite is Ni-poor. The sulphide assemblage is interstitial amongst olivine and pyroxene primocrysts.

The Reinfjord intrusions is layered and develops from olivine clinopyroxenites in the lower part to wherlite and dunite in the upper part. Earlier studies suggest that the parental melts comprise olivine pyroxenites whereas dunites and wherlites formed by fractional crystallization (Bennet et al., Bull. NGU, 405, 1-41). During our fieldwork we observed spectacular examples of cumulus structures, not previously reported, and including modally layered and modally graded dunite/wherlite, cross-bedding, slumping and mush-diapirs. Finally we saw an example of magma-replenishment an irregular olivine pyroxenitic dike was emplaced and mixed with the olivine/wherlite mushes!

Along the contacts, it was observed that the country rock gabbros were partially melted and assimilated during the emplacement of the ultramafic magma, in a zone extending tens of metres in to the gabbros. Interestingly, uneconomic sulphide dissiminations are common throughout the gabbros and may have provided the sulphide liquids required in ore-formation.

In conclusion, the high proportion of ultramafic intrusions in SIP provides a rare insight in to the roots of giant magmatic plumbing system. Voluminous emplacement of ultramafic magmas in the deep-seated Reinford intrusion, featuring convection, slumping, replenishment, massive assimilations of sulphide bearing gabbros and de facto sulphide deposits, imply large-scale ore-forming processes at work throughout the SIP.

Posters

EC1 – Glaciers and glacial processes

P01

Glacier retreat and ice-front evolution at Virkisjokull since 1990

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Iceland's glaciers are evolving rapidly in the current period of climate warming (since approx. 1990). Consequently, dynamic glacial and geomorphological processes are now operating at rates that can be monitored and recorded over shorter timescales - years, months and even days. Capturing this change generates valuable data essential for establishing drivers, mechanisms and rates of glacier change. The Oraefajökull ice cap, the southern-most portion of the Vatnajökull ice mass, has 13 named outlets. Eight of these glacier margins are monitored annually by the Icelandic Glaciological Society. We present research focusing on the twin outlet glacier of Virkisjökull-Falljökull, visited regularly by members of the British Geological Survey team since 1996. Aerial photographs spanning the last 25 years, combined with detailed geomorphological mapping and field measurements have identified successive annual ice-front positions charting continuous glacier recession between 1990 and 2011. Over 400 m of ice-front retreat has occurred in this time, with almost half of this retreat (190 m) since 2005. Terrestrial LiDAR surveys of the ice front completed each year since 2009 have captured this rapid change in centimetre-precise detail. These data allow inter-annual comparisons of Digital Elevation Models (DEMs) covering a 5 km^2 area of the glacier margin and foreland. Analysis of these high-resolution DEMs coupled with field observation reveals a highly complex pattern of geomorphological evolution and ice front retreat, forced by climate and conditioned by supraglacial debris, buried ice and englacial hydrology.

P02

Micromorphological evidence of basal shearing, liquefaction and decoupling during the emplacement of ice marginal mass flow deposits

Emrys Phillips
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Eyjafjallajökull tephra was brought to worldwide attention and put under detailed scientific scrutiny with the eruptions of 2010. Previous historical eruptions have been studied in some detail also, but until recently few details have been known about prehistoric explosive activity. Tephrochronological investigations have shown that explosive activity from the central crater of Eyjafjallajökull in the mid-6th century AD produced a distinctive tephra deposit, the Hoftorfa tephra (also previously known as Layer H or E500). This paper describes this tephra layer, it's distribution and volume, based on over 100 profiles from south Iceland.

The Eyjafjallajökull Hoftorfa eruption produced a pale white to yellow, silicic tephra that is thickest on the northern flanks of the volcano. The tephra deposit generally has a matrix of medium to fine grained ash supporting coarse grained ash to lapilli and in some locations bedding and grading are apparent. The extent of the tephra is similar to the Eyjafjallajökull 1821-3 eruption though it is somewhat greater in volume and is considerably thicker on the northern flanks. It is significantly smaller in volume and area than the 2010 Eyjafjallajökull tephra. Hoftorfa (the bedrock outcrop anchoring the north east margin of the great terminal moraine of Gígjökull) is proposed as the type site for this tephra layer being close to its thickest point and easily accessible for further study, following Dugmore (1987; 45).

Deposits have only been found within 20 km of the crater, but being highly visually distinctive, the Eyjafjallajökull Hoftorfa tephra layer still forms a very useful key marker horizon in the late prehistoric geological record, covering at least 600 km^2 including the forelands of 8 major outlet glaciers from two separate icecaps. Despite being of a limited volume and visible extent this tephra is important because its identification extends the record of known activity in the central crater of Eyjafjallajökull from the 17th century AD to the 6th century AD. It shows that the style of activity observed in 1821-3 also occurred some 1300 years previously; moreover, the same stratigraphic sections that have been used to identify this tephra also show that no similar events have taken place in the last c.7000 years.

P03

Minus 2 to 1000 degrees centigrade: comparing pre-full crystallisation fabrics in plutonic igneous rocks with microfabrics developed in subglacial tills

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CO_2 mineral sequestration in basalt may provide a long lasting, thermodynamically stable, and environmentally benign solution to reduce greenhouse gases in the atmosphere. Multi-dimensional, field scale, reactive transport models of this process have been developed with a focus on the CarbFix pilot CO_2 injection in Iceland. An extensive natural analog literature review was conducted in order to identify the primary and secondary minerals associated with water-basalt interaction at low and elevated CO_2 conditions. Based on these findings, a thermodynamic dataset describing the mineral reactions of interest was developed and validated.

Hydrological properties of field scale models were properly defined by calibration to field data using iTOUGH2. Resulting principal hydrological properties are lateral and vertical intrinsic permeabilities of 300 and 1700-10-15 m^2, respectively, effective matrix porosity of 8.5% and a 25 m/year estimate for regional groundwater flow velocity. Reactive chemistry was coupled to calibrated models and TOUGHREACT used for running predictive simulations for both a 1,200-ton pilot CO_2 injection and a full-scale

400,000-ton CO_2 injection scenario. Reactive transport simulations of the pilot injection predict 100% CO_2 mineral capture of within 10 years and cumulative fixation per unit surface area of 5,000 tons/km^2. Corresponding values for the full-scale scenario are 80% CO_2 mineral capture after 100 years and cumulative fixation of 35,000 tons/km^2. CO_2 sequestration rate is predicted to range between 1,200-22,000 tons/year in both scenarios.

The developed numerical models have served as key tools within the CarbFix project where they have strongly influenced decision making. The models were e.g. used as engineering tools for designing optimal injection and production schemes aimed at increasing reservoir groundwater flow in the pilot CO_2 injection Reactive transport simulations imply calcite to be the most abundant carbonate to precipitate but magnesite-siderite solid solution also forms in smaller amounts. Silicate precipitation is modeled to be associated with carbonate formation. Despite only being indicative, it is concluded from this study that fresh basalts may comprise ideal geological CO_2 storage formations.

P04

The drumlin field at Múlajökull, a surge-type glacier in Iceland: New ideas about drumlin evolution

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The drumlin field in front of Múlajökull, a surge-style, outlet glacier from Hofsjökull in Iceland, is the only known active drumlin field (Johnson et al., 2010). The aim of this study is to further explore the formation of drumlins and drumlin fields in a modern glacial environment.

We use data from geological sections, Digital Elevation Models (DEMs), aerial imagery and field mapping. Here we present preliminary results from section logging and geomorphological mapping in the summer of 2011.

Geomorphological mapping of the drumlin field both with DEMs and ground proofing has revealed over 100 drumlins and a number of drumlinized ridges. The drumlins furthest from the present ice margin appear broader and have lower relief than those closer to the ice. We suggest that this reflects an evolution of the drumlin form during recurrent surging. The drumlins farther away from the ice have experienced fewer surges than those that have just been uncovered due to retreat of the ice margin. During successive surges, the drumlins become narrower and develop higher relief.

In one section close to the present ice margin, we identified at least 9 till beds in the crest of a drumlin, each likely the product of a surge, representing approximately 1/3 of the drumlin relief. The top till bed parallels the drumlin form and truncates the older tills. The older units also dip parallel to the drumlin form, but at a slightly lower angle. We believe that this represents an earlier, broader shape of the drumlin prior to the more recent surges, implying an evolution of form similar to that seen in the evolution in form in the drumlin field.

The Múlajökull drumlins have thus grown during surging by erosion on the proximal end and sides of the drumlin followed by accretion of till sheets on top of the drumlin and on the distal side.

Reference:

Johnson, M.D., Schomacker, A., Benediktsson, Í. Õ., Geiger, A. J., Ferguson, A. and Ingólfsson, Ó., 2010, Active drumlin field revealed at the margin of Múlajökull, Iceland: A surge-type glacier: Geology v. 38, p. 943-946.

P05

Exploring the seabed west of Iceland with multibeam bathymetry

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The Marine Research Institute has been using multibeam bathymetry in connection with it´s various research fields, such as exploring new and known fishing grounds, effects of fishing gears on seabed, research on spawning fields or benthic communities and habitats. Detailed bathymetric maps as well as information from the backscatter is used. Data is presented from the outer part of the shelf area west of Iceland, i.e. west of Vestfirðir peninsula and west of Breiðafjörður, but also from a deeper part outside the shelf margin.

Glacial landscape characterises the shelf area. Here are glacially eroded troughs, moraine ridges and iceberg plough marks. Subbottom profiling reveals a thin sediment coverage. The 90 km long Látra moraine ridge is now mapped in detail, but earlier on it was mapped by the institute with a single beam echo sounder. The northern end of this moraine ridge rests on the Víkuráll trough, confirming an older age of the latter one. Several low ridges and other features are exposed on the landward side of the Látra moraine ridge. The distribution of fishing grounds and spawning areas is reflected in this landscape.

Kolluáll is a trough just west of Snæfellsnes. Sediment thickness as observed in subbottom profiles exceeds several tens of meters. The northern flank of the trough is densely covered with pockmarks, 5-10 m deep and 100-200 m in diameter.

Outside the shelf margin, at 900 - 1.300 m waterdepth at about 100 nautical miles westnorthwest of Snæfellsnes, there are several 40-200 m high conical features, both single and coherent. These are though to be mud volcanoes. If so, then these are the first mud volcanoes discovered in Icelandic waters. At the northern part of this area there is a 450 m high mountain with a striking look of a real volcano, with a flat crater on the top. It is not clear if this is a real volcano or a large mud volcano.

It is obvious that multibeam bathymetry has added significantly to our knowledge of the seafloor in Icelandic waters.

P06

Holocene glacier dynamics and fluctuations of the Drangajökull ice cap, NW Iceland: problems and potentials

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Drangajökull ice cap, situated over the glacially eroded Tertiary plateau basalt landscape of NW Iceland, covers an area of approximately 200 km^2. Three outlet glaciers of the ice cap are known to have surged since the 19th Century, up to three times each. Some Holocene glacier marginal fluctuations are known from earlier studies, and well preserved moraine ridges and glacial landforms have also been described. There are lakes in the area that are currently fed by surface runoff, but glacial melt water spills into them during more advanced stages of the glacier.

We will use geomorphological, sedimentological and remote sensing methods for documenting, describing and interpreting the landforms and sediments around the Drangajökull ice cap. Time-series of Digital Elevation Models (DEMs) of Drangajökull will be produced and used to estimate the ice volume displaced during several surges in the last decades, as well as the amount of erosion and deposition in the glacier forefields. We aim for sediment coring in some threshold lakes which we expect to contain sediment archives back to the last deglaciation. 14C dating and cosmogenic exposure dating will be used when possible in order to obtain absolute ages.

Our first field season was the summer of 2011; the focus was on the valley Reykjafjörður at the northeast side of Drangajökull and the adjacent fjords to north, Þaralátursfjörður, and Furufjörður. Sedimentological data from sections in Reykjafjörður and geomorphological mapping indicate existence of a Holocene glacial lake in the valley. We also mapped marginal moraine ridges that indicate a hitherto undescribed advanced stage of the outlet glacier Reykjafjarðarjökull. Samples for cosmogenic exposure dating were collected from erratics and striated bedrock in order to date the last deglaciation and to determine ages of terminal moraines. Threshold lakes that have possibly captured glacial melt water during more advanced stages of the glacier were identified for sediment coring in the 2011-2012 winter season.

P07

The largest end moraines in Iceland: Sedimentology, internal structure and formation of the Gígjökull and Kvíárjökull end moraines

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Gígjökull and Kvíárjökull are icefalls which drain the Eyjafjallajökull and Õræfajökull calderas, respectively. Their end moraines are about 80-150 m high and up to 600 m wide, which makes them the largest end moraines in Iceland. The aim of this project is to study the sedimentology and internal structure of the moraines in order to explain their formation and size, and to increase our knowledge on active icefalls, their glacial erosion, sedimentation, and landscaping. This project will be carried out in 2011-2013.

Little research has been done on the Gígjökull and Kvíárjökull end moraines and therefore their structure and formation is poorly known. The internal structures of the moraines will be studied with gravity surveys, resistivity measurements and Ground Penetrating Radar (GPR), focusing on whether or not an ice core exists in the moraines. The sedimentology of the moraines will be carried out with conventional methods in glacial geology, including particle size and shape measurements, to obtain information on the sediment transportation. With more information on the sedimentology and internal structure, we aim to erect a model that describes and explaines depositional processes at work at the margins of active icefalls. Apart from increasing knowledge on unique natural formations in Iceland, the results from this project will enhance understanding of icefall erosion and deposition and help to recognize and understand landscapes formed by former icefalls.

EC 2 – Glacial and climate history of Arctic, Antarctic and Alpine environments

P08

Propagation of the Storegga tsunami into ice-free lakes along the southern shores of the Barents Sea

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Deposits in coastal lakes in northernmost Norway reveal that the Storegga tsunami propagated well into the Barents Sea ca. 8100-8200 years ago. A tsunami deposit - found in cores from five coastal lakes located near the North Cape in Finnmark - rests on an erosional unconformity and consists of graded sand layers and re-deposited organic remains. Rip-up clasts of lake mud, peat and soil suggest strong erosion of the lake floor and neighbouring land. Inundation reached at least 500 m inland and minimum vertical run-up has been reconstructed to 3-4 m. In this part of the Arctic coastal lakes are usually covered by >1 m of solid lake ice in winter. The significant erosion and deposition of rip-up clasts indicate that the lakes were ice free and that the ground was probably not frozen. We suggest that the Storegga slide and ensuing tsunami happened sometime in the summer season, between April and October.

Reference

Romundset, A. and Bondevik S. 2011. Propagation of the Storegga tsunami into ice-free lakes along the southern shores of the Barents Sea. Journal of Quaternary Science 26 (5): 457-462.

P09

Climatic sensitivity of mountain glaciers at Kerlingarfjöll: a pilot study

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Debris flows, debris floods and related landslide processes occur in many regions all over Norway and pose a significant hazard to inhabited areas and transportation corridors. Within the framework of the production of a nationwide debris flows susceptibility map, we develop a modeling approach suitable for the unique geological setting of Norway.

The landscape of Norway comprises several types of mountainous regions with varying topography, bedrock- and quaternary geology, formed by the combined actions of crustal uplift, extensive glaciations and Holocene weathering and erosion processes. Debris flows and floods initiate either in active or passive stream channels or on open hill slopes, and the outrun deposits (fans) of many previous events often form the core of inhabitated areas in the narrow valleys due to the general lack of suitable building ground elsewhere in the mountain dominated landscape.

To develop a nationwide debris flow susceptibility map, we have to take into account both the complexity of the phenomenon and varying specific climate and geological setting of different regions. The GIS-based approach incorporates an automatic detection of the starting areas and a simple assessment of the debris flow runout, which provides a basis for first susceptibility assessments. We use the Flow-R model (IGAR, University of Lausanne). This model is based on an index approach for the discrimination of starting zones including topographic parameters extracted from a digital terrain model (DTM) and the hydrological setting based on the upslope contributing area (also derived from DTM). A probabilistic and energetic approach is used for the assessment of the maximum runout distances.

Simulations were performed at test sites in different parts of Norway and model calibration was based on mapping of quaternary deposits and geomorphology, orthophotos and field investigations. The results show that the approach for starting zone detection and runout model reproduce historical debris flows with good accuracy when using DTMs with 5 to 10 m cell size, but results rapidly deteriorates in accuracy with less resolution. Additionally, climatological, lithological and morphological criteria were used for classification of different "debris flow regions"in Norway, to allocate specific model-parameterization to the different topographical and geological settings. Field investigation and parameter calibration was in 2011 performed at test sites in the different "debris flow regions", to fine-tune the regionalized models and aid in finalizing a first nationwide debris-flow susceptibility map.

P10

Early Holocene hybridisation in Icelandic birch

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At the Pleistocene/Holocene transition the dwarf birch Betula nana was among pioneer species and the downy birch B. pubescens was often the first tree species colonizing deglaciated areas in northern Europe. In Iceland B. pubescens has been the only tree species creating continuous woodlands during the Holocene. Both species respond readily to climatic variation and while their distribution can overlap, climatic conditions seem to control the borders of reciprocal dominance.

Downy birch in northern Scandinavia and Iceland generally has low and scrub-like growth compared to the same species further south. The most probable cause is gene flow via introgressive hybridization between downy birch and dwarf birch, which has been confirmed with experiments and genetical field researches [1, 2]. Downy birch is tetraploid with chromosome number 2n = 56, but dwarf birch is diploid with 2n = 28. In natural woodlands in Iceland, triploid hybrids (2n = 42) deriving from hybridisation between the two species are relatively common. However, little is known about the history of birch hybridization in Iceland, e.g. if the process is continuous or what environmental factors may have promoted the hybridisation and consequent introgression.

Measurements of Betula pollen have shown that B. pubescens pollen grains are on the average bigger than B. nana pollen grains and their pollen pores are also deeper [3]. Pollen grains of triploid hybrids tend to be small like the pollen of B. nana, with deep pores like the B. pubescens pollen, resulting in a low diameter/pore ratio. Furthermore the triploids produce a lot of abnormal pollen grains [3].

We have used these attributes of Betula pollen for identification of pollen from early Holocene peat. The ratio between downy birch and dwarf birch pollen in each sample has been calculated, assuming two normal distributions with different means for grain diameter. Evidence of hybridisation was found by counting abnormal Betula pollen grains.

A study of previously analysed peat from Eyjafjördur, North Iceland, covering the period from 10.3 to 7.0 cal ka BP, revealed a low proportion of downy birch pollen in the oldest peat samples and again around 7.8 cal. ka BP, when dwarf birch predominated. The proportion of downy birch pollen peaked approximately at 8.7 and 7.2 cal. ka BP. Numbers of abnormal Betula pollen grains, indicating the presence of Betula hybrids, was found in several samples most prominent simultaneously with the earlier B. pubescens peak [4].

Climatic and ecological conditions may have favoured hybridisation of birch species during the expansion of downy birch over dwarf birch colonies in warm periods.

We have recently made a comparative study on a peat section in Southwest Iceland [manuscript submitted]. The results seem to support our conclusions from North Iceland. A third study, focused on Northeast Iceland in the early Holocene, is proposed.

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P11

Lateglacial fossiliferous marine sections in Vestfirdir, Iceland

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Numerous sites in southwestern and western Iceland contain marine data on Lateglacial environmental changes in the region. Among well known localities are fossiliferous deposits from the Bølling, Allerød, and Younger Dryas chronozones in Reykjavík, as well as in Hvalfjördur, Borgarfjördur, and in Hvammsfjördur. We present two new localities from Vestfirdir (Skutulsfjörður and Kerlingarfjörður) with marine fauna, and a comparison with new data from a locality in southwestern Iceland (Hvalfjördur). These sites add to the regional coverage and add information about the Lateglacial record of environmental change in coastal regions during the deglaciation of Iceland. Radiocarbon age determinations show that marine sediments were accumulating at all three localities during the Allerød chronozone, corresponding to the Greenland Interstadial GI-1. All three sections contain invertebrate fossils, mainly molluscs, and the sequences at Kerlingarfjörður and Hvalfjörður also contain foraminifera. The sediments have been raised above the present sea level by isostatic rebound. There is no direct lithological evidence of glacial erosion subsequent to the deposition of these marine sediments. However, the Skutulsfjörður molluscs are preserved in a diamicton deposited on a slope in front of a cirque above Skipseyri, and this cirque may have been occupied by an active glacier at the time of deposition. Synchronous pulsations in the marine environmental conditions, which may be related to variations the input of glacial meltwater to the coastal areas, are indicated by faunal changes both in Vestfirðir and in Hvalfjörður.

P12

Potential for extending and improving Quaternary chronologies using luminescence dating

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The application of optically stimulated luminescence (OSL) dating has been limited to the last glacial cycle due to the low characteristic saturation dose in quartz and anomalous fading in feldspar; the later results in age underestimation, for which reliable correction is not available beyond ~50 ka. Recent work at the Nordic Centre for Luminescence Research has focused on finding and testing a feldspar infrared stimulated luminescence (IRSL) signal with low or negligible fading rates, in the hope to significantly extend the age range.

Physical and empirical studies have shown that fading in the laboratory and in nature is negligible for the so-called post-IR IRSL signal stimulated at 290°C (pIRIR290, in which an IR signal is measured at 290°C after IR stimulation at 50°C). We have compared pIRIR290 data with independent age control and shown that our technique results in reliable ages up to ~500 ka (depending on the dose rate in the sediment).

Since the pIRIR290 signal is not as light sensitive as the more commonly used quartz OSL, the application to very young samples is expected to be limited; however the problem of signal resetting is of less significance for older samples (since the size of any residual is independent of the subsequent burial dose). In addition, the different signal resetting rates of the various luminescence signals can be used to identify those which have been completely reset prior to deposition, thus providing an independent evaluation of one of the most significant sources of uncertainty in the luminescence dating of daylight-bleached sediments.

We present an overview of recent work carried out by the Nordic Centre for Luminescence Research on pIRIR290 dating in a large variety of environments, focusing on coastal and (fluvio-) glacial deposits from high latitudes. The potential of this method to date the base of the Greenland ice sheet is also discussed and other ongoing research presented.

P13

New constraints on the deglaciation and sea-level history at the southern tip of Norway

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Geological Survey of Norway, TRONDHEIM, Norway

We present new field data that document the recessional pattern and chronology of ice-sheet retreat in coastal areas of southernmost Norway (from Kristiansand to Lista). The Ra moraines of probable Younger Dryas age are here found 30-40 km inland and above the marine limit, whereas several zones of terminal deposits that cross the fjord areas indicate earlier halts in the recession of the Scandinavian Ice Sheet. The outermost coastline was therefore possibly among the earliest ice-free areas of Norway, but its deglaciation history has hardly been investigated since the classic work of Bjørn Andersen some 50 years ago. We have mapped surficial deposits and glacial landforms during two field seasons, using a combination of detailed field surveys and mapping in 3D digital aerial photographs. In spring 2011, we also cored five coastal lake basins near Søgne, Mandal and Lyngdal. The deposits have been analysed for remains of marine and limnic macro-organisms and show that three of the basins hold isolation sequences. Moreover, two isolated basins were again flooded during the regional Tapes transgression. We submitted 12 samples of terrestrial plant remains for radiocarbon dating - both from isolation/ingression boundaries and from the earliest occurrence of plant remains that were washed into the basins from the watershed. The resulting ages are expected to be available in time for the Nordic winter meeting and will be discussed.

EC 4 – Climate change impacts in the Nordic region during the 21st century

P14

Modelling the 20th and 21st century evolution of Hoffellsjökull glacier, SE-Vatnajökull, Iceland

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The Little Ice Age maximum extent of glaciers in Iceland was reached about 1890AD and most glaciers in the country have retreated during the 20th century. A model for the surface mass balance and the flow of glaciers is used to reconstruct the 20th century retreat history of Hoffellsjökull, a south-flowing outlet glacier of the ice cap Vatnajökull, which is located close to the southeastern coast of Iceland. The bedrock topography was surveyed with radio-echo soundings in 2001. A wealth of data are available to force and constrain the model, e.g. surface elevation maps from _1890, 1936, 1946, 1989, 2001, 2008 and 2010, mass balance observations conducted in 1936-1938 and after 2001, energy balance measurements after 2001, and glacier surface velocity derived by kinematic and differential GPS surveys and correlation of SPOT5 images. The approximately 20% volume loss of this glacier in the period 1895-2010 is realistically simulated with the model. After calibration of the model with past observations, it is used to simulate the future response of the glacier during the 21st century. The mass balance model was forced with an ensemble of temperature and precipitation scenarios derived from 10 global and 3 regional climate model simulations using the A1B emission scenario. If the average climate of 2000-2009 is maintained into the future, the volume of the glacier is projected to be reduced by 30% with respect to the present at the end of this century. If the climate warms, as suggested by most of the climate change scenarios, the model projects this glacier to almost disappear by the end of the 21st century. Runoff from the glacier is predicted to increase for the next 30-40 yr and decrease after that as a consequence of the diminishing ice-covered area.

P15

Geometry, mass balance and climate change response of Langjökull ice cap, Iceland

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The geometry of the surface and bed of Langjökull, Iceland, was constructed from GPS and radioecho surveys in 1997. The mass balance of the ice cap has been measured since 1996/1997, and every summer since 2001 linked to climatic variables recorded in automatic weather stations on the glacier and to the records of the Hveravellir meteorological station east of the ice cap. A degree-day mass balance model was calibrated against stake observations of winter and summer balance on the glacier. We use the mass balance model, coupled to a 2D ice flow model, to simulate the evolution of Langjökull over the next two centuries in response to climate change scenarios for Iceland obtained with the Nordic Climate and Energy System (CES) project (derived from 10 global and 3 regional climate model simulations using the A1B emission scenario). If the average climate of 2000-2009 is maintained into the future, the volume of the glacier is projected to be reduced by 20% with respect to the present at the end of this century. If the climate warms, as suggested by most of the climate change scenarios, the model predicts a total loss of more than 50% at the end of the 21st century.

P16

Hydrological response to recent climatic variations in Iceland

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This study analyses how climatic variations have affected streamflow characteristics in Iceland during the period 1958-2006. Runoff from snow-covered areas and glaciers plays an important role in the hydrology of Icelandic rivers and is expected to be sensitive to variations in temperature and precipitation. A set of nine river basins with various origins of flow formation, of various sizes and having at least 30 years of streamflow observations has been studied. Changes in streamflow properties such as seasonality, magnitude and flood characteristics have been jointly analysed with changes in snowpack condition, snow and glacial melting rates and rainfall, derived from high resolution gridded precipitation and temperature data sets and a simple degree-day snow and ice melt model. Results indicate that inter-annual temperature variations greatly affect snow storage seasonality and runoff generation from snow and glacial melting for all catchments which in turn impact on streamflow seasonality. During warm years, the intra-annual streamflow variations are reduced; Winter flow increases because a larger fraction of precipitation falls in form of rain; The spring flood peak occurs earlier and is smaller in magnitude, in response to a shift in the timing of peak snowmelt and a snowpack depletion; For catchments without glaciated areas, the summer flow is lower in warm years in response to the reduction of spring snowmelt while for catchments with glaciated areas, an increased glacial melting in summer during the warm years keeps the summer streamflow at similar or higher levels than in cold years. The number of moderate floods is increasing in warm years at most studied catchments because of an increase in the number of warm spells in winter and associated snowmelt. Very large floods are caused by extreme snowmelt and heavy rain on frozen ground and the change in the number of such events between warm and cold years depends on geographical location, as the spatial distribution of precipitation is linked to topography and atmospheric circulation. Inter-annual precipitation variations greatly affect streamflow magnitude but streamflow seasonality is not as much affected between wet and dry years as between cold and warm years.

EP 1 – Tectonic evolution of the North Atlantic area

P17

Western Iberian Continental Margin – Insights from regional gravity data

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Gravimetric maps have long been used to interpret continental crustal limits and continental scale structural domains. Regional gravimetric maps created from publically available satellite data, allow us to interpret important regional structures, such as the continental crustal limit, major faults and lithological contacts, if they show a sufficient density contrast. This work provides an interpretation of the geometry of the continental margin in western Iberia; using unconventional methods to show gravity maps created using conventional methods such as vertical derivative and total horizontal gradient.

The Western Iberia continental margin is composed of several elongated, NW-SE trending juxtaposed terranes. From south to north, these are: South Portuguese Zone, Ossa-Morena Zone, Central Iberia Zone, Cantabrian Zone and Asturian-Leonese Zone. This collage of tectonic terranes composes the core and western flank of the Ibero-Armorican Arc, an orocline formed in the heart the Variscan orogeny during the amalgamation of Gondwana and Laurasia. The lateral extent of these terranes offshore is uncertain, as is their geometry beneath the offshore basins.

The structural map suggest that these units could have been rearranged by a curved, NNE-SSW trending dextral strike-slip fault zone. This model also suggests that Lusitanic and Peniche basins could be underlain by the Ossa Morena and South Portuguese domains.

This study of offshore Western Iberia is an important contribution to the understanding of the regional offshore arrangement of terranes formed during the Variscan orogeny.

P18

Geochronologic Reappraisal of a Middle Miocene Rift Relocation in Iceland

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The crustal accretion process in Iceland active for the past 17-16 million years is complicated by repeated eastward rift jumps in response to westward plate drift over the Icelandic mantle plume. The youngest volcanics of the extinct Northwest Iceland rift zone are preserved below a lignite-bearing sediment horizon striking NE-SW in the extreme northwest of Iceland. The lava flows below this unconformity dip NW toward the paleo-rift they were erupted from, while the overlying lavas dip SW toward their parental Snæfellsnes-Húnaflói rift zone active between ~15-7 Ma. The length of time represented by this horizon has been examined by both K-Ar [1] and Ar-Ar [2] geochronology of the enveloping basalts. The results disagree and interpretations suggest that the hiatus could represent up to 1 m.y. or just 200 k.y.

Here we present Ar-Ar ages on basaltic lava flows from stratigraphic profiles across this unconformity. The results show that the preserved lavas below the unconformity were erupted between ~17 Ma and ~16 Ma at a low extrusion rate of 350m/m.y. The onset of volcanism above the unconformity occurred by 14.5-15.0 Ma and at a significantly higher extrusion rate. This suggests that the period of volcanic quiescence and sedimentary supremacy was very long-lived (1-1.5 m.y.).

This period between ~17 Ma and ~15 Ma, characterized by a very low lava extrusion rate and ending with a prolonged time of no volcanic activity, correlates remarkably well with an equally long-lasting trough in the residual depth variation across the v-shaped ridges on the Reykjanes ridge. As such, the initiation of a v-shaped ridge at ~15 Ma corresponds to a rift relocation leading to initiation of the Snæfellsnes-Húnaflói rift zone. The significantly older ages that we here report call for reappraisal of the magnetostratigraphy of the oldest lava piles in Iceland, and suggest that the interbasaltic sediments from this period are contemporaneous with the Middle Miocene Climatic Optimum.

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P19

Sm-Nd isotopic systematics of Greenland basement rocks.

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During the formation of "granitic"or supracrustal rocks of felsic compositions, that are derived from very mafic or ultramafic rocks, then they are associated with a marked enrichment in the light REE in general - and particularly in the Nd/Sm-ratios. Subsequent fractionation of such LREE (and Nd/Sm) enriched rocks will typically result in enriched levels of REE, but the Nd/Sm ratios remain only marginally affected by the most common mineralogical fractionations.

This lack of fractionation of Nd/Sm allows for the model ages of the 143Nd/144Nd - 147Sm/144Nd system to have preserved information of the age of extraction from the mantle - or at least from very mafic or ultramafic rocks of mantle origin.

The Proterozoic and Archaean rocks from different terrains and fold belts in Greenland display different age trends in conventional 143Nd/144Nd - 147Sm/144Nd diagrams, where age trends are projected from a chondritic mantle composition. Amble evidence suggests that projection from a depleted mantle composition, would be a more reasonable method.

P20

Age of metasedimentary rocks and metaigneous bodies in Jæren (western Norway)

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We present Sensitive High Resolution Ion Microprobe (SHRIMP) U-Pb zircon age data from a foliated granite to the SE of Stavanger at Hommersåk and from metasedimentary rocks (schists and quartzites) located in the town of Stavanger. The metagranite is exposed E of a fault separating the Baltica basement from the Lower Allochthon of the Caledonides. This intrusive body is composed of fine to medium-grained euhedral to subhedral quartz, anorthoclase and few microcline. Accessory phases are biotite, zircon, apatite, ilmenite and monazite, while epidote and fine-grained biotite are secondary phases. The dominant mineralogy and major element geochemistry point to a granodioritic to quartz-dioritic rock with shoshonitic characteristics. Rare earth element (REE) patterns are steep with pronounced negative EuN/Eu* (0.1-0.5) anomalies, incompatible elements are strongly enriched and Ta, Nb and Ti show negative anomalies. Hence, a volcanic arc setting could be propsoed. SHRIMP II data on zircons from the Hommersåk Granite span a time interval of c. 895 - 1808 Ma, with the oldest age being from a single inherited grain. We determined an upper intercept age of 1101 ± 68 Ma, which we interpret as crystallisation age, and a lower intercept age of 549 ± 130 Ma, although this age is too old for the Caledonian orogeny it may potentially be related to variable Pb-loss during at or prior to this event.

Metasedimentary rocks from Stavanger are more strongly metamorphosed and are multiply deformed. Medium-grained quartzites and meta-quartz-wackes exhibit a mylonitic fabric with newly grown fine-grained muscovite defining the fabric. Accessory minerals are zircon, allanite, detrital apatite, monazite, ilmenite, rutile and zircon. The schists are dark and dominated by quartz and feldspar in a fine chloritic and silica-rich matrix and represent the dominant lithology of the region. While quartzites and metawackes show typical geochemical characteristics for strongly reworked rocks, the schists have very low Zr/Sc and Th/Sc ratios below 0.9 and point together with other trace element ratios (La/Sc, Ti/Zr) to the strong influence of less fractionated sources in the detritus, possibly arc derived. Detrital zircon ages of quartzites range between 740 to 1800 Ma. There is a defined population at 1135 and 1010 Ma tentatively correlated with the Sveconorwegian orogeny. A second population at ~1450 Ma that can be related to a tectono-magmatic event during the Earliest Mesoproterozoic, also recorded in Oslo, southern Sweden and Bornholm. Other detrital zircons record ages between 1586 - 1664 Ma that are not related to the latter event. The oldest detrital zircon grain age was 1796 Ma and is potentially related to the terminal phase of the Svecofennian orogeny. Detrital zircons from the associated schists do show a similar abundance of main ages but the oldest found zircons dates to 2013 Ma while the maximum depositional age could be determined by grains of Middle Cambrian ages. It is possible to speculate that the black schists are possibly equivalent of the Alun shale successions, which is exposed in the Oslo region, southern Sweden and Bornholm (Denmark) and would be then belong to the margin of Baltica.

P21

Provenance and hydrocarbon content of Neoproterozoic to Palaeozoic shales in northern Spain

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The Cantabrian Mountains host one of the most complete Palaeozoic succession in Europe. The Palaeozoic rocks overly a thick package of metasedimentary rocks of Ediacaran age (Mora Formation). Shales are associated with different lithologies such as wackes, dolomite, limestone, griotte, red beds, tuffs and quartz-arenites. The metamorphic grade is very low and most of the rocks are even only diagenetic overprinted.

Recently, some authors argue for a typical shale-composite for the Iberian Peninsula represented by the pelitic metasedimentary rocks of the Mora Formation implying recycling and the occurrence of one major provenance. The packages of shales are furthermore of specific interest as some of them might be source rocks for different hydrocarbon deposits in the region, especially for Mesozoic rocks. In particular Lower Silurian shales deposited after a major transgression caused by the deglaciation of Hirnantian aged rocks, which are exposed in the region.

This study will therefore combine C isotope data of different shales with major and trace element geochemistry and mineralogical data of the fine-grained deposits. We also sampled organic matter from the different formations to compare the isotopic composition with the shales.

We sampled Ediacaran shales from the Mora Formation, Lower Cambrian shales from the Herrería Formation, Upper Cambrian shales from the Oville Formation with a high content of trilobite fragments, Upper Ordovician shales and tuffs from the Barrios Formation, Hirnantian and post-Hirnantian shales (Formigoso Formation), deep sea deposits of the Devonian Huergas Formation and slope successions as part of the La Vid Group and syn- and post Variscan shales of shallow marine successions of the San Emiliano Formation as well as clastic successions of Upper Carboniferous strata. Sampling was confected between the type locality of the Mora Formation (N42° 48′ 13″ 5W° 49′ 51″) in the south, in post-Hirnantian shales (N42° 56′ 53″ W5° 10′ 55″) to the east (which was also the northernmost sample point) and in the La Vid Group 2 (Pizarras de Valporquero y Calizas de Coladilla N42° 57′ 30″ W6° 7′ 33″) in the west, which covers an area of c. 150 x 80 km^2 large basins when back-stripping the Variscan compression.

The pelites of the Mora Formation do not match the Iberian shale composite in its type locality as the rocks host an arc provenance and not a typical upper continental crust composition (UCC). Their La/Sc lower and Ti/Zr are higher, respectively, than UCC values, and Nb, Ta and Ti concentrations are depleted in comparison to UCC. The Mora Formation reflects the margin of peri-Gondwanan terranes and the detritus in the younger shales might have been mixed with other cratonic and oceanic rocks. The variety of provenance information is large in the metawackes of the Mora Formation with detrital zircon ages varying from 3.6 to 0.56 Ga, hence homogeneous shale composition through time should not be expected. Furthermore, the Variscan orogenic phase might have exhumed other rock successions covered by Lower Palaeozoic strata.

P22

Detrital zircon provenance of Late Ordovician to Early Silurian successions in Northwest Argentina

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The Ordovician succession in northwest Argentina hosts a transition from a passive margin setting developing into a continental arc and show the extinction of this volcanic arc during the Llandeilo.

In some exposures, mafic and ultramafic rocks are associated with these volcanosedimentary successions and have been interpreted as an Ordovician suture zone. Geochemical and isotope geochemical data demonstrated that the rocks are not related to the Ordovician palaeotectonic scenario and associated with older tectonic processes.

The host rocks of the gabbros are immature arenites, shales and greywackes and devoid of macrofossils. The geochemistry of this strata points to typical nearly non-reworked upper continental crustal material without major recycling character with Zr/Sc ratios between 15-30 and a narrow range in Th/Sc ratios (1.5-2.7). Arc-typical geochemical signatures are absent.

Detrital zircon grains reveal a very restricted population of U-Pb ages with 90% of the ages between 500 and 435 Ma (n=74). The two oldest grains are Mesoproterozoic in age and the youngest grain of Earliest Silurian age. The rocks do show two Cambrian aged grains, which could be related to the so-called Pampean Orogeny (550-530 Ma). A small population (2 grains) shows the same age as a locally exposed granitic intrusion (Santa Rosa de Tastil) of Middle Cambrian age. All other grains are of Ordovician age but show a nearly constant magmatism between 505 and 440 Ma, throughout the entire Ordovician. Some of those can be associated with the Early Ordovician continental arc (Puna-Famatina Arc) other with extensional magmatism during the Middle and possibly Late Ordovician. The extinction of the Puna-Famatinian arc in northwest Argentina was always based on the observed strong decrease of volcanoclastic detritus and the absence of arc related volcanism after the Llanvirn. However, possibly the active continental margin might have produced magmas until the Early Silurian but extrusive equivalents have not been deposited. Late Ordovician sediments received during active tectonism (Oclóyic Orogeny) the detritus of plutonic rocks with a weak or even absent geochemical arc signature. Other source areas of detrital zircons were not of importance in this specific detrital mix. The absence of Ordovician zircons in associated gabbroic rocks supports the independence of these magmatic rocks from the Ordovician basin evolution, as the host rocks are characterized by exactly this Ordovician age fraction of zircons - as are regionally exposed Ordovician sedimentary successions.

P23

The influence of Me3+ cation on the compressibility of NaMe3+Si2O6 silicates

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The Na-clinopyroxenes (cpx), having general formula NaMe3+Si_2O6 with Me3+ at the M1 site and space group C2/c at ambient conditions, represent an important volume fraction of the rocks formed at high-pressure conditions. Several investigations have been made under non-ambient conditions for Na-cpx and among the most recent studies were for $NaCrSi_2O_6$ (Boffa-Ballaran et al. 2009, Origlieri et al. 2003), $NaTiSi_2O_6$ (Ullrich et al. 2010), $NaVSi_2O_6$ (Ullrich et al. 2009), $NaAlSi_2O_6$ (Nestola et al. 2006, 2008), NaFe3+Si_2O_6 (Nestola et al. 2006, McCarthy et al. 2008) and $NaGaSi_2O_6$ (McCarthy, pers. comm.). Their unit-cell volume compression appeared to be strongly related to the cation radius of the element located at the Me3+ site but, as a previous work on CaMe2+Si_2O_6 C2/c silicates suggested, the compressibility behaviour for isostructural C2/c silicates is determined also by its electronic configuration.

In the present work in situ high-pressure single-crystal X-ray diffraction experiments have been performed on a synthetic sample of $NaInSi_2O_6$ using a diamond-anvil cell (DAC) in order to determine its equation of state and the high-pressure crystal structure evolution at room temperature. The aim was to obtain precise and accurate parameters for the equation of state of this compound in order to supplement information on the high-pressure systematic of NaMe3+Si_2O_6 compounds and on the role played by 3d and no 3d transition elements in this structure type. Moreover, measurements of the crystal structural evolution at high-pressure for the $NaInSi_2O_6$ allow to better constrain the general high-pressure crystal structure deformation mechanisms for Na-cpx.

The unit-cell parameters for the NaInSi2O6 cpx were investigated at 12 different pressures up to 7.830 GPa. No evidences of phase transformation were found throughout the pressure range investigated and a third-order Birch-Murnaghan equation of state was used to fit the P-V data, refining simultaneously the unit-cell volume V_0 (463.42(3) Å3), the bulk modulus K_{T0} (109.0(6) GPa) and its first pressure derivative K' (3.3(2)). In addition we collected intensity data on the same compound at 16 different pressures up to 9.467 GPa using the same DAC. For our NaInSi2O6 sample, the tetrahedral chain compression, one of the main deformation mechanisms for cpx angle, shows the maximum compression compared the other Na-cpx investigated and this would justify the lowest bulk-modulus among Na-cpx previously studied. The O3-O3-O3 kinking is strongly correlated to the longest Na-O distance (Na-O3long). Plotting the linear compressibility β of the Na-$O3_{long}$ bond distance versus the M1 cation radius for the sample investigated and the other Na-cpx previously studied, two parallel trends can be defined between the Na-cpx having a 3d transition element at M1 site and those without a 3d transition element. For each series the compressibility increases as the cation size at M1 increases but for the M1 with a 3d transition element in Na-cpx the bulk compressibility is slightly greater. In conclusion, the $K_{T0} \times V_0$ = constant relationship proposed by Anderson et al. (1970) for isostructural compounds could not be confirmed for the sodium clinopyroxene family.

P24

Two newly recognized magmatic events in the Proterozoic crystalline basement of eastern Lithuania: SHRIMP U-Pb zircon ages

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Two previously unknown events of magmatic activity have been recognized in the Paleoproterozoic crust within the Drūkšiai-Polotsk deformation zone (eastern Lithuania) by using the Sensitive High-Resolution Ion Microprobe (SHRIMP IIe) at the Korea Basic Science Institute (KBSI). The dated mylonitized granite and granodiorite were recovered by deep drill holes Novikai-1 and Tverečius-336, which are situated close to the Lithuania-Belarus border.

The coarse K-feldspar granite of the Novikai drill core contains metamictized and fractured magmatic zircon of 1793±7 Ma mean 207Pb/206Pb age, broadly overlaping with the zircon age of the 1813±20 Ma charnockitic rocks in the West Lithuanian granulite domain (Claesson et al., 2001, Tectonophysics 339). This magmatic event is also related to the early stage of the formation of the Transscandinavian Igneous Belt (1810-1770 Ma) in Sweden (Högdahl et al., 2004, Geol. Surv. Finland Spec. Pap. 37), which marked the development of an active continental margin of the East European Craton in the Paleoproterozoic.

The Tverečius mylonitized granodiorite contains zircon grains showing complex zoning patterns and a wide range of 207Pb/206 Pb ages between c. 1590 and 1435 Ma. The well-preserved and oscillatory-zoned magmatic cores yield near-concordant ages of c. 1590 to 1570 Ma. These are similar to the 1580 Ma age of the huge Riga anorthosite-mangerite-rapakivi pluton in Latvia and Estonia (Rämö et al. 1996, Precam. Res. 79) and to that of mafic magmatism in central Sweden (Soderlund et al. 2005, Contib. Min. Petrol., 150).

Thus, the magmatic activity in the crystalline basement of eastern Lithuania correlates well with that in the Baltic Shield and expresses both the Paleoproterozoic orogenic evolution and the Mesoproterozoic intracratonic extension of the crust.

This is a contribution to the project ”Precambrian rock provinces and active tectonic boundaries across the Baltic Sea and in adjacent areas”of the Visby Programme of the Swedish Institute.

P25

New zircon U-Pb and Lu-Hf constraints on the evolution of the Lofoten-Vesterålen islands

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The Lofoten-Vesterålen archipelago is dominated by Palaeoproterozoic high grade rocks that make up an AMCG suite, and Archaean gneisses. The Lofoten Block is traditionally interpreted as a westwards continuation of the Archaean core of Baltica, but Caledonian thrust sheets obscure the precise nature of the relation. In this study two Archaean gneisses (Hinnøy gneiss from Gullesfjordbotn and Langøya gneiss from Stø) were dated to 2.6 Ga by zircon U-Pb LA-ICPMS. Their Lu-Hf data reveal negative εHf(2.6 Ga) values, ranging from -16.1 to 0.5 and from -4 to -0.1 respectively, which testifies to reworking of older crust. The average εHf values correspond to model depleted mantle ages of 3.2 Ga and 3.1 Ga, respectively. However, the spread in the data amounts to nearly 4 and 16 εHf units in the two samples, far exceeding the ca. ± 1.5 εHf unit precision of the method, suggesting heterogeneous source rocks. The oldest model depleted mantle age exceeds 3.5 Ga, but the entire range of values overlap the published Hf signature of Archaean rocks in the Karelian Province in Finland (Lauri et al. 2011).

Zircons from granites (Torset and Lødingen), charnockite (Hopen) and mangerites (Hopen and Eidsfjord complex) belonging to the AMCG suite yield U-Pb ages ranging from ca. 1870 - 1790 Ma, corresponding to previously published ID-TIMS ages. The Hf data reveal negative εHf(1.87-1.79 Ga) values, with averages of -9.7 and -8.1 for the granites, -7 for the charnockite and -6.4 and -9.1 for the mangerites. These εHf(1.87-1.79 Ga) values are distinctly different from the typical TIB signature (3 ± 3 εHf units). Though the εHf values demonstrate input from older crust, the data cannot be explained purely by reworking of the late Archaean gneisses. The data are therefore interpreted to reflect mixing of mantle derived magma and older crustal components. Late Paleoproterozoic mafic magmatism is demonstrated by the presence of gabbro in the AMCG suite. The data do not resolve the question of whether the Lofoten Block is a westward continuation of Fennoscandia or an exotic Caledonian or Svecofennian terrane.

In addition to constraining the evolution and origin of the Lofoten rocks, the new data may help distinguish Lofoten as a sediment source in heavy mineral provenance studies.

Reference

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P26

Glass and volatile chemistry of the 2004 Grímsvötn eruption, Iceland

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The Grímsvötn 2004 eruption produced 0.047 km3 (DRE) of plagioclase-bearing, sparsely porphyritic, basaltic tephra. This study evaluates major oxide and trace element glass compositions, volatile contents and mineral chemistry of the eruption products in order to determine (i) the nature of the shallow crustal storage system beneath Grímsvötn central volcano; (ii) effects of conduit processes on magma fragmentation and eruption style; (iii) the extent of SO2 and Cl release to the atmosphere during a typical small volume, high frequency englacial basaltic eruption. Melt inclusions hosted in late-growing plagioclase crystals track magmatic degassing and melt evolution within the conduit. New, high-resolution geochemical data from this chemically stratified deposit reflect a history of fractional crystallisation and open-system degassing prior to eruption onset, which resulted in an initial two-phase (volatiles-magma) flow regime in the conduit which later gave way to a homogenous flow regime. Glass inclusions in phenocrysts contain a maximum of 1600 ppm S and 520 ppm Cl, as compared with averages of 815 ppm and 180 ppm, respectively, in matrix glass. Application of the petrologic method indicates that at least 96,000 metric tonnes of SO2 and 19,000 tonnes of Cl were released to the atmosphere during the G2004 eruption. Component analysis indicates that magma was fragmented at shallow levels by almost exclusively phreatomagmatic mechanisms. The effect of phreatomagmatic quenching and fragmentation was to arrest the degassing process, such that ~45% of the potential magmatic sulphur budget escaped to the atmosphere, compared to a fully degassed equivalent of >70%.

P27

Magma ascent and fragmentation in the explosive 2007–2008 eruption of Oldoinyo Lengai, Tanzania

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After more than 25 years of effusive natrocarbonatitic activity the Oldoinyo Lengai (OL) volcano in northern Tanzania started erupting explosively in September 2007. The eruption continued for 8 months and was surprisingly vigorous (occasionally the plume reached up to 15 km in altitude). It has previously been proposed that thermal decomposition of older natrocarbonatites (and release of CO_2) inside the main crater of the volcano was responsible for the vigour associated with the explosive 1966-67 eruption.

From the recent eruption we sampled the initial ash-fall (3 days after the onset) in Al-canisters during a 24 hour period, which was later complemented by tephra samples collected from 140 profiles around the volcano during a field campaign in May 2011. Petrologically, bulk-rock analyses show a trend from being a mechanical mixture of natrocarbonatitic and nephelinitic material in the beginning of the eruption, to being dominated by nephelinitic composition at the end of the eruption.

SEM-studies of the first ash-deposits (i.e., September 7th) show a dominance of non-vesicular natrocarbonatitic droplets (containing nyerereite and gregoryite phenocrysts) mixed with a small amount of sub-spherical nephelinitic pyroclasts with low vesicularity (<25 vol.%). Deposits from the later phases of the eruption (as deduced from the tephra-stratigraphy) are dominated by well-sorted, near-spherical, lapilli. In these deposits, the natrocarbonatitic component is absent and individual tephra layers can be distinguished based on variations in grain-size. SEM studies of pyroclasts reveal that approximately 60% of the lapilli are cored by a crystal (predominantly nepheline, garnet, pyroxene, wollastonite) which is covered by a thin melt film. The nephelinitic melt film varies in vesicularity between 20 and 50 vol.% with a clear predominance of near-spherical vesicle shapes. An abundance of small particles and crystals are adhered/welded to the fluidal outer surface of the nephelinitic melt droplets. In addition to this, most of the studied deposits display an absence of particles produced by breaking/rupturing of vesicle walls.

Thus, the observed pyroclast textures in the OL-deposits strongly suggest that the nephelinitic magma was erupted in a similar fashion as an aerosol (i.e., melt droplets carried by a gas stream). Decomposition of carbonates which is required to generate such high gas-fluxes cannot occur inside the crater as this material is highly porous and only constitute the uppermost 80 m of the conduit (leaving little time for gas expansion to occur inside the conduit). Based on the observed pyroclast textures we find that the nephelinitic magma must have interacted with a deeper carbonatitic reservoir, in order to allow the CO_2 to expand during ascent (i.e., decompression). This interpretation is also supported by the petrological data.

POSTERS
EP 4

P28

Designing low temperature geoenergy systems in Finland

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The Geological Survey of Finland promoting geoenergy in Finland

Today Finland is one of the countries with fastest growing number of heat pumps. The Geological Survey of Finland (GTK) has invested in research, development and promotion of ground heat in Finland. GTK focuses mostly on large scale commercial geoenergy projects, like office buildings, shopping centers and industrial buildings, including hybrid solutions (solar-/bio-/wind-) and energy storage systems. There is close cooperation with private companies from designers and financiers to manufactures of equipments as well as with the governmental and other public authorities. GTK offers geological and geophysical field studies, Thermal Response Tests (TRT), modeling and dimensioning of the boreholes and follow-up temperature measurements with Distributed Temperature System (DTS).

Low temperature geoenergy

Despite the northern climate and low bedrock temperatures, Finland has great potential in geoenergy. The average ground surface temperatures in Finland vary from about +1 degree in the north to about +7 degrees in the south. Average heat flow in Finland is 0,037 W/m^2, which is far below continental average 0,065 W/m^2. Geothermal gradient is typically only 8-15 K/km, due to Precambrian geology with very thick lithosphere (150-200 km). (Kukkonen, 2000)

Crystalline bedrock in Finland consists typically of granitoids, gneisses and other metasedimentary or metavolcanic rocks. The water content and rock porosity of bedrock are low. The bedrock is covered by Quaternary sediments and the depth of groundwater is usually about 2-4 meters.

A hybrid geoenergy plant for a logistics center in Sipoo

The largest geoenergy project in Finland so far is the new logistics center of a Finnish retailing cooperative organization, S Group. The logistics center is situated in Sipoo, in Southern Finland, and will begin operations in 2012. A significant part of the heating energy and all of the cooling energy demand will be covered with 150 borehole heat exchangers (BHEs), each 300 meters deep. The rest of the heating required will come from wood pellets and the last few percents from oil.

Since 2008 the Geological Survey of Finland has conducted detailed geological and geophysical studies on the site in Sipoo. Geological bedrock mapping revealed a diagonal contact of two different rock types, diorite and granite gneiss, in the middle of the area. In addition, the granite gneiss was much more fractured than the diorite. Therefore, test boreholes were drilled on both sides of the contact and an additional borehole was placed near the contact. Thermal response tests (TRTs) were performed in order to get information about the effective thermal conductivity, groundwater movements and the thermal resistance in the boreholes. The results were used for dimensioning and modeling of the BHE field.

In the upcoming years GTK will monitor the temperature development of the borehole field in use with Distributed Temperature System. For this purpose 15 kilometers of optical cable has been installed into the boreholes. The information obtained by the monitoring system will help to balance the hybrid plant and the use of geoenergy can be optimized.

P29

Strontium isotope shift in geothermal alteration minerals and geothermal fluid in the Hellisheidi Geothermal Field: Implications for water-rock interaction

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Strontium isotope shift in hydrothermal alteration minerals from geothermal wells and in geothermal fluid from the Hellisheidi Geothermal Field was analyzed by detailed 87Sr/86Sr isotope ratio measurements with ICP-MS-MS.

The Hellisheidi Geothermal Field is located in the Western Rift-Zone of Iceland on the southern flanks of the Hengill volcanic center. Within the Hellisheidi Geotohermal Field the alteration mineralogy is well known based on extensive mineralogical survey of drill-cuttings down to a depth of 2.5-3.1 km. A succession of five alteration zones is defined, Smectite zone, Mixed layer clay zone, Chlorite zone, Chlorite-epidote zone and Chlorite actinolite zone. Thickness and depth of the different alteration zones is variable across the Hellisheidi Field depending on the different thermal history of individual fissure swarms and uneven rate of glacial erosion of the Quaternary lava pile and hyaloclastite ridges..

Within the upper alteration zones, strontium mostly resides in clay minerals, zeolites, and calcite while epidote is the most important strontium host mineral in the chlorite-epidote and chlorite-actinolite alteration-zones. All analyzed epidote crystals from geothermal systems in Iceland are chemically zoned, showing an iron rich core and aluminous margins. In the Hellisheidi Geothermal Field the composition of epidote ranges from 20-32 %Ps at a depth of about 1100 m. The deeper, more extensive, epidote assemblages contain less iron than the uppermost assemblages, ranging from 15-26 %Ps. The epidote contains up to 0.5 wt% SrO, the average being 0.2 wt% SrO.

Strontium isotope analysis was conducted on acid leachate of the well cuttings and on hand picked epidote crystals from two geothermal wells, HE-50 (2000 m deep) and HE-51 (1600 m deep). The acid leachate contains most of the strontium residing in clay, zeolites, calcite, and chlorite.

The isotope analysis confirm that during early alteration of basaltic rocks, characterized by hydration of igneous rocks and formation of zeolites and smectite-clay, a significant amount seawater-derived strontium from meteoric water is taken up by the alteration minerals. The 87Sr/86Sr isotope ratio of acid leachable strontium, from the uppermost 500 m of both wells ranges from the average rock value of 0.70314 to 0.70387. Adsorption of strontium from meteoric water continues down to the upper chlorite-epidote zone to a depth of about 1000 m. At and below 1000 m the 87Sr/86Sr isotope ratio of epidote and chlorite remains about 0.07318. At depths greater than about 1000 m the continued growth of epidote and other alteration minerals proceeds by dissolution-precipitation reaction of the remaining igneous phases, mainly feldspar. The 87Sr/86Sr isotope ratio of the alteration minerals thus trends towards the local rock-values at depth.

At the same time the geothermal fluid, derived from meteoric water, initially with 87Sr/86Sr ratio of 0.709 shifts towards the regionally prevailing 87Sr/86Sr 0.70314 of the rift-zone basalts. Geothermal fluid seems to exchange seawater-derived strontium at the early stages of water-rock interaction, the least reacted fluid sample being as low as 0.7038 in 87Sr/86Sr.

The observed 87Sr/86Sr isotope ratio of alteration minerals and geothermal fluid suggests that Sr-isotopic equilibration within the Hellisheidi Geothermal Field takes place within the uppermost 1000 m. It is also confirmed that the 87Sr/86Sr isotope ratio of the geothermal fluid is a measure of water-rock interaction within the geothermal system.

ER 2 – CO_2 sequestration

P30

Preparation for CCS in Finland – geological intermediate storage of CO_2

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Finland is aiming at reducing its CO_2 emissions by more efficient energy use, more nuclear power, more use of renewable fuels and through Carbon Capture and Storage (CCS). This will be challenging, since the production and utilization of power and heat is already efficient and the base industry in Finland is very energy-demanding. The largest point sources of CO_2 emissions in Finland are power plants, oil refineries and heavy industry, which are all situated in the coastal region. Developments in CCS, EU's climate and energy policy as well as the directive of geological storage of CO_2, have in recent years, further increased interests for CCS in Finland.

CCS does not however, provide an easy answer for Finland because it seems there is no suitable geological formations for long-term storage of CO_2 in the predominantly crystalline bedrock of Finland. Due to erosion and continental conditions, Finland is almost totally lacking sedimentary rocks younger than the Precambrian. The existing Finnish sedimentary formations are small and unsuitable for CCS due to their geological character e.g. density.

Transportation of CO_2 out of Finland will thus play an important role in the application of CCS, due to large distances to areas with high potential for storage. Depending on the geography and on the transportation distance required, marine transportation would, at least in the beginning, be a cheaper solution compared to pipe transport. This transportation will require development of terminals, ships, intermediate storages and especially procedures and legal options concerning cross boarder transportation.

In the case of shipping a buffer would be needed and the CO_2 should be intermediately stored in the same form as during the transport, which is at about 7 bars and -55 °C. Intermediate storage could be in the form of steel tanks or cryogenic pressurized rock caverns. Steel tanks are a proven technology but tank size is limited by the constraints set by material properties. Rock caverns could give cost reductions with increasing storage size and it seems that rock cavern storage would be a cheaper option for storage volumes exceeding 50 000 m^3. Analogy exist from Liquified Petroleum Gas (LPG) storage in pressurized or refrigerated caverns. Storing of CO_2 would however, require both pressurizing and refrigerating.

The site selection criteria for intermediate underground storage, of CO_2 in Finland, would be based on techno-economic and geological considerations. In connection to the Finnish CCS program (CCSP), started this year, three cases have been chosen for more detailed geological investigations. The environments of a Steel mill in Raahe (northern shore of the Gulf of Bothnia), a coal-fired power plant in Meri-Pori (west coast of Finland) and a oil refinery in Kilpilahti (south coast of Finland) will all be included in this study. Functional requirements of the planned rock cavern and possible effects of the stored CO_2 are important issues which requires further investigation and modeling.

P31

Experimental studies of CO_2 sequestration in basaltic rocks: A plug flow reactor study

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Mineral trapping of CO_2 in silicate rocks is the most stable form of CO_2 storage and is the end product of geological storage of CO_2 [1]. The relative amount of mineral storage and the rate of mineralization depend on the rock type, injection methods and temperature. Rates could be enhanced by injecting CO_2 fully dissolved in water and/or by injection into silicate rocks rich in divalent metal cations such as basalts and ultra-mafic rocks. Conceptual model of CO_2 mineral fixation in basaltic rocks in SW-Iceland (CarbFix pilot project) assumes that acidic carbonated waters injected into basaltic rocks will initially cause rock dissolution and release of divalent cations such as Ca2+, Mg2+ and Fe2+. As reactions progress, these elements will combine with CO32- and precipitate as carbonates due to increasing pH [2].

To simulate this process in the laboratory - plug flow reactor was built. Reactor provides an opportunity to study the rate of basaltic rock dissolution and solid replacement reactions under controlled CO_2 conditions, as a function of time and distance along the flow path within the column. The reactor consists of 7 titanium compartments assembled into a 2.5 m long pipe with 5.8 cm outer diameter and 5 cm inner diameter, corresponding to a volume of ~ 5 dm3. The column can be filled up with mineral, glass or rock grains of known chemical composition and surface area. Carbon dioxide saturated water can be pumped through the reactor from ambient up to 120 bar total pressure and up to 50°C.

Data obtained from the experiment (liquid chemistry) will be used in reactive transport models to elucidate the advance of reaction fronts, forecast porosity changes and estimate the upper limit for CO_2 injected into a given geological formation. Secondary solid phases (carbonates and clays) will be characterized and quantified to determine molar volume and porosity changes with time.

To condition the column and simulate basaltic glass - meteoric water interactions at the injection site before sequestration, deionised water was pumped at 5 ml/min through the column filled up with basaltic glass grains, 45-100 µm in diameter, under ambient conditions for 15 weeks. The residence time of the water in the column ranged from 50 minutes along the 1st compartment up to 6 hours along all 7 compartments. At the 1st level, release rates of major elements (Si, Al, Ca, Mg) reached steady-state in the 1st week. Elemental concentrations increased gradually with subsequent compartment along the flow path, however, in 4th, 5th, 6th, 7th level they overlap what indicates slower dissolution and/or precipitation of secondary minerals further in the column. The pH in all compartments was greater than 9. This pre-liminary experiment very nicely simulates the initial water rock interactions at the CO_2 injection site in SW-Iceland, before injection [3].

[1] Oelkers et al. (2008) Elements 4, 333-337

[2] Gislason et al. (2010) JGGC, 4, 537-545

[3] Alfredsson et al. (2011) JGGC (in prep.)

P32

The effect of carbonate coating on the dissolution rate of basaltic glass and diopside – implications for CO_2 injection at Hellisheidi

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The Hellisheidi geothermal power plant outside Reykjavik has been selected as a test ground for injection and storage of industrial produced CO_2. Ideally, a water-geochemical process is going to lead from dissolved CO_2 gas at the earth's surface to CO_2 trapped as stable Mg, Fe, Ca carbonates in the basaltic formations at 400 meters depth underlying Hellisheidi [1]. Prior to injection several laboratory experiments were set up to test conditions that can potentially affect or even block the geochemical processes leading to the formation of carbonates. These include the effect of carbonate precipitates on basaltic glass and -minerals. It is essential to the CO_2 sequestration process that primary basaltic silicates are continuously dissolving and providing divalent cations to the solution, which can combine with aqueous carbonate ions from dissolved CO_2 and form carbonates. Carbonate coatings could potentially fill up all available pore space and cover primary silicate surfaces, and thus inhibit continuous dissolution of basaltic rocks.

All experiments conducted within this study were set up using mixed-flow reactors, containing either basaltic glass or diopside powder, immersed into a water bath kept at 25 or 70 °C. To create calcite supersaturation inside the reactors, two inlets were connected to the reactors, one carrying a $NaHCO_3$ solution and the other a $CaCl_2$ solution. Simultaneously, control experiments on basaltic glass and diopside dissolution were carried out at identical pH and under conditions, where no secondary precipitates were forming. Hence, it was possible to compare dissolution rates from experiments with and without carbonate coatings, and from a glass versus a pyroxene mineral.

Results of these experiments illustrate an interesting difference between basaltic glass and diopside with respect to calcium carbonate coatings. In the case of basaltic glass, both calcite and aragonite are forming, but rather as discrete, individual clusters than precipitates on the basaltic glass surfaces. Diopside crystals on the other hand are extensively covered with calcite coatings, and no aragonite is observed. The difference most likely stems from the different crystallographic properties of the two silicates making diopside a better platform for calcite nucleation. When comparing dissolution rates from experiments with and without calcite precipitates no difference is observed. Thus dissolution rates of both basaltic glass and diopside are unaffected by the calcium carbonate present. The dissolution of the primary silicates can continue unhindered through a seemingly porous calcium carbonate layer, and will not significantly affect the CO_2 sequestration process.

[1] Gislason S.R., Wolff-Boenisch D., Stefansson A., Oelkers E.H., Gunnlaugsson E., Sigurdardóttir H., Sigfússon G., Brocker W.S., Matter J., Stute M., Axelsson G., Fridriksson T., 2010. Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project. Int. J. Greenhouse Gas Control 4, 537-545.

P33

Effect of ionic strength on the dissolution rates of basaltic glass at pH 3.6 and 25°C

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Mineral sequestration of carbon involves dissolution of silicate minerals providing divalent cations that combine with dissolved carbon to form carbonate minerals. The dissolution rates of various silicate minerals suggest that the most efficient source of divalent cations for carbonatization process are basalts and ultramafic rocks. To limit the risk associated with buoyancy of injected CO_2 and to enhance CO_2-rock interaction it is advantageous to dissolve the gas into an aqueous solution, prior to its injection. Carbon dioxide dissolution however, requires large water volumes that may not be available. In such cases seawater might be the only viable option.

At low ionic strength and pH, expected during CO_2 injection, ultramafic rocks dissolve about 6 times faster than crystalline and glassy basalt. This difference diminishes with increasing ionic strength up to sea water concentrations (1). As both the identity of dissolved cations changed in previous experiments and ionic strength was increased in the reactive fluids, it was not possible to determine directly the cause for the changing basalt rates (1).

The objective of this study is to measure the effects of individual cations on basaltic mineral and glass dissolution rates. Here we report on the basaltic glass experiments. The dissolution rates were measured under steady state, far from equilibrium conditions in a flow through experimental reactors with inlet pH of 3.6 at 250C. Inlet solutions of varying concentrations of each individual cation-Cl salts; Na, K, Ca and Mg were simultaneously pumped through three different reactors. This way we measured the dissolution kinetics of the glass concurrently at the same pH and temperature but at different cation concentrations.

The reactor system was composed of acid washed PE™ 300 mL reactors maintained at constant temperature in a thermostat controlled water bath. These reactors were stirred by floating stir bars on the bottom of the reactors and propelled by a magnetic stirrer located underneath the water bath. Pumping rates from 0.85-1.0 mL/min were maintained using a Masterflex™ cartridge pump. All the reactor components were made of Teflon to avoid corrosion. At the beginning 4 g of dry basaltic glass powder were put in the reactor, it was then filled with the inlet solution, closed tightly, and placed in the water bath. Flow, temperature, and stirring rates were adjusted to desired settings. The outlet flow was sampled, filtered through a 0.2 µm cellulose acetate filter, acidified with concentrated supra-pure HNO3, and analysed for the silica content.

Steady-state silica release rates (rSi) determined suggests that rates did not change with varying individual cation concentration for Na, K and Ca while the highest Mg concentration (500 mM) is observed to inhibit dissolution rates. Rates in Ca and Mg solutions, covering seawater concentrations, are faster than rates measured in Na and K solutions.

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P34

Calcium carbonate formation at the Eyjafjallajökull volcano: a carbon capture and storage analogue

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Injection of CO_2 into rocks creates corrosive CO_2 charged waters with the pH of 4 to 3. The low pH can lead to mobility of heavy metals at the early stage of water/rock interaction. Dilution and rock dissolution, especially of mafic rock, will increase the pH and lead to precipitation of carbonates and other secondary minerals. The question remains, how fast are the heavy metals sequestrated by precipitation and/or adsorption to the secondary minerals. The 2010 eruption of the Eyjafjallajökull volcano, Iceland, provides a unique opportunity to study the mobility of heavy metals, related to the injection of CO_2 into shallow basaltic aquifer and the ensuing precipitation of carbonates.

Following the eruption of the Eyjafallajökull volcano in the spring 2010, a new strong outlet of riverine CO_2 was observed via the river Hvanná, which indicates deep degassing into the water. A white mineral layer; at some places several cm thick, for hundreds of meters downstream was observed. The precipitation was identified solely as calcite with X-ray diffraction. Low concentrations of riverine Al and Fe provide a unique opportunity to examine the scavenging role of the precipitating carbonates exclusively. A gradual decrease of: conductivity from 1.8 to 1.1 mS/cm, alkalinity from 20.8 to 8.8 meq/kg, concentration of Ca, Mg, Cd, Cu, Mn, Sr, Ba and CO_2, and increase in the pH from 6.5 to 8.5, strongly correlated with the amount of precipitated travertine. Dissolution experiments show that bulk travertine incorporates the same metals. The water temperature was below 5 °C and an elevated atmospheric CO_2 partial pressure was detected near the river. The river water degassed downstream and pH increased, resulting in calcite supersaturation and precipitation. Our thermodynamic models suggest that, in addition to CaCO3, Mg-, Sr- and Ba-carbonates and two phyllosilicate phases were supersaturated.

Our study provides valuable information for assessing environmental impacts for, e.g., volcanic eruptions or carbon capture and storage (CCS) projects in basaltic rock, such as the Icelandic multi-collaborator project "Carbfix".

P35

Ultrasonic velocity anomalies in the Draupne Formation shales (Upper Jurassic, Norwegian Sea)

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Fluid migration through caprocks is a crucial process when it comes to evaluate their sealing capacity for underground CO_2 storage. Migration mechanisms such as flow through fault systems or along wells are quite easily identified by their relatively large size and because these features can be monitored by the use of reflection seismic data or well logs. However, microcracks in rocks, which can allegedly cause fluid migration through tight rocks, are difficult to detect from large scale observations and can only be deduced from thorough investigation. The objective of this work is to evaluate the likelihood of microfracture networks in potential seals (shales) through the analysis of well log data.

This study focuses on the Draupne formation which is a deep-marine mudstone of Kimmeridgian age (Upper Jurassic) in the Norwegian North Sea. It has been deposited syn-rift during the second episode of the Viking graben formation in the Upper Jurassic, and thus has a burial depth ranging from 914 to 4573 m. This formation is identified in well logs by its sharp decrease in ultrasonic velocity and density, and specifically high resistivity and gamma ray readings.

Public well log data from 104 boreholes in the Norwegian sector of the North Sea have been analyzed and among them, 87 had a complete set of logs that are necessary for our analysis: ultrasonic velocities, gamma ray, density and resistivity.

This study shows that the first-order variation of the ultrasonic velocity for the Draupne Formation in the Norwegian North Sea is due to depth. Diagenesis, whether mechanical or chemical, stiffens the rock by strengthening the grain contacts and/or cementing them.

Two other parameters are likely to influence the velocity, namely TOC and the presence of gas in the porous network of the rock. When taking into account the influence of both depth and TOC, around 80 % of the studied wells follow a distinct pattern. When taking into account gas as a pore fluid, around half of the other studied wells follow the same trend.

The ultrasonic velocity of the remaining 10 % of the studied wells is thus influenced by a third order parameter that has to be determined. Among the possible parameters is a dense microfracture network that could be linked to neighbouring faults (North of 59°N) or underlying salt domes (South of 59°N).

ER 4 – Ore deposits and fossil fuel

P36

Petrography and geochemistry of REE-bearing apatite-iron oxide ores and host rocks at Blötberget, Bergslagen, Sweden.

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The apatite-iron oxide deposits at Blötberget comprise the northeastern continuation of the Grängesberg mining district (GMD) in the northwestern part of the Bergslagen ore province, south central Sweden (Geijer & Magnusson 1944). The Blötberget mines, closed in 1979, are now targeted for re-opening. The Blötberget ore represents the second biggest ore field in the Grängesberg-Blötberget-Idkerberget zone, and is one of the biggest iron ore accumulations in southern and central Sweden. The present study is based on drill cores and represents a section through part of the Blötberget deposit and its host rocks. The host rocks to the mineralisation are metavolcanic (to metasubvolcanic) in nature, and in the studied section predominantly exhibit dacitic to rhyolitic compositions. Later granitic intrusives of two separate generations have then cut the metavolcanic rocks as well as the ores.

Host-rock alteration occurs both in the form of what is interpreted as regional-style K alteration and as more localised Mg-K alteration. These, now regionally metamorphosed equivalents, of the K-Mg-altered zones exhibit variably abundant phyllosilicate ± amphibole assemblages.

The Blötberget iron oxide ores are magnetite-dominated, with additional hematite (making them locally hematite-dominated) and minor ilmenite. The oxide ores occur both as massive, partly apatite-banded types, as well as variably rich bands and impregnations to disseminations. In one studied drill core, magnetite-apatite (± hematite) ore occurs brecciating the metavolcanic host rock. This breccia, featuring angular host rock fragments cemented by massive apatite-iron oxide ore is directly comparable with breccias observed at both Grängesberg and the Kiruna deposit in northern Sweden.

Spatial relations and geochemistry suggest that the apatite-iron oxide mineralisation is related to the localised (Mg-K) phyllosilicate ± amphibole-bearing alteration assemblages, implying a component of hydrothermal alteration related to ore formation. Based on mineralogical and textural information, this occurred prior to regional (Svecokarelian) metamorphism.

The ores are significantly enriched in rare earth elements (REE), and specifically LREE, hosted by fluorapatite and minor allanite - REE-epidote, monazite-(Ce) and xenotime-(Y). Both mineralogy and REE patterns show a marked similarity to the Grängesberg deposits (Jonsson et al. 2010). This includes features of REE-bearing fluorapatite and alteration-reaction relations leading to formation of e.g. monazite and allanite. All observations thus suggest that the Blötberget apatite-iron oxide ores belong to the Kiruna-type class of deposits. Despite the features of hydrothermal alteration related to the ore-bearing units, no observations speak against a major process of orthomagmatic ore formation at Blötberget.

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P37

Mineralogy of hydrothermal alteration zones of the Nuuluk gold prospect, Tartoq gold province, Sermiligaarsuk Fjord, South-West Greenland

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POSTERS ER 4

In the Nuuluk gold prospect, South-West Greenland, extensive gold exploration has been carried out since 1970 [1, 2]. The gold mineralization is tied to hydrothermal processes inside synclinal structures of typical Archaean greenstone belts. Fluid flow is suggested to be confined to high-strain zones, controlling the gold occurrences [3]. In the present work, two auriferous zones and hydrothermal carbonate-sericite alteration zones [3] have been explored. The spacing between the two zones is about 500 m and both zones are located in the foot wall of thrust contacts. The western carbonate zone (WCZ) is approximately 60 m wide and comprises hydrothermally altered greenstones, narrow quartz veins and minor magnetite and graphite schist. The samples yield up to 59 wt% quartz, between 5 and 38 wt% carbonate (ankerite, calcite), together with variable concentration of chlorite (< 36 wt%) and albite (< 24 wt%). Micas are present as muscovite (< 25 wt%), coexisting with paragonite (< 12 wt%) and margarite (< 6 wt%) in close spatial relationship with gold mineralization. The eastern carbonate zone (ECZ) is approximately 130 m wide and is mainly composed of hydrothermally altered greenstones with zones of massive carbonate alteration. The mineralogy consists of up to 45 wt% quartz and up to 40 wt% carbonate, chlorite between 3 and 31 wt%, chloritoid (< 6 wt%) and coexisting muscovite (< 6 wt%), paragonite (< 20 wt%) and margarite (< 22 wt%). The hydrothermal alteration, comprising inceasing quartz, carbonate and white mica contents towards the central auriferous quartz veins, is similar in both zones, but in the ECZ magnetite and graphite schists are lacking. Detailed mineralogical and geochemical data are presented here, with the aim to characterize the host rocks and hydrothermal alteration associated with gold mineralization.

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P38

Rare earth-bearing phosphates and silicates and their relations in metamorphosed Kiruna-type deposits, Bergslagen, Sweden

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Apatite-iron oxide ores belonging to the Kiruna-type class of deposits host significant amounts of rare earth elements (REE). In conjunction with other investigations, we have studied the distribution, textures and mineral chemistry of REE-bearing minerals in the Grängesberg mining district (GMD) in the Bergslagen ore province in south central Sweden. In the GMD, REEs are mostly hosted by fluorapatite, but also occur in monazite-(Ce), xenotime-(Y), allanite and REE-enriched epidotes, as well as in sparse, Ce-dominant REE-fluorocarbonates. In addition, a gadolinite-like phase has also been observed.

Based on REE patterns and textural relations of fluorapatite, and particularly monazite and allanite, three main types of fluorapatite have been identified in the GMD ores: I) granoblastic fluorapatite, strongly zoned in terms of LREE+Y, often with slightly depleted outermost rims, intermediate or "inner" REE-rich ($Y>Ce\geq La,Nd$) zones, and REE-poor cores. This type typically features sparse amounts of allanite and/or monazite at the granoblastic grain boundaries, and in rare cases tiny, (up to 3μm) monazite inclusions in the cores; II) fluorapatite with frequent and variably distributed monazite inclusions and monazite-free parts with allanite along the rims, and in intra-crystal fractures; and III) REE-poor fluorapatites, generally without discernible zoning, and with sparse inclusions of monazite. Also in these fluorapatite crystals allanite is usually present as intra-crystal fracture-fillings or occur along grain boundaries. Fluorapatite type I is interpreted to represent the least chemically modified, and possibly earliest formed generation. Most crystals of this type exhibit distinct compositional zoning, which probably represents either a primary magmatic or peak metamorphic feature. Type II represents an evolved stage of fluid-mediated REE remobilisation, where most of the originally fluorapatite-hosted REE have been remobilised to newly-formed monazite inclusions. Subsequently, during continued fluid infiltration larger monazite crystals formed through Ostwald ripening. The REE-depleted type III fluorapatite represents the most chemically altered variety, and ranges from containing few monazite inclusions to being totally devoid of this mineral. The REE are hosted by allanite and monazite that form larger crystals outside the fluorapatite grains, and in rare cases occur as rims or as fracture fillings in the fluorapatite host. This late stage of fluorapatite alteration is related to fluid infiltration and/or metamorphic overprint. Moreover, in the phyllosilicate-rich, K-Mg altered host rocks, monazite has formed corona textures indicating of later fluid infiltration and breakdown reactions. In this type III assemblage, fluorapatite + allanite coronas are not uncommon, and more rarely have coronas of fluorapatite + a gadolinite-like phase and REE-fluorocarbonate(s) formed. This final stage of REE mobilisation is suggested to be related to geological event/s significantly post-dating regional peak metamorphism.

The three main types of fluorapatite and their relations to other phases represent different aspects of REE incorporation, mobilisation and phase transitions in a regionally metamorphosed apatite-iron oxide ore. This has direct implications for understanding the evolution of these deposits as well as for possible future beneficiation of REE in this ore type.

P39

A new occurrence of indium sulphide mineralisation in the Svecofennian of western Bergslagen, Sweden

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This study documents a new discovery of the copper-indium sulphide roquesite (CuInS2) in the westernmost part of the Bergslagen ore province in south central Sweden. Roquesite-hosted indium mineralisation in Sweden was first observed by Burke & Kieft (1980), and not least due to increasing global demand for indium, new discoveries have recently been made in the Fennoscandian shield (e.g. Cook et al. 2011, and references therein).

The roquesite-bearing assemblage described here occurs in a polymetallic, copper-rich sulphide mineralisation, the Lindbohm prospect, situated west of the sulphide bearing Fe-Mn oxide deposit at Långban. At the Lindbohm prospect, the Cu-In-sulphide occurs in bornite, characteristically in close association with sphalerite. The Cu mineralisation hosts omnipresent Bi-bearing phases and sporadic cassiterite in intimate association with banded Fe oxide mineralisation and modest volumes of skarn, within a dolomitic carbonate host rock. The sulphide assemblages exhibit textural and structural relations indicative of emplacement in epigenetic positions, i.e. occurring in veins and stringers often discordant to the banding in the host rock. Assessing the paragenetic sequence, the mineralised system was originally dominated by magnetite, a high-T Cu sulphide phase, sphalerite and cassiterite, where the oxide phases typically formed prior to the other ore minerals.

At the Lindbom prospect, roquesite occurs as c. 10 - 20 micron-sized subhedral to anhedral, mostly equant crystals within bornite, characteristically in direct association with sphalerite. In some cases, roquesite occurs rather intimately intergrown together with wittichenite. Upon cooling of the system, the high-T Cu sulphide phase transformed to bornite, and exsolved e.g. native bismuth droplets. Chalcopyrite lamellae formed subsequent to bismuth exsolution and reactions forming wittichenite. This Cu-Bi-sulphide typically occur as reaction zones between the exsolved bismuth droplets and the bornite host. Cu-bearing galena has also been observed. The textural evidence suggests that roquesite formed as a consequence of reactions between earlier-formed indium-bearing sphalerite and bornite (-progenitor). A later stage of brittle deformation led to access for oxidising fluids along newly-formed fractures, in turn leading to the formation of chalcocite and covellite in Cu-rich assemblages, and finally, azurite and malachite together with goethite. Alteration of bismuth-rich assemblages also led to formation of (as yet unspecified) secondary bismuth minerals.

Not least based on comparisons with the Långban deposit, it is likely that the appearance of the present In-Cu-mineralisation was due to local, high-temperature remobilisation of a pre-existing (Svecofennian) sulphide assemblage. This remobilisation was probably related to regional (Svecokarelian) amphibolite grade metamorphism.

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POSTERS
ER 4

GA 1 – Geohazards in the Nordic and Arctic regions

P40

Recent landslide movements in the Almenningar area in Central North Iceland

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The Almenningar area, in the outermost part of the eastern side of the Skagafjörður fjord in Central North Iceland, is characterised by numerous large and small landslides. The Tjarnadalir landslide, located in the northern most part of the area is the most active of those. The main road to the town of Siglufjörður leads through the Almenningar area. Since the road was constructed, almost 50 years ago, landslide movements have repeatedly caused extensive damages to the road.

The Tjarnardalir landslide originates from the western side of the mountain Mánarfjall. The scarp is about 800 m long from north to south and about 850 m long from east to west. The mean width of the slide is around 1400 m and its mean length is about 1550 m. The total volume of the slide is estimated to be at least 110,000,000 m^3. The front of the landslide reaches the present coast, forming up to 60 m high coastal cliffs that show clear evidence of extensive coastal erosion. The frontal part of the landslide can be divided into two zones. The southern one, reaching from the Kóngsnef cliff to the Kvígildi hill, is characterized by a 450-500 m wide and 250-300 m long slide scar. The road to the town of Siglufjörður is situated within the landslide head scarp, about 100-250 m from the coastline, which there forms about 20-30 m high sea cliff. In this area recurrent measurements show westward movements with mean rates up to 60 cm/year. The northern side of the landslide, from the Kóngsnef cliff to the Skriðnavík cove, is characterized by up to 60 m high steep coastal cliff. In this part the road is situated only 20-50 m from the cliff edge, at about 80 m a. s. l. A steep 30-40 m high slope is located above the road. The costal erosion in this part of the landslide is extensive, and the slope below the road shows clear signs of movements. Several large transverse tension cracks have formed in and above the road. Measurements in this area show westward movements with mean rates up to 26 cm/year.

Stratigraphical records of the costal cliff show fine grained (silt/fine sand) sediments underlying the landslide material. There the groundwater, which percolates through the overlaying coarse landslide material, forms a sliding plan. It is assumed that the main part of the landslide movement takes place on this boundary. A clear correlation appears between landslide movements and meteorological conditions. Most sliding movements occur from April to June, i.e. during the snowmelt period and from August to October, i.e. during the autumn rain period. It is also known that extensive costal erosion occurs, but its impact in the sliding movement is not fully understood.

P41

Valley-fill stratigraphy and past mass-wasting events from onshore, high-resolution shear-wave seismic, Trondheim harbour area, central Norway

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Detailed, stratigraphic information at greater depths may be difficult to obtain from the terrestrial part of fjord valleys. Also, detailed, 2D stratigraphic information is often difficult to obtain near the shoreline of fjords using marine-seismic methods due to the presence of coarse sediments at the sea bed. This is in contrast to the deeper parts of fjords or fjord lakes where detailed 2D(3D) seismic information is easily achieved from survey vessels. A non-invasive shear-wave seismic system developed at LIAG, Germany, gives the possibility to study fjord-valley fills even in urban areas. The focus of this presentation is on the stratigraphic interpretation of shear-wave seismic data that were successfully collected from the onshore harbor area in Trondheim, central Norway. The infilled harbour area is located on the submerged part of a delta plain, and land reclamation is still going on. Historic and older submarine landslides are known to have taken place along the shoreline and ground information is of high interest. Following the last deglaciation the region has been subjected to a fall of relative sea level of totally 175 m due to glacioisostatic rebound. The relative sea-level fall was accompanied by river erosion of emerging (glacio) marine deposits, large landslides, and delta progradation into the fjord. The investigations achieved a highly resolved image of the fjord-valley fill and clear bedrock detection. Vertical resolution is within a few meters over the entire profile whereas horizontal resolution decreases with depth. The entire fjord-valley fill is up to 160 m thick and four main stratigraphic units have been identified, including bedrock, and several subunits. The fjord-valley fill is interpreted as consisting of glaciomarine deposits overlain by marine fjord sediments grading upwards into delta deposits. The change from continuous to more discontinuous or irregular reflection patterns reflects a progressive influence of delta-derived processes and mass-wasting during progradation of the shoreline. Localized sediment accumulations such as landslide debris or the deposits of more diluted flows are also present. The fjord-valley succession is draped by anthropogenic fill. Existing drill-hole data and seismic data offshore help to constrain the interpretation of the shear-wave seismic data. However, deeper and more targeted cores are needed to validate the geophysical and geological model. It is shown that the S-wave method has a great potential for the investigation of a fjord-valley stratigraphy even on man-made fills.

GA 2 – Risk assessment and management of geohazards

P42

Landslide monitoring in western Norway using high resolution TerraSAR-X and Radarsat-2 InSAR

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Bedrock surfaces beneath tempered glaciers are frequently coated by subglacial mineral incrustations. These crusts are millimeter-thick and located where meltwater flow and regelation occurred. They seem to be unstable under atmospheric conditions since they are most abundant close to the margin of retreating glaciers. They also show increasing corrosion signs with increasing distance from the ice (i.e. increasing age of exposure). This implies that the crusts formed under conditions of 0°C temperature and a few bar pressure underneath the flowing ice.

Previous work on sub-glacially formed crusts only described crusts composed of carbonate, on both carbonate and non-carbonate bedrock. However, in this study, non-carbonate crusts were examined in samples from Mexico, Switzerland, Antarctica, Tibet and New Zealand. Crusts were observed under binocular microscope, in thin sections using a polarized microscope in both visible and ultraviolet light, and with a Scanning Electron Microscope (SEM). Chemical analyses were made using an Energy Dispersive Spectrometer (EDS) and by XRF .

The crusts are layered irregularly and contain variable but significant amounts of cemented rock flour with grain sizes <0.2 mm. Two sets of samples (Mexico and Switzerland) were enough thick to contain areas of sufficiently pure cement for chemical analysis.

The cement of the crusts from Mexico, found on intermediary to acidic quaternary lavas of Mount Citlaltépetl, is white and composed of hyalite (opal-AN), organic compounds and traces of sulphur. It is not easy to find a chemical reaction forming opal at 0°C except when taking into account the activity of extremophile bacteria. The amorphous SiO_2 could be a metabolism product of bacteria growing in a wet environment with abundant rock flour, i.e. finely ground crystalline (e.g. Pyrite) and hyaline phases of the volcanic bedrock.

Crusts from Switzerland were sampled on a two-mica schist bedrock at Mount Diavolezza, Canton Graubünden. The cement of these black and yellow crusts is composed of pyrolusite (MnO_2) and limonite (FeOOH). The formation of these minerals at 0°C has not been described so far, therefore, as in the opal crusts, the influence of bacterial activity on their formation must be discussed.

P43

Debris-flow susceptibility modeling in Norway – from basin scale analysis to national map

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Debris flows, debris floods and related landslide processes occur in many regions all over Norway and pose a significant hazard to inhabited areas and transportation corridors. Within the framework of the production of a nationwide debris flows susceptibility map, we develop a modeling approach suitable for the unique geological setting of Norway.

The landscape of Norway comprises several types of mountainous regions with varying topography, bedrock- and quaternary geology, formed by the combined actions of crustal uplift, extensive glaciations and Holocene weathering and erosion processes. Debris flows and floods initiate either in active or passive stream channels or on open hill slopes, and the outrun deposits (fans) of many previous events often form the core of inhabitated areas in the narrow valleys due to the general lack of suitable building ground elsewhere in the mountain dominated landscape.

To develop a nationwide debris flow susceptibility map, we have to take into account both the complexity of the phenomenon and varying specific climate and geological setting of different regions. The GIS-based approach incorporates an automatic detection of the starting areas and a simple assessment of the debris flow runout, which provides a basis for first susceptibility assessments. We use the Flow-R model (IGAR, University of Lausanne). This model is based on an index approach for the discrimination of starting zones including topographic parameters extracted from a digital terrain model (DTM) and the hydrological setting based on the upslope contributing area (also derived from DTM). A probabilistic and energetic approach is used for the assessment of the maximum runout distances.

Simulations were performed at test sites in different parts of Norway and model calibration was based on mapping of quaternary deposits and geomorphology, orthophotos and field investigations. The results show that the approach for starting zone detection and runout model reproduce historical debris flows with good accuracy when using DTMs with 5 to 10 m cell size, but results rapidly deteriorates in accuracy with less resolution. Additionally, climatological, lithological and morphological criteria were used for classification of different "debris flow regions"in Norway, to allocate specific model-parameterization to the different topographical and geological settings. Field investigation and parameter calibration was in 2011 performed at test sites in the different "debris flow regions", to fine-tune the regionalized models and aid in finalizing a first nationwide debris-flow susceptibility map.

P44

Physical properties of marine aggregates in the vicinity of Reykjavik, Iceland

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Marine aggregate extraction for deepening harbours in Iceland began at the turn of the last century. Trailer dredgers were first used in 1953, when experimental dredging for shell fragments took place at Sydra-Hraun for the cement factory in the town Akranes. In the year 1963 extraction of gravel and sand as construction material started in Hvalfjordur and 1970 in Kollafjordur.

In the period 2000 to 2009 approximately 11.6 M m^3 of marine aggregates and shell fragments were extracted from these three areas, which is about 95% of the total extracted marine aggregates in Iceland. It should be kept in mind that these three areas are close to the major market of construction aggregates, i.e. the Reykjavik area and neighbouring communities, where about 65% of the population of Iceland lives.

In August 2008 the responsibility for administration of extraction licenses was moved from the Ministry of Industry, Energy and Tourism to the National Energy Authority (NEA). In the year 2009 NEA granted licenses until 2019 for 15.9 M m^3 in 15 extraction areas in Kollafjordur, Hvalfjordur and Sydra-Hraun area. It is therefore important for the NEA to have a good overview of the properties of sand and gravel deposits from all the licensed marine aggregate extraction areas.

The National Energy Authority has started a research project which involves systematic mapping of the physical properties of sand and gravel extracted from the seabed in the Reykjavik vicinity. The project is carried out in collaboration with the Innovation Center Iceland, PP-Consult and the Faculty of Earth Science at the University of Iceland.

The main purpose of this project is:

1. To establish a database including type and physical properties of gravel, sand and shell fragments extracted from Icelandic seabed.
2. Material quality assessment as a basis for a tariff for marine aggregate extraction.
3. Material quality assessment as a basis for decision making concerning issuing licenses for utilization of marine aggregates in the future.

The first licensed marine aggregate extraction areas to be studied in this project are situated in Kollafjordur. In the period 2000 to 2009 the extraction from Kollafjordur amounted to 4.9 M m^3, or about 40% of the total marine aggregate extraction in Iceland. The quality of the material in the Kollafjordur extraction areas has not been analyzed in detail before, although one dredged sample from each area had previously been collected for grading and petrographic analysis. This is insufficient to be representative for the physical properties of the materials in these vast extraction areas. Still these analyses suggest that variation in quality is broad in the Kollafjordur extraction areas, which would benefit the establishment of the database. Trailer dredgers are used to obtain samples, trailing a pipe along the seabed at relatively shallow depths. Besides testing of physical properties of the dredged material, such as grading, petrographical composition, shape, mechanical strength and weathering resistance, other factors that possibly influence the test results will be studied, such as:

- Repeated sampling in selected areas to analyze the variations in grading and petrography.
- The variation in petrographical composition of different grain sizes.
- The relationship between grading and petrographical composition.
- The minimum frequency of sampling and testing required.
- The sampling procedure which will be validated.

The second and third licensed marine aggregate extraction areas to be studied are situated in Hvalfjordur and Sydra-Hraun. In the period 2000 to 2009 the extraction from Hvalfjordur amounted to 4.8 M m^3, or about 39% of the total extraction and in the Sydra-Hraun area the extraction amounted to about 2 M m^3, mostly shell fragments, or about 16% of the total extraction.

P45

Changes in seabed topography related to marine aggregate dredging, Hvalfjörður, Iceland, 1940–2010

Árni Þór Vésteinsson[1], Björn Haukur Pálsson[1], Níels Bjarki Finsen[1], Sigríður Ragna Sverrisdóttir[1], Bryndís G. Róbertsdóttir[2]

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The Hydrographic Department of the Icelandic Coast Guard (ICG-HD) is responsible for hydrographic surveying and nautical charting in the waters around Iceland. In the year 1991, M/V Baldur, a new survey vessel was launched. It was the first vessel specially built for the Icelandic Coast Guard to carry out the task of hydrographic surveying. In 2002 it was fitted with RESON SeaBat 8101 240 kHz multibeam echosounder.

The department's main responsibility is hydrographic surveying for navigational purposes but on occasions it takes on contract surveys. Licensed aggregate dredging areas and their surroundings in Hvalfjörður were surveyed for the National Energy Authority in 2010.

The area was surveyed by the ICG-HD survey section in July. The hydrographic data processing system, CARIS HIPS, was used in processing the survey data and to create 3D images of the extraction areas.

The area surveyed in 2010 was previously surveyed by the UK

Royal Navy in 1940. This survey from 1940 that covers the whole fjord and its entrance was conducted with a single beam echosounder and is considered to be of good quality. The outer part of the fjord was surveyed with M/V Baldur in 2003.

The 2003 survey overlaps slightly with the 2010 survey. Parts of two aggregate dredging areas, Kiðafell and Brekkuboði, can be seen on the 2003 survey. The 2010 survey shows status of the four aggregate dredging areas: Eyri, Kiðafell, Laufagrunn and Brekkuboði.

Generally a comparison of depths between the 1940 survey and 2010 survey shows that changes are not apparent outside the four above mentioned aggregate dredging areas.

P46

Marine aggregate dredging in Kollafjörður, Iceland. Multibeam survey 2002 – a basis for comparison

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Following installation and initial testing the Kollafjörður to the north and east of Reykjavík was surveyed. A number of hydrographic surveys have been carried out in the fjord over the course of some fifty to sixty years especially on its south side where marine traffic enters Reykjavík harbour. The surveying has not been on regular basis and the fjord has never been surveyed in one go as was done in 2002.

Marine aggregate extraction has been considerable in Kollafjörður for decades. More than 20 sites of aggregate dredging are known and the 2002 survey includes them all. By far the largest and the one that led to the publication of two new editions of Reykjavík harbour chart No. 362 is the Akurey aggregate dredging site. The second new edition published in 2003, a result of the 2002 multibeam survey, revealed increased depth in the outer part of Engeyjarsund, the entrance to Reykjavík harbour, of some 12 to 15 metres. Research by the Icelandic Maritime Administration showed increased waves and was one of the factors contributing to the abandonment of the Akurey aggregate dredging site.

The aggregate extraction sites in Kollafjörður were surveyed in 2005, in relation with an environmental impact assessment with modern single beam equipment by Jarðfræðistofa Kjartans Thors. The 2002 and 2005 surveys have not been compared.

The National Energy Authority has suggested to the Hydrographic Department of the Icelandic Coast Guard that a resurvey would be ideal in 2012. If these intentions will be carried out it will be possible to compare the two data sets and document changes over the past 10 years.

P47

The 1973 Heimaey Eruption, off South Iceland. The role of man-made barriers and water cooling in diverting the lava flow

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From January 23th to June 1973 a volcanic eruption took place on the eastern edge of the small town Vestmannaeyjar (pop. 5300) on the 11 km² island of Heimaey in the Westman Islands archipelago, lying 9 km off South Iceland. Attempts were made to stop or divert the lava that eventually flowed over part of the town. The methods used were mainly construction af barriers, made of the ash and pumice formed earlier in the same eruption, and by cooling the lava by pumping sea water on the lava front. Much has been written about the water cooling but very little attention has been paid to the effect of the barriers, which stopped the movement of the lava front long enough for the water cooling to take effect and obstruct or divert the lavaflow towards the sea. The barriers stopped the lava front for a considerable time, and with the effect of the sea water cooling, the lava would not advance over the barrier until the lava front had become about 4-5 times higher than the barrier. In hindsight it is highly likely that if the barriers and dykes had been aligned differently, or additional dykes had been constructed early enough, up to 200 houses would have been saved on Heimaey island, including costly fish factories and the power station.

Early in the Heimaey eruption the easiest way for the lava to flow from the crater was to the east and northeast, straight into the sea, but later on, movement to the north west, i.e. towards the harbour entrance and the town was inevitable. After the eruption had lasted a few weeks the western edge of the main lava started to creep westwards along and upon the old shore of Heimaey island. Had it been possible to contain the lava behind barriers, most of the central town would have been saved, but events turned out differently. Already as early as January 30th construction of lava barriers started. The barriers were made by modified bulldozers, armoured against volcanic bombs, scooping up ash and pumice into well compacted dykes with rather flat slopes, located just west of the easternmost houses of the town.

In trying to contain the lava, the combination of barriers and water cooling proved quite effective, as the barriers stopped the lava front long enough for the water spraying to be able to solidify some considerable volume of the lava front and thus in effect "enlargen"the dyke. Still, the water pump capacity at this time was only 10% of what it became in the first week of April, after most of the damage had been done to the town.

In hindsight the situation in the Heimaey eruption must be considered quite favourable with regard to the possibility of diverting the lava away from the town looking at the following factors. A) The lava was quite viscous slow moving aa lava giving considerable time for various kind of action before the lava arrived, B) There was plenty of area to divert the lava into, i.e. into the sea towards northeast and east. C) There was enough sea water for pumping, but unfortunately the most powerful pumps (with a tenfold increase) did not arrive until too late, or just after the lava had flowed through the town centre. D) There was plenty of good material for making earth barriers, but unfortunately the alignment of part of the barriers was not favourable and additional barriers with a more favourable layout could have been made as second defence.

GD 2 – Active tectonics and volcano geodesy

POSTERS
GD 2

P48

Surface Displacements at Katla 2003–2009: Disentangling deformation due to ice load reduction and magma movement using InSAR measurements

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Katla is a very active volcano, partially covered by Mýrdalsjökull ice cap. The largest ice cap in Europe, Vatnajökull, lies approximately 80 km to the north-east. Climate warming over the last century has resulted in a loss of ice mass from these and the other icecaps in Iceland. Surface displacements caused by magma movements, landslides and plate spreading sum with deformations due to the ice retreat. GPS campaigns on and around Katla have been performed since the 1990's, and since 2000 several continuous stations have been installed. The GPS measurements indicated a magmatic intrusion beneath Katla's caldera, lasting until 2003. In the following years, two of the continuous stations on the south flank of the volcano showed unexpected horizontal movements when compared to the predicted plate spreading velocities. These horizontal movements are unlikely to be caused by continued magma intrusions, as they were still being detected up to summer of 2009, at which point deformations related to the 2010 eruption of the neighboring Eyjafjallajökull volcano affected the data. Besides magmatic intrusions, ice load reduction, local landslides and flank sliding could also explain the horizontal movements. Differentiating between these causes will not only reveal if Katla has been exhibiting increased volcanic activity in the last decade, but will also improve our understanding of ice mass unloading and other processes acting around Katla.

We applied radar interferometry (InSAR) to Envisat ASAR data to generate 21 interferograms covering the Katla area between 2003 and 2009, using the superior spatial sampling of InSAR compared to the GPS data to differentiate between the different deformation sources. We used the Stanford Method for Persistent Scatterers (StaMPS) to select a set of pixels with stable phase behavior in time. We subtracted a model of ice mass unloading [Árnadóttir et al, 2009] from the unwrapped phase results, leaving an estimate of the deformation signal, which exhibits variation only over a relatively small spatial extent.

We find no indications of residual deformation signals that could be related to magma movements on Katla's south flank, nor on any other part of the volcano. Furthermore, local causes of the unexpected horizontal movements at the two GPS stations, such as land sliding, are not likely, as we detect no significant variation in the deformation signal in the area surrounding them. We also find no difference between the residual mean displacement rates on the south flank and an area to the east, ruling out flank instability. We therefore conclude that the model of ice unloading at Vatnajökull and, to a lesser extent, Mýrdalsjökull is able to explain the anomalous horizontal movement at the GPS stations on the south flank. At Eyjafjallajökull, which abuts Katla to the west, we find a previously undetected movement away from the satellite on the south flank. From the location and spatial pattern we infer that this signal is most likely deflation related to cooling magma volumes intruded in 1994 and 1999.

P49

Earthquakes and geothermal systems: Insights from low- and high-temperature fields of South Iceland

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Seismicity and geothermal activity are closely related processes in Iceland. During the past decade, we carried out extensive surface geological exploration in two structural domains of South Iceland. In this paper we highlight a few results relevant to the relation between earthquakes, tectonics and geothermal activity, for which an understanding of the complex geological context is necessary.

The active Western Rift Zone (WRZ) and Eastern Rift Zone, which are loci of high-temperature geothermal fields, are controlled by NNE-striking faults, dykes and eruptive fissures. Within rift segments, earthquakes occur in swarms, rarely exceeding Mw 5. The South Iceland Seismic Zone (SISZ) connects these rift segments and hosts low-temperature fields, except at Hengill high-temperature field where rift and transform zones intersect. Within the SISZ, earthquakes occur in sequences of Mw ~ 6.5 mainly along deep N-S dextral strike-slip source faults, which are expressed as arrays of left-stepping en echelon surface ruptures. The Hreppar Rift jump block (HRJB) is a micro-plate caught between these active plate boundaries with low-temperature geothermal activity mostly in its central part. The examples of low and high temperature fields we studied in South Iceland demonstrate that geothermal fields are fracture-controlled and sensitive to earthquakes regardless of their temperatures.

We mapped a N-S fault, the Laugarás-Reykjavellir (LR), in the eroded HRJB. The fault has 10 m apparent normal-slip, but a number of hot springs organised in left-stepping arrays on this fault indicates its relative recent dextral strike-slip. The LR Fault extends southwards and connects to the mapped surface ruptures of the 1784 earthquake in the SISZ where a few productive wells are on the trace of the source fault. Our mapping of faults and geothermal activity, along with historic records demonstrate that the rupture of the 1784 source fault also activated portions of the LR Fault, opening paths for hydrothermal circulation in several places. The data explain why the historic damage zone extended into the HRJB. Additionally, historic reports of fall and rise of water level in the springs can be explained as co-seismic pressure effects of the rupture of the LR Fault and the source fault of the 1784 earthquake. Such a pattern of pressure changes was already recorded in boreholes after the 2000 earthquakes in the SISZ.

In 2008 an earthquake doublet (M 5.8 and 5.9) hit the SISZ at the junction with the WRZ. We mapped the N-S Reykjafjall source fault of the second earthquake, as well as the local springs over three years beginning a day after the earthquake. The fault crosses the easternmost high-temperature field of the Hengill Area where NNE rift-parallel fractures are expected to be the main permeable fractures. At the surface, the mapped ruptures align on six tightly parallel N-S segments in a deformation zone of less than one km width. Only the two westernmost segments host geothermal activity. Our observations of groundwater level over a large area and the borehole measurements by other colleagues agree that the 2008 earthquakes caused a rise and fall of water level, which returned to normal after three days.

In both cases studied, we observe that secondary sinistral strike-slip fractures striking ENE, E-W, WNW and NW also ruptured during the earthquakes and host geothermal activity. Along with the main N-S source faults, these fracture sets form a Riedel shear pattern that compensates the sinistral motion of the entire SISZ. Our results are conclusive that the rupture of the Riedel shears within the transform zone is the dominant source of permeability in low-temperature geothermal activity. This is also partly valid in high-temperature field of Hengill where the transform zone intersects the rift segment.

GD 3 – Glacial Isostasy, Sea level change and Mantel dynamics

P50

Accessing the 3D Viscosity Structure Beneath Iceland Using Glacial Isostatic Adjustment (GIA): Insights Into Dehydration Stiffening and the Rheology of the Upper Mantle

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Laboratory data show that water in nominally anhydrous mantle minerals will significantly reduce the viscosity of the mantle. Dehydration upon melting of the mantle can therefore result in a sharp viscosity contrast, referred to as de-hydration stiffening. Beneath a mid-oceanic ridge or in a mantle plume a high viscosity layer (HVL) will form above the depth of the dry solidus. For typical MORB source water contents (125±75 ppm) a viscosity contrast of a factor of 500±300 has been suggested. Thus far, the effects or the magnitude of dehydration stiffening have not been observed outside the laboratory. As the GIA process is to first order dependent on the viscosity structure of the mantle, the existence of such a viscosity contrast can be accessed in situ. Iceland, located on top of a mantle plume and cut through by the Mid-Atlantic ridge, is currently undergoing GIA. It is estimated that the largest glacier, Vatnajökull, has lost 435 km^3 of ice between 1890-2004, causing the land to uplift with vertical velocities in excess of 20 mm/yr close to the glacier. This offers a unique opportunity to study the effect dehydration stiffening beneath Iceland. We set up a 3D model of present day GIA on Iceland including the 5 largest Icelandic glaciers. To constrain the model predictions we use the vertical surface velocities estimated from two nation wide GPS campaigns in 1993 and 2004, as well as continuous GPS station data. For this data set we find that the GIA model is sensitive to viscosity contrasts in the mantle down to at least 200 km. We first test a conceptual model of the viscosity structure in the mantle consisting of a lower viscosity plume conduit embedded in the mantle beneath a higher viscosity layer, HVL, directly beneath the lithosphere. The best fit to the GPS data is achieved for a background mantle viscosity between 8-12 x 10^{18} Pa s and a viscosity contrast of a factor of 1-3 between the background mantle and the HVL, while larger viscosity contrast demands a mantle viscosity lower than 8 x 10^{18} Pa s. For our next set of models we use a self-consistent effective viscosity field from dynamic modeling of the plume-ridge interaction using a non-linear rheology. An initially wet mantle and a moderate dehydration upon melting yields a reasonable fit to the observed GPS data. However, even if the viscosity contrast between the HVL and the background mantle locally can reach a factor of 40, the mean viscosity contrast is of a factor of 10. Our conceptual model does not yield an acceptable fit to the observed data for large viscosity contrasts unless the viscosity of the mantle is extremely low. Alternatively, if the rheology of the mantle is nonlinear and the system evolves under a state of constant viscous dissipation, the expected viscosity contrast is of the order of 10 which is compatible with our findings.

IS 2 – Developments in data aquisition, modelling and visualization

P51

FINMARINET – Marine habitat mapping from a geological point of view

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Inventories and planning for the marine Natura 2000 network in Finland (FINMARINET) is a Life + -funded project that carries out inventories of the marine habitat types of the EU Habitats Directive along the Finnish coastline including the Finnish territorial waters and the Finnish exclusive economic zone (EEZ). The target is to produce cartographic images (thematic maps of the habitats and key species, spatial assessments) to underpin decision making regarding the key marine habitat types related to the Habitats Directive.

The project is coordinated by the Finnish Environment Institute (SYKE), with four associated beneficiaries: the Geological Survey of Finland (GTK), Metsähallitus Natural Heritage Services, Åbo Akademi University and the University of Turku. The FINMARINET project is implemented in close relationship to the Finnish Inventory Programme for the Underwater Marine Environment (VELMU).

In the FINMARINET research areas, geological inventories of seabed topography and substrate are carried out alongside biological surveys of habitat types and their flora and fauna. Marine geological features offer a setting for benthic flora and fauna; in fact marine surface substrates are one of the primary parameters in marine habitat modelling. GTK has carried out marine geological inventories in 5 research areas with special emphasis on marine habitat mapping. Areas are located in and around marine Natura 2000 sites along the entire Finnish coastline. Research methods include continuous sub bottom profiling, reflection seismic, side scan sonar and multibeam echo sounding as well as bottom sampling. Outputs of the geological studies consist of substrate, seafloor feature and landscape maps. Research areas represent different geological environments, giving an overview of geological habitats in the Finnish waters.

P52

Evaluation of geological specimen composition and structure using X-ray µCT. Part 1: principles, procedures, problems and solutions

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X-ray computed (micro)tomography (µCT) is a non-destructive analytical technique that can be used to create digital volumetric three-dimensional (3D) models representing the internal composition and structure of lithified and undisturbed unlithified sediment, and other material, samples. The data that comprises such models can be mined in a variety of ways, thus permitting the quantification of all specimen elements detected and differentiated using the technique. This (poster) presentation outlines the technique, its current limitations and both existing and possible future solutions. In part 2 (oral) a variety of examples are presented, primarily as movies, illustrating the applicability of the technique to geological specimens and some quantitative analyses of particular interest to the geological community are outlined.

X-rays are attenuated by matter, according to the material's density and the atomic number of its constituent elements. A sequence of digital radiographs are acquired at different angles as the specimen is rotated, the data used to (re)construct a volume image where each voxel (3D pixel) represents the X-ray linear attenuation coefficient of the corresponding volume element in the specimen. Voxels of a specific grey-scale value, or between two values, can be converted (where required) into a binary dataset. As the location and size of each voxel is known a number of quantitative analyses can be undertaken, ranging from object volume to morphology, orientation and distribution calculations. When object numbers are large, e.g. >>1000, statistically significant analyses can be conducted automatically and very efficiently.

The contrast resolution achievable is dependant on the composition of the specimen, spatial resolution controlled by sample size. However, advancements in scanning, reconstruction and visualisation methods continue to enhance results in both respects. Laboratory based µCT facilities produce a polychromatic X-ray beam, which leads to the production of artefacts in the reconstructed images. Standard methods of artefact reduction partially resolve this issue only. Advanced µCT technologies are demonstrated to provide a much improved result.

IS 3 – Earth history – stratigraphy and palaeontology

P53

Sedimentary environments and evolution of the Middle Weichselian basin, SE part of the Baltic Sea depression

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Little is known about the Middle Weichselian time in the territories covered by the Scandinavian ice sheet. This study reveals sedimentary facies description of the clastic deposits of the Middle Weichselian basin, which has been dated to a range from 52 - 26 ka BP (Saks et. al., in print). The study is based on facies analysis from outcrop and drilling core data in western Latvia, SE Baltic. The aim of the study is to describe the depositional environments and reconstruct the basin evolution during the Middle Weichselian time.

In total 19 sedimentary logs have been studied from outcrop sections and facies analysis carried out. Borehole lithological data from the borehole database was used to map the distribution of these sediments.

Up today 11 sedimentary facies have been distinguished, which reveal deposition under various sedimentation rates. The succession is composed mainly of very fine- to medium-grained sand with silt interlayers and with thin mica, silt and heavy mineral drapes. The most dominant facies are: current and wave ripple-laminated sand, cross-stratified sand with silt and mica drapes, structurless sand, plane-parallel stratified sand, sand with deformation structures. Other facies, such as sand with gravel interlayers, large scale cross-stratified sand, parallel-laminated sand with heavy mineral and silt drapes, parallel-laminated sand and silt, irregularly laminated sand and silt are also abundant. The facies assemblage reveal deposition under following hydrodynamic conditions: i) low energy environment - deposition from low energy currents by migration of ripples; deposition from plain beds in lower flow regime and occasionally from suspension; ii) high energy environment.- deposition from traction currents by migration of 3-D dunes and possibly larger scale bedforms; deposition from plain beds in upper flow regime, and rapid sedimentation due to high deposition rates with no preservation of sedimentary structures or with secondary soft sediment deformations caused by shear stress and escaping pore water .

This study is still ongoing and thus does not allow yet interpreting the depositional environments in detail. However the preliminary results suggest sedimentation in a shallow basin and lagoonal environments.

P54

Finally a snowball earth tillite? – Detrital zircons with Gaskier ages in the diamictic Bloupoort Formation of South Africa

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The Bloupoort Formation contains a diamictite, which has been interpreted as being of glacial origin. It is exposed in western South Africa as part of the low-grade metamorphic Neoproterozoic Gifberg Group. This rock succession is composed of a basal palaeovalley infill (Karoetjes Kop Formation), which is capped, in some areas, by thick marine limestone marbles of the Widouw Formation. The latter is, in turn, overlain by sericitic and graphitic schist, phyllite, greywacke and impure dolomitic limestone of the Aties Formation, which underlies the Bloupoort Formation.

The Bloupoort Formation is composed of the Rooihoogte banded iron formation, the diamictic Swartleikrans Rudite (Swarleikrans Bed), the Witkleygat Gritty Dolomite and the Ondertuin Breccia Dolomite.

The diamictic bed is about 35 m thick at Swartleikrans, very poorly sorted and consists of clasts, which vary from pebble and cobble to boulder-sized (±0.3 to 1 m). Clasts consist of dolomite (~40 volume %), granite gneiss (~30 volume %), green greywacke and quartzite (~20 volume %) and ironstones, chert, jasper and vein quartz (c. 10 %) in a fine ferruginous matrix. Most of the larger clasts are well rounded (boulder-size) whilst the smaller clasts and fragments are predominantly angular. Laminae and cross bedding are preserved in some instances in the matrix. The Swartleikrans Bed is capped by finely laminated impure red to pink turbiditic ferruginous dolostone, which is interbedded with thin, discontinuous bands of calc-arenite and conglomerate. Besides the diamictic texture - no indicators of a glacial depositional environment could be identified.

The occurrence of the two diamictites (Karoetjies Kop Formation and Bloupoort Formation) was often used to correlate the rocks with other successions containing two diamictites on a global scale. However, age constraints are uncertain as some authors interpreted the Karoetjies Kop Formation as Sturtian, others as Marinoan and therefore the Bloupoort Formation as being Marinoan or Gaskier, respectively. Previously, chemostratigraphy was used to define depositional ages, but later it has been shown that the isotope data do not reflect syndepositional seawater composition and cannot be applied at all.

The U-Pb, detrital zircon age population (n=70, < 10% discordance) from the Bloupoort Formation is dominated by mainly Mesoproterozoic aged grains. They can be divided into fractions with ages between 1005 and 1210 Ma; and between 1323 and 1459 Ma. Two Palaeoproterozoic zircons could be found with the oldest being 1853 Ma. Few Neoproterozoic grains have been identified in the Bloupoort Formation with the youngest being 574 Ma +/-7 Ma. Therefore, if the Bloupoort Formation is a glacial deposit, it can be classified as of Gaskien age.

P55

Bio- and lithostratigraphy of the Precambrian-Lower Cambrian Herrería Formation in northern Spain

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The Herrería Formation is of particular interest for biostratigraphic and the paleogeographic understanding of northern Gondwana as it host a succession, which crosses the Precambrian- Cambrian boundary. The base of the Herrería Formation lies unconformable above the Ediacaran Mora Formation (youngest detrital zircon 564 Ma, Naidoo et al., this congress) and Triptychnus pedum was identified 5 m above the regional unconformity.

The Herrería Formation was sampled in three stratigraphic positions. The base was sampled 5 km southeast of the town Mora at N42°48'21.3" W5°49'23.3" GPS point, the middle part of the unit south-east of Barrios de Luna (GPS N42°49'40" W5°51'51") and the top of the formation with the transition to carbonates of the Láncara Formation west of the town Barrios de Luna (GPS N42°50'25.48" W5°52'11.23").

The Herrería Formation underlies conformably well-dated carbonates of the Láncara Formation using detailed trilobite biostratigraphy. It is suspected that the Herrería Formation represents a transition from continental fluvial-deltaic facies to a shallow marine, coastal environment. However, the lack of macrofossils hampers a clear facies classification, but might point for the base of the succession to a continental facies. Flute casts and large-scale cross-bedding point to a marine depositional environment. To the top few and thin carbonate-rich shaley layers occur and a transition to a carbonate depositional environment of Middle Cambrian age is exposed. Microfossil techniques will be applied to control if biostratigraphic markers can be found, identified and used for a further stratigraphic and facies understanding of this unit.

Currently, microfossil data are controversial as they contradict the trace fossil and fossil record. The achritarch assemblage points to a Marianian age, which was also determined in the central Iberian zone. The trilobites ad trace fossils would point to a Corduban and Ovetian age. Particularly striking are the Marianian aged achritarchs at the bottom of the Herrería Formation followed by younger forms (Bilbilian) in higher stratigraphic levels.

P56

Provenance of the Precambrian-Lower Cambrian Herreria Formation in northern Spain

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The Herrería Formation is of particular interest for biostratigraphic and the paleogeographic understanding of northern Gondwana as it host a succession, which crosses the Precambrian- Cambrian boundary. The base of the Herrería Formation lies unconformable above the Ediacaran Mora Formation (youngest detrital zircon 564 Ma, Naidoo et al., this congress) and Triptychnus pedum was identified 5 m above the regional unconformity together with the occurrence of Rusophycus and Cruziana. The Herrería Formation was sampled in three stratigraphic positions. The base was sampled 5 km southeast of the town Mora at N42°48'21.3" W5°49'23.3" GPS point, the middle part of the unit south-east of Barrios de Luna (GPS N42°49'40" W5°51'51") and the top of the formation with the transition to carbonates of the Láncara Formation west of the town Barrios de Luna (GPS N42°50'25.48" W5°52'11.23").

The rock succession includes very different lithotypes. The base is characterised by a conglomerate covering the regional unconformity over the Ediacaran Mora Formation. These rocks are followed by thin-bedded (< 50 cm) poorly sorted and friable yellow to red sandstones, which intercalates with shales and thin carbonates. The middle part of the formation is composed of grayish to brown sandstones with bed thicknesses up to 1.5 m. Shales are rare but fine-grained sandstones and siltstones occur in thin layers. The top of the Herrería Formation is characterized by the transition from a clastic to a carbonate environment. Yellowish, friable and feldspar-rich sandstones intercalate with hard blueish quartz-arenites. The former contain flute-marks and large-scale cross-bedding and might point to a deltaic or slope environment. Stratigraphic up the shale content increases and the composition from pure clastic to carbonate-rich shales can be observed.

Macrofossils are mostly absent, besides some Corduban aged trilobites and trace fossils at the base, while typical Ovetian aged trilobites occur at the top of the formation in its facies transition. However, achritarch studies demonstrate so far a younger age for the entire succession, being Marianian. We will apply more detailed microfossil studies as well as detrital zircon analyses to possibly resolve this enigma and reveal more information about facies and the stratigraphic position of this formation using geochemical proxies.

P57

Ar-Ar ages, provenance and palaeontology of Lower Cambrian successions from Bornholm (Denmark)

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The Danish island of Bornholm hosts proposed to be Lower to Middle Cambrian sandstones and shales well preserved in tilted blocks along its southern coastline. Unmetamorphosed and undeformed clastic rocks of this age are seldom found in northern Europe.

The oldest succession, the Nexø Sandstone Formation rests unconformable on Mesoproterozoic basement with a non-conformable contact to overlying sandstones of the so-called Balka sandstones (Hardeberga Sandstone Formation), which is, in turn, covered by green shales, the Broens Odde Member of the Læså Formation. The two latter formations contain glauconites, which are currently subject of Ar-Ar dating. The exact depositional age of the lower two arenitic successions is unknown, the green shales are associated with trilobite-bearing clastic rocks, hence a Upper or Middle Cambrian age is proposed. In an isolated exposure of green shales further west on the island, earlier proposed to be of Late Triassic age, Upper Cambrian glauconites were determined and reworking excluded. This project will study the microfossil record of the different successions and the geochemical and petrographical composition of the three rock units.

Sampling was executed for the Nexø Sandstone Formation at N55° 3' 41,8" E15° 3' 16,6" (Gadeby) and N55° 3' 55,1" E15° 4' 43,7" (Bodilsker), for the Hardeberga Sandstone Formation at N55° 1' 41,7" E15° 7' 6,9" (Snogebæk) and the Broens Odde Member at N: 55° 0' 49,0" E15° 7' 7,5". The Nexø Sandstone Formation contains the most friable sandstones with a high feldspar content. The latter is strongly weathered and shales are very rarely deposited. Hence, the lack of fossils and the dominant sandstone facies allowed in suspecting a continental depositional environment. However, thin layers of green minerals, currently under study, might point to shallow marine incursions with the development of glauconites.

In contrast, the Hardeberga Sandstone Formation hosts different lithotypes with feldspar-rich sandstones, layers of extremely hard quartz-arenites and abundant trace fossils pointing to a shallow marine or coastal environment. Most of the bioturbations can be found in fine-grained sandstones and siltstones. The overlying green shales might be part of the formation or belong to a different sedimentary cycle, but indicating a large transgression. However, the timing of the transgression is not known.

All three formations do not have equivalents in southern Norway where black shales of Upper Cambrian to Middle Ordovician age overlie the same Mesoproterozoic basement. In southern Sweden exposures of possible age equivalent rocks are known and correlated based on their fossil content and the occurrence of glauconite layers.

The main objective of the study is to contribute to the regional stratigraphy and likes to understand the regional paleogeography in more detail.

IS 4 – General contributions to geosicence – Open for session proposals

P58

The SEDIBUD (Sediment Budgets in Cold Environments) Programme, ongoing activities and relevant tasks for the coming years

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POSTERS IS 4

Amplified climate change and ecological sensitivity of cold climate environments is a key environmental issue. Projected climate change in cold regions is expected to alter melt season duration and intensity, number of extreme rainfall events, total annual precipitation and balance between snowfall and rainfall. Similarly, changes to thermal balance are expected to reduce the extent of permafrost and seasonal ground frost and increase active layer depths. These effects will change cold regions surface environments and alter fluxes of sediments, nutrients and solutes. Absence of quantitative data and coordinated process monitoring and analysis to understand the sensitivity of the Earth surface environment is acute in cold climate environments.

The SEDIBUD (SEDIment BUDgets in cold environments) Programme of the International Association of Geomorphologists (I.A.G./A.I.G.) was formed in 2005 to address this key knowledge gap.

The central research question is to assess and model the contemporary sedimentary fluxes in cold climates, with emphasis on both particulate and dissolved components.

Initially formed as European Science Foundation (ESF) Network SEDIFLUX, SEDIBUD has expanded to a global group of researchers with field research sites in polar and alpine. Research carried out varies by programme, logistics and available resources, but represent interdisciplinary collaborations of geomorphologists, hydrologists, ecologists, permafrost scientists and glaciologists. SEDIBUD has developed a key set of primary surface process monitoring and research data requirements to incorporate results from these diverse projects and allow coordinated quantitative analysis. SEDIBUD Key Test Sites provide data on annual climate conditions, total discharge, particulate and dissolved fluxes, information on other relevant surface processes. A number of selected Key Test Sites is providing high-resolution data on climate conditions, runoff and sedimentary fluxes, contributing to the SEDIBUD Metadata Database which is currently developed. In addition, a framework paper for characterizing fluvial sediment fluxes from source to sink in cold environments has been published by the group. Comparable datasets from different SEDIBUD Key Test Sites are analysed to address key research questions of the SEDIBUD Programme as defined in the SEDIBUD Working Group Objective.

SEDIBUD currently has identified 44 SEDIBUD Key Test Sites worldwide with the goal to further extend this network to about 50 sites that cover the widest range of cold environments possible. Additionally, it is expected that collaboration within the group will act as a catalyst to develop new sites in underrepresented regions. The frequently updated SEDIBUD Key Test Site Database and the SEDIBUD Fact Sheets Volume provide significant information on SEDIBUD Key Test Sites. SEDIBUD is open for proposals for possible additional SEDIBUD Key Test Sites to be included in the programme.

Defined SEDIBUD Key Tasks include:

- The continued generation and compilation of comparable longer-term datasets on contemporary sedimentary fluxes and sediment yields from Key Test Sites
- The continued extension of the Metadata Database with these datasets
- The testing of defined Hypotheses by using the datasets continuously compiled in the SEDIBUD Metadata Database.

Information on the I.A.G./A.I.G. SEDIBUD Programme, Meetings, Publications, Online Documents and Database is available at the Website: www.geomorph.org/wg/wgsb.html
www.geomorph.org/wg/wgsb.html

P59

Soil development along a chronosequence on moraines of Skaftafellsjökull glacier, SE-Iceland

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Worldwide glaciers are melting due to a warmer climate, exposing surfaces where weathering and new soil formation commences. Since the end of the Little Ice-Age, Icelandic glaciers have been retreating after reaching their maximum extent in 1890, leaving behind deposits of glacial till of basaltic rock fragments mixed with tephra. The presence of end moraines mark the location of the glaciers' terminus, and a chronosequence can be established along proglacial areas. In a chronosequence, it is hypothesized, that except time, all other soil forming factors (climate, parent material, biota, and topography) remain unchanged. Thus, it is possible to assess the role of time on the rate of pedologic processes. As soils develop, organic carbon accumulates in the soil. In fact soils encompass the largest terrestrial carbon pool containing ~1500 Pg of organic carbon in the upper 100 cm. Sequestering carbon in soil is an option of mitigating climate change.

Thus, the aim of this research was to investigate how the soil develops over time, determine the rate at which carbon is sequestered in the soil under natural circumstances, and to study the relationship among soil properties, landscape and vegetation.

The research was conducted at Skaftafellsjökull glacier, SE-Iceland. Soils in different stages of development were sampled along three moraines representing surfaces of ~ 8, 65 and 120 years. Several parameters were analysed to investigate early stage soil formation and its relation with time; formation of A-horizon, bulk density, organic matter, organic carbon and nitrogen, soil reaction (pH), and clay content. To compare the properties under a mature ecosystem, which may develop on the glacial moraines in the future, soils were also sampled in the birch forest on the Skaftafellsheiði heathland adjacent to the glacial moraines.

The data indicate that after 120 years of development, the proglacial soils are still young compared with the older soil under the birch forest. Bulk density decreased with time as did the soil pH, and these changes were more evident in the 0-10 cm than 10-20 cm depth. The formation of A-horizon and the proportion of organic matter and soil organic carbon increased over time. After 120 years, the A-horizon was 8 cm thick and the soil contained 19.6 Kg C m^{-3} of organic carbon. When compared to the organic carbon of 29.7 Kg C m^{-3} under the forest soil, it was apparent that the soil had not yet reached its climax carbon sequestering capacity. Further, the young soils contained a substantial amount of secondary clay minerals characteristic of soils of volcanic origin, but the increase in the concentration with age was not clear.

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P60

Cooperation between Academia and Industry; solving problems of common interest

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Our society is becoming increasingly complex, and problems to be solved often demand research based on large, multivariable, and sometimes non-linear data sets. In this situation, we see a tendency for shrinking resources being available for research and education, even in research fields that are clearly of great importance for the society. For example, the number of permanent scientific positions at the Department of Geosciences at the University of Oslo has been slashed from 45 to 35 over a period of five years.

Academia and industry share many problems in research and advanced education. Two such problems are the recruitment of young and motivated candidates and the development and maintenance of state-of-the-art competence in research and technology development. Although globalization has opened a network of more flexible recruitment of researchers and people with technological background, it is desirable that the recruitment at the local level is not reduced.

At the Department of Geology of the University of Oslo, an Industrial Liaison arrangement has been in function since 1978, particularly aimed at the petroleum industry. After a period of lowered activity, this is now growing fast, including 21 national and international industry members. The arrangement facilitates a closer contact between the academia and industry, both on the organizational and individual levels. The Department invites industry members to discussions on scientific and strategic matters as well as arranging meetings between students and industry partners. The industry members contribute with financial support for through the fund for the students of geoscience actively to take part in scientific conferences with talks and posters , and hence strengthen recruitment.

P61

An analysis of snow cover changes in the Himalayan region using MODIS snow products and in-situ temperature data

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Amidst growing concerns over the melting of the Himalayas' snow and glaciers, we strive to answer some of the questions related to snow cover changes in the Himalayan region covering Nepal and its vicinity using Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover products from 2008 to 2008 as well as in-situ temperature data from two high altitude stations and net radiation and wind speed data from one station. The analysis consists of trend analysis based on the Spearman's rank correlation on monthly, seasonal and annual snow cover changes over five different elevation zones above 3,000m. There are decreasing trends in January and in winter for three of the five elevation zones (all below 6,000m), increasing trends in March for two elevation zones above 5,000 m and increasing trends in autumn for four of the five elevation zones (all above 4,000 m). Some of these observed trends, if continue, may result in changes in the spring and autumn season river flows in the region. Dominantly negative correlations are observed between the monthly snow cover and the in-situ temperature, net radiation and wind speed from the Pyramid station at 5,035 m (near Mount Everest). Similar correlations are also observed between the snow cover and the in-situ temperature from the Langtang station at 3,920 m elevation. These correlations explain some of the observed trends and substantiate the reliability of the MODIS snow cover products.

P62

The Grímsvötn 2011 airfall deposits

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The Grímsvötn eruption 2011 started in the afternoon on the 21st of May. Initial eruption plume did reach about 20 km in altitude and was divided into two lobes. An upper part heading towards the east and a lower part heading to south. Air fall started in populated areas few hours later. While the eastern branch of the plume was cut off around 03:30 on the morning of 22nd of May the southern branch was fed throughout the major explosive phase that lasted for about 3 days. Most of the distal air fall was precipitated in high wind throughout the eruption. This caused primary tephra accumulation to be most important in sheltered and wet areas, while open spaces accumulated tephra in dunes, being stripped of tephra in-between. This presentation shall focus on the difficulties in collecting and documenting eruptions under severe weather conditions. It also shed light on the origin of many older tephra layers found within the Icelandic tephra record, thought to have been subject to post eruptive erosion. Tephra fall in heavy wind does generate layers that do show crossbedding and over thickening. It also causes the layers to be highly sporadic within the affected area.

P63

Identification and isopach maps of recent Jan Mayen tephras; based on XRF core scanner data from marine cores.

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Jan Mayen is a volcanic island at 71°N and 8°W situated on the northern tip of the microcontinent the Jan Mayen Ridge. The volcanic history of the island is still little known with the exception of the four eruptions documented to have occurred at the island since early 18th century. To extend our knowledge of the volcanic history of the island a grid of marine sediment cores have been retrieved from the surrounding area. They are expected to be a continuous and long archive for tephra layers produced during at least the major eruption events at Jan Mayen. This mapping will also give a new insight into the recent volcanic history of Jan Mayen. A number of 1-5 metres long sediment cores were retrieved on a cruise to Jan Mayen the summer 2011 with R/V G.O.Sars from the sea-floor in the Jan Mayen area. The preliminary results of the physical property (MST) and bulk element XRF core scanner analyses performed on the cores will be presented and discussed. These logger results are expected to give us the possibility for a preliminary first order cross-core correlation. Major tephra layers identified in the cores will also be presented and a tentative thickness distribution.

P64

Age and stratigraphy of three mid-late Weichselian tephra layers from the Faroe Islands margin

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We have investigated the stratigraphical position of three discrete tephra layers in three marine sediment cores from the Faroe Islands margin. Two of the tephra have recently been reported from the Greenland ice cores and thus provides key tie-points between marine and ice-core records. One tephra is the Fugloyarbanki Tephra, also referred to as Faroe Marine Ash Zone II (FMAZ-II). This tephra occurs above the warm phase of interstadial 3 in both the marine cores and the Greenland Ice core. The other tephra is the Faroe Marine Ash Zone III (FMAZ-III). It occurs in the warmest peak of interstadial 8 in the marine cores and in the same stratigraphical position in ice core. The third tephra is a hitherto unknown basaltic tephra recorded in the lower part of interstadial 12. This new tephra is named FMAZ-IV. FMAZ-II and FMAZ-III have previously been described and dated from ENAM93-21 and several other cores from the Faroe Islands margin (Rasmussen et al., 2003). In the present investigation we compared these observations with two new records from the same general area, namely LINK15 from the central Faroe-Shetland Channel (1600 m water depth) and LINK16 from the Fugloy Ridge (773 m water depth). In LINK15, FMAZ-II was dated at 4 cm intervals both below, above and within the ash, while FMAZ-III was dated at 2 cm intervals. Previous dates of FMAZ-II from 5 different cores gave an age span of 22,850-23,900 14C years BP (400 year reservoir correction). The new results date the peak tephra fall-out of FMAZ-II to 22,840±90 14C years BP, while the peak fall-out of FMAZ-III is dated to 32,863±164 14C years BP. The dates were calibrated using Calib6.01, Marine09 (Reimer et al., 2009) to 27,600±370 cal years BP and 37,300±390 cal years BP, respectively. In the Greenland ice core the two tephra are dated to 26,740±390 and 38,122±723 years b2k (before year AD 2000), respectively (Davies et al., 2008, 2010). The marine age of FMAZ-II is 1100 years older than the ice core age, while the marine age of FMAZ-III is 770 years younger than the ice core age. We attribute the discrepancies to changes in the reservoir age of the subsurface ocean, which apparently was much higher during MIS 2 than during MIS 3. The new FMAZ-IV tephra dates c. 43,400 14C years BP according to the age models, which calibrates to 46,300 years BP.

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P65

A comparison of Trace Elements chemistry of the Saksunarvatn ash in lacustrine- and marine records as well as from the GRIP ice core

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Volcanic ash identified in lake and marine sediments, as well as in ice-cores is a promising method to correlate chronologies over large areas e.g. the North Atlantic region. Tephrochronology is an important tool not only for archaeological dating but also for the timing and understanding of palaeoclimatic events. Major element chemistry is the standard analytical method for identifying source volcanoes and to differentiate between eruptions. The Saksunarvatn ash is a widely spread ice-varve dated horizon dated to 10,436-10,258 cal. yr BP. However, new results point in the direction of a 500 year long early Holocene period of intense explosive eruptions from Grímsvötn volcano producing up to five identical tephra layers of this well known Icelandic isochrone. A new tool for discriminations where major element composition of tephra deposits is identical is trace element analysis, LA-ICP-MS (Laser ablation inductively coupled plasma mass spectrometry). It enables a full suite of major and trace elements geochemical data for individual tephra grains and could improve the discrimination between eruptions.

We have plotted trace element data from the Saksunarvatn ash retrieved from lacustrine sediments from the Faroe Islands, including the type site on Streymoy together with trace element data from marine sediments outside the East Faroe shelf trough and data from the Greenland GRIP ice core. The results indicate differences in geochemical trace element chemistry between the compared datasets, suggesting layers with different trace element composition. If isolated layers could be identified and discriminated by trace element analysis an even better chronology for the early Holocene and North Atlantic could be the result.

POSTERS Sp 3

P66

Major and Trace Element Chemistry of Holocene silicic marker tephra layers from Iceland

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Explosive volcanic eruptions are instantaneous events in geological terms and the tephra layers they produce often form widespread marker horizons in Quaternary sequences. Icelandic tephra have been identified as layers or distinct horizons of micro-tephra in Greenland ice cores as well as in soil, lacustrine and marine sediment archives across the North Atlantic. Consequently tephrochronology, granted that accurate tephra identification is obtained, provides a robust methodology for dating and correlation of sediment and glacier archives in this region that is applicable for palynological, archaeological, palaeoclimatic and sedimentological studies.

The compositional diversity of Icelandic volcanic rocks is the result of the interaction between active rifting of the Mid-Atlantic Ridge and intraplate volcanism. The location of a volcanic system within this setting affects the overall chemistry and petrographic character of its products, resulting in a discrete chemical fingerprint. These fingerprints can be used as a tool for identifying source volcanoes and individual tephra layers.

As part of the international research group Volcanism in the Arctic System (VAST), workers at Edinburgh University are developing a new robust reference chemical database of major Holocene Icelandic tephra marker layers. This database comprises major-, trace- and rare earth element data collected via electron microprobe, ion probe and laser ablation ICP-MS by analysis of the vitreous groundmass phase. The database also records the physical characteristics of each deposit and details of proximal reference localities.

Major element chemistry is the favoured analytical method for tephra studies as data can be collected rapidly, at relatively low expense with minimal damage to samples. This method has proved useful in the identification of individual volcanic systems allowing for reliable discrimination of products from different systems. However, the use of major element chemistry to distinguish between individual tephra layers sourced from the same system has been less successful. Application of major element data to rhyolitic tephra layers from the Hekla volcano creates two geochemically distinct clusters (H4-H5; H1104-H3-HS), within which individual tephras cannot be distinguished. The identification and distinction of intra-system eruptions is dependent on identifying subtle variations in chemistry representative of minor changes in magma evolution through time. These variations are highlighted when using incompatible trace- and rare earth elements. Preliminary trace element data collected for Hekla tephra layers have confirmed the potential of this approach. Previously indistinguishable tephra layers are identifiable with minimal data overlap when major- and trace element data is combined. Distinction between H4 and H5 is possible using Zr, Sc, Nd. Improvements in distinguishing between H1104: H3: HS have been achieved using Zr, Sc, Sr, Ba, MgO and FeO.

SÞ 4 – Volcanic pollution: its environmental and atmospheric effects

P67

The impact of the 1783–1784 AD Laki eruption on cloud condensation nuclei, cloud droplets and indirect radiative forcing.

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We address the impact of the Icelandic 1783-1784 AD Laki eruption on atmospheric chemistry, aerosol microphysical processes and the Earth's climate system by means of a global aerosol microphysics model (GLOMAP). In contrast, previous studies have examined the impact of the eruption on the formation of sulphate aerosol and on climate using chemistry transport models or general circulation models. Using GLOMAP, we are able to study the aerosol microphysical processes such as the nucleation of new particles, condensation and coagulation as well as particle growth to cloud condensation nuclei (CCN) and cloud droplet sizes. Explicitly simulating microphysical processes is important for determining the size, the number concentration and the lifetime of climate-relevant particles.

We show that the Laki eruption fundamentally altered the microphysical processes driving the evolution of the aerosol size distribution in the Northern Hemisphere, and that the total particle number concentrations in the free troposphere increased by a factor of around 16 over large parts of the Northern Hemisphere during the first three months of the eruption. The simulations suggest that Laki completely dominated as a source of CCN in the pre-industrial atmosphere increasing 3-month mean concentrations by up to a factor of 65 in the upper troposphere. We find a very widespread impact on CCN number concentrations at low-level cloud altitude, with increases by a factor of ~6 over Europe and by a factor of ~14 over Asia as a result of long range transport of freshly nucleated particles. These results highlight that Laki had the potential to profoundly alter cloud microphysical properties and cloud droplet number concentrations far away from the source resulting in a substantial aerosol indirect effect on climate. The calculated northern hemisphere mean aerosol indirect effect peaks at -5.2 W/m^2 in the month after the onset of the eruption and remains greater than -2 W/m^2 for 6 months. Therefore, our estimate of the aerosol indirect effect due to the Laki eruption is comparable to the magnitude of the direct radiative effect calculated in previous studies with implications for our understanding of the climate response to such an eruption.

Moreover, we investigate the role of the season in which a Laki-style eruption commences and show that the season plays an important role with regard to the magnitude of the aerosol indirect effect. Thus, numerical simulations of large-scale, high-latitude volcanic eruptions need to take into account that variability regarding the magnitude of the climate impact will arise depending on the season an eruption commences.

P68

Diagnostic criteria for Icelandic volcanic landforms based on remote sensing data: Constraints on morphology and optimization of mapping methodologies

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Abstract
The current plethora of remote sensing (RS) data allows varied thematic and quantitative characterization of volcanoes, but requires great computational efficiency and formalization with respect to information extraction. In order to assess the capabilities of RS data for volcanoes, a correlation of field- and RS- data has been carried out for a variety of landforms, such as lava flows, shields, tuyas and hyaloclastite ridges. This includes evaluation of spatial and temporal resolution control on geomorphic information by field to pixel- evaluation. The perspectives of this study is faster and optimized mapping of volcanic areas, change detection and statisitcal information on the distribution on a variety of volcanic landforms.

Introduction
Today human visual geomorphic analysis and interpretation is more sofisticated than computational analysis, but has obvious drawbacks such as the risk of subjectivity, reproducibility and time consumption. This pilot study focuses on constraining what geomorphic information is available from different types of RS data and how it effectively can be incorporated into image segmentation.

Study area
Reykjanæs Peninsula host a variety of easily accessible volcanic edifices allowing frequent field visits, which is important for spatial and temporal ground verification. Moreover, Reykjavik Peninsula is among the youngest and most pristine parts of Iceland and the only region in Iceland to have been completely mapped in 1:100,000.

Data and methodology
A variety of RS data is available for the Reykjanes Peninsula ranging from SPOT, MODIS, Landsat and aerial photographs covering the visible, near-, short-, mid- and long wavelengths. These have spatial resolutions from 15 cm per pixel to 1000 m per pixel and with temporal resolution down to 1 week for SPOT and MODIS. Moreover, digital elevation models (DEM) with a resolution of 10-20 m/pixel are used for geomorphometric analysis of volcanic edifices.

The imagery is correlated to GPS referenced pixels made in the field (1; 2.5; 5; 10; 20 m/pixel) on different landforms, and thus there is a direct correspondence between field and RS observations. Therefore, the scale of each landform is evaluated with respect to pixel resolution as well as seasonal variations for constraining temporal variance of RS data.

Initial results and conclusions
Preliminary analysis shows that shields and subglacial edifices are very distinct on both imagery and DEM. Hyaloclastite ridges and tuyas are significantly steeper (12-35 degrees) than shields (0-8 degrees) and are very distinct on false color multispectral imagery. Internal morphologies in lava flows such as: sky lights and traverse ridges (Observed on 0.5 m/pixel) tumulies, inflated smooth pahoehoe, entrailed pahoehoe (observed on 2.5 m/pixel data), big tumulies (observed on 10 m/pixels) can be resolved. Moreover, lava flow fronts can be distinguished by slope derived from the DEM. Internal layering in hyaloclastite is visible on 15-50 cm/pixel. Initial image segmentation provides satisfactory segmentation of different volcanic edifices and do also resolve different lava flow.

P69

Petrology and field-relations of the Hverfjall fissure eruption, northern Iceland: implications for eruption reconstruction

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The Hverfjall fissure eruption occurred approximately 2900 years BP, near Lake Mývatn in northern Iceland. The deposits formed in this >3 km long fissure eruption can be subdivided into three separate phases: (I) Hverfjall fallout, (II) Jarðbaðshólar scoria cones and lava flows, and (III) Hverfjall base-surges and ballistic bomb cover. The characteristics of the resulting deposits are largely controlled by the exact location of vents along the eruptive fissure, and the larger extent of Proto-Lake Mývatn (i.e., the availability of water required for explosive interactions with the rising magma). In addition to these main phases, there are three small-volume lava flows located north along strike of the fissure that has been suspected to belong to the same eruption.

Here we present geochemical compositions of the main phases of the eruption, as well as the three lava flows to the north. The magma erupted at both the Hverfjall and Jarðbaðshólar vents show identical bulk-rock compositions, as well as identical petrographic textures. This also includes two small lava flows sampled E and W of the Jarðbaðshólar vents. The magma erupted in this fissure eruption is best characterized as moderately evolved tholeiitic basalt (Mg#=~45), with broad similarities to many other eruptions within the Krafla fissure swarm. The only sample that stands out from the rather homogeneous composition is the Hverfjall fall deposits (Phase I), which has slightly lower Mg# (i.e., ~43). These fall deposits were sampled relatively far from the vent and we interpret this to reflect a relative depletion of dense olivine crystals (due to gravitational settling from an eruption plume) with increasing distance away from the vent. The three lava flows located north of Jarðbaðshólar, on the other hand, show distinctively different bulk-rock chemistry with slightly lower Mg# (41.5-43.6) and also an overall higher K2O content (i.e., 0.35±0.01 wt.%). Thus, although there are some slight variations within these lavas it is likely that all three lava flows belong to a single eruption, but they do not belong to the Hverfjall eruption.

Our results suggest that the Hverfjall magma was residing, and fractionating, in a single reservoir in the crust prior to the eruption. At the onset the eruption the activity was focused in a shallow lake at the Hverfjall vent producing fine-grained tephrafall around the volcano. This phase was probably also characterized by the highest eruption rate. Some time into the eruption a new vent opened up in the north (on land) at Jarðbaðshólar, which built the scoria cones and emplaced the lava flows to the E and W. Probably, the eruption rate was lowered during this phase as two vents were drawing from the same magmatic reservoir simultaneously. As the activity at Jarðbaðshólar ceased, the Hverfjall vent continued erupting material, but at lowered intensity. However, as the eruption rate decreased water magma interactions took place deeper into the crust (as indicated by the increased lithic content) and the consequent eruption plume got colder and more dilute, hence the emplacement of base-surges.

P70

The dating of Midtungugil and Skerin, two late Holocene flank eruptions of Eyjafjallajökull, Iceland

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The eruptions of Eyjafjallajökull in 2010 caused widespread travel chaos across the globe, with over 100,000 cancelled flights which affected up to 10 million passengers. While the events of 2010 are well known the recent history of the volcano is not. This paper extends the volcanic history of Eyjafjallajökull by dating two flank eruptions- late prehistoric activity along Miðtungugil about 1500 years ago and the ca. 920 AD eruption of the Skerin fissure. The pursuit of improved understanding of recent volcanic activity highlights two key issues: how to approach the identification of past eruptions and what might be the relationship between long-term patterns of activity in Eyjafjallajökull and its close neighbour Katla. The Miðtungugil and Skerin eruptions have been dated using tephrochronology even though they did not produce extensive tephra deposits, because they did generate floods. Tephrochronology using layers from other volcanoes is applied to the identification, correlation and chronology of these flood deposits. Evidence is scattered, lacks clear sedimentological markers and could have completely escaped attention but for the precise correlations possible with tephra layers. There is evidence that both the Miðtungugil and Skerin eruptions coincided with Katla eruptions.

P71

Two lahar deposits in Iceland; The Eyjafjallajökull 2010 deposit, and the Hekla-S deposited 3900 years ago (BP). A comparative study.

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Subglacial eruptions are common in Iceland and glacial outburst of a mixture of water, ice, tephra and rock fragments (jökulhlaup), generally accompany these eruptions. The flows are generated by melting of ice and snow and/or by remobilization of tephra in unstable environment. However, well preserved debris flow deposits of the lahar type are rarely encountered in Iceland, mainly for two reasons. First, although some glacial outbursts probably begin as concentrated debris flows they frequently transform to muddy streamflows by steadily increasing water supply, and sediments erode easily in the glaciofluvial environment. Secondly, potential debris flows occurring on the slopes of snow-capped stratovolcanos in earlier times are buried beneath more recent lava flows. During the Eyjafjallajökull 2010 eruption, tephra fallout on the glacier slopes was remobilized, resulting in debris flow producing deposit of 0.12 x 106 m3. Mean thickness of the deposit was 30 cm. Mapping and sedimentological analyses of the freshly settled deposit revealed characteristics of concentrated lahar flow. An explosive eruption in Hekla volcano 3900 years BP ago (Hekla-S) produced debris flow deposit which has also been classified as lahar deposit. Estimated mean thickness of the flow is 3 m and the volume is estimated at 300 x 106 m3, more than three orders of magnitude larger than the Eyjafjallajökull lahar deposit.. Despite different size dimensions, the two deposits have several features in common, regarding mode of transfer and sedimentation. On the other hand, different characteristics reflect dissimilar origin and composition of the two concentrated flows. The Eyjafjallajökull lahar deposit resulted from rain-triggered remobilization of fine-grained volcanic ash. The Hekla-S lahar probably burst out when a rim of an erupting crater lake collapsed, releasing water saturated mixture of pumice and rock fragments from the crater lake.

P72

The Fimmvörðuháls eruption 2010

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Just before midnight on 20th of March an eruption began in the region between the two glaciers Eyjafjallajökull and Mýrdalsjökul in south Iceland and in the first hour of 21 March a reddish glow was visible on the east flank of Eyjafjallajökull. Surveillance overflight revealed a 300 m long, north-trending fissure featuring a curtain of 15 discrete lava fountains. The fissure was located at the crest of the Fimmvörðuháls mountain pass, directly above the popular nature reserve of Thórsmörk. In early stages of the eruption, the lava flowed towards the northeast, cascading into the gorge of Hrunagil. Then continued its advance down the gorge towards the outwash plain of the Krossá River. For the first three days of the eruption observations were confined to surveillance by air, but on 24 March the weather was favourable for on-site field observations. At that time only 4 vents where active on the fissure, with lava fountains reaching heights of 100 m. Lava continued to flow to the northeast until 26 March lava advancing on top of the fresh winter snow without any vigorous interaction detectable between the two. During this period, observations showed that the lava did not evoke any substantial melting of the substrate snow. After few days, radiation heat transfer at active flow fronts resulted in non-contact melting of the snow a few meters ahead of the lava forming meters high banks along the side and in front of the advancing lobes. Explosive interaction (i.e. rootless eruptions) between the lava and meltwater occurred where the lava cascaded into the Hrunagil gorge and within the main lava field northeast of the craters, producing a plume of steam and ash. On 27 March, the northeast lava field had build up to the extent that lava began to advance to the northwest. As the eruption progressed and the flow field thickened, the snow beneath the lava began to melt, as indicated by sagging of the lava in certain sectors of the flow field. Occasional rootless eruptions where observed within the field on 27 and 28 March, when individual events lasted for 10 to 15 minutes and sustaining a steam-rich ash plume rising several hundred meters above the eruption site. On 31 March, a new northwest-trending fissure formed from the northern end of the initial vent system, situated west of the water divide and thus directing the flow of lava to the northwest. Here in terms of the advancing lava, the course of events was identical to that observed at the beginning of the eruption; the lava advanced over the snow with minimal interaction and melting, but as it reached Hvannargil it spilled into the gorge and generated occasional rootless eruption. Few days later the heat from the lava began to melt the underlying snow with corresponding sagging of the lava field.

UV 2 – Ancient volcanism in Scandinavia

P73

The Felsic and Intermediate volcanic Footwall to the Cosmos Nickel Sulphide deposits, Agnew-Wiluna greenstone belt, Yilgarn Craton, Western Australia

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The Yilgarn Craton contains several world-class, nickel-sulphide ore bodies. Komatiite-hosted massive nickel sulphide deposits are typically found at the basal contact of ultramafic bodies, which are thought to have formed during the eruption of long-lived komatiite flow fields, which flowed over an underlying, often felsic, substrate. The volcanic footwall successions of many commercially exploited nickel-sulphide deposits are often poorly understood. Consequently investigation, combining core logging, geochemical analysis and petrology, into the succession at Xstrata Nickel Australasia's Cosmos mine, will enhance the understanding of komatiite-felsic interaction and Archean volcanism. Despite the region experiencing amphibolite metamorphism and several deformation events, primary textures within the footwall are well preserved, aiding protolith identification. The footwall to the Cosmos nickel sulphide deposits consists of a complex succession of both fragmental and coherent extrusive lithologies, ranging from andesites to rhyolites, plus later-formed felsic intrusions. The occurrence of thick sequences of amygdaloidal intermediate lavas intercalated with extensive sequences of dacite tuff, coupled with the absence of marine sediments or hydrovolcanic products, indicates that the succession was formed in a sub-aerial environment. The chemical composition of the footwall lithologies is dominated by a calc-alkaline signature, indicative of a volcanic arc setting. REE data shows that the compositional variability was not achieved via fractional crystalisation alone, and that crustal assimilation and/or different sources must be invoked to explain the observed andesite to rhyolite magma suite. Complex relationships between komatiite-hosted sulphide deposits and the underlying footwall, imply that the eruption of felsic, intermediate and komatiite magmas was near co-eval.

P74

The Eggøyan eruption in 1732, Jan Mayen; an emerging ankaramitic surtseyjan type eruption

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Jan Mayen is a volcanic island situated at 71°N and 8°W. The Island is build up of two main edifices, Sør Jan and Nord Jan (Beerenberg). Volcanic activity on the island is little known, and however at least 4 eruptions are documented at the island since early 18th century. An expedition to the island in summer 2011 reveals that the first of these eruptions formed the tuffcone Eggøya in 1732 AD. The Eggøya tuffcone is situated at the south west foot of the Beerenberg volcano, about 2.5 km from the coastline marked by Valberget. The tuffcone is about 1.5 km in diameter and emerges from about 35 m depth to reach the altitude of at least 217 m above sea level. Pre Eggøya lava flows on the sandy coast west of the edifice are covered by up to 1.6 m of ash some 3 km from the vent. These lava flows have been suggested to be formed in the 1732 eruption and the 1818 eruption of Jan Mayen. However, they are covered with the Eggøyan tephra and thus considerable older. Volcanic tephra from the Eggøya eruption forms the uppermost tephra layer on the Eastern flanks of Beerenberg. Contemporary description of the 1732 eruption, tell of violent explosive eruption at the east side of Beerenberg observed by German whalers for 28 hours, while sailing past the island in May that year. A Dutch whaler group arriving to the island in June that year, report fine ash covering the island in such a way they sink up to mid leg into it. Our study this summer shows that the only eruption these descriptions can refer to are the Eggøyan eruption, dating it precisely to the spring 1732. The eruptive products are made up of frothy glass and ol, cpx and opx crystals, which characterize the flank eruptions of Beerenberg. In this presentation we shall present first results of intense fragmentation of deep gas rich ankaramitic magma from the Jan Mayen area and its interaction with seawater in shallow coastal settings.

P75

Petrology of Jurassic Highly Alkalic Intrusives of West Central Virginia: Implications for Lithospheric Instabilities During the Rift-to-Drift Transition

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The swarm of nepheline syenite and alkali basalt intrusions occurring in west central Virginia has been described by several geologists since their discovery in the 19th century. However, the only geochemical data published to date are four analyses by Watson and Cline (1913). The aim of this study is to present new major and trace element data to shed light at the petrogenetic source of these distinctive magmas and to present a coherent geodynamic model for their formation.

The studied magmas have an unusual position in the central Appalachians as dykes from the Eastern North America province have generally a tholeiitic composition (e.g. McHone et al. 1987), however this Virginia alkaline complex has some geochemical similarities to the New England-Quebec lamprophyre province. These alkaline intrusions are confined to a 1000 square kilometre elliptical area covering most of Augusta County in western Virginia. The magmas penetrated northwest-southeast fractures in the lower Palaeozoic limestone and dolomite of the Valley and Ridge physiographic province. Available potassium-argon age determinations define a late Jurassic age for the alkaline intrusions. Zartman et al. (1967) conclude that this period of alkaline magmatism post-dates the surrounding intrusions of the Late Triassic Eastern North America province tholeiitic dolerites.

Recent experimental petrology studies of basalt systems from the Sierra Nevada, CA. (Elkins-Tanton & Grove, 2003; Meyer & Elkins-Tanton, 2011) can be used to evaluate possible means of petrogenesis for the highly alkaline magmas, due to similar compositions. The melting conditions from these experiments have been used to place constraints on the gravitationally-driven loss of the Sierra Nevada lower lithosphere. In addition, numerical experiments show that gravitational instabilities are likely to form in extensional settings (e.g. Esedo et al., 2011). During a gravitational loss of the lithosphere the first responding magmas would be hot asthenospheric decompression melts similar to tholeiitic basalts. Only when the sinking lithosphere has volatiles it may devolatilize and carry so volatiles and low degree melts into the asthenospheric mantle. Later melting of this metasomatized asthenospheric mantle will result in Large Ion Lithophile Element enriched alkaline magmas, similar in composition to the sampled Virginia alkaline complex rocks.

These magmas from the Virginia alkaline complex are the first passive continental margin melts, causally linked by geochemistry to the numerically predicted process of lithosphere removal during the rift-to-drift transition.

P76

Hybridization processes in a partially crystallized magma chamber (Austurhorn intrusion, SE Iceland): Multiple magma mixing scenarios

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The Tertiary Austurhorn intrusive complex in SE Iceland is believed to represent a large exhumed magma chamber with an extensive history of magma mixing and mingling. The basal part of the intrusion consists of granophyric host rocks which have been intensively intruded by different pulses of more mafic rocks. The association of granophyres, basic and hybrid rocks at Austurhorn are known as a simple "net-veined complex"in the literature, but field relations suggests a much more complex history. Different mafic pillows can be distinguished in the field and morphologies range from near-ideal pillow shapes to fragmented pillows incorporated into intermediate rocks. Rapid quenching of some mafic pillows results in chilled margins, whereas others do not seem to follow the same thermal history. In pillows which lack a chilled rim plagioclase phenocrysts are randomly distributed and can be identified extending all the way to the outer rim compared to an absence of phenocrysts in outer parts of the quenched pillow margins. Complex cross-cutting correlations between different hybrid generations can be distinguished in numerous exposed outcrops. Trace element compositions of hybrid rocks suggest multiple replenishment events of mafic magma into a felsic host reservoir. Mixing proportions in different hybrid generations obtained from Rare Earth Element bulk partition coefficients show that in the beginning of magma mixing hybrid compositions are dominated by the felsic magma but with time hybrids get more mafic in composition as a result of an inversion of mixing endmember proportions. Plagioclase phenocrysts in hybrid rocks often display reverse and oscillatory zoning indicating repeated replenishment events of mafic magmas. Distinct plagioclase zonation patterns represent the mixing history of a single hybrid generation and suggest in case of Austurhorn that magma mixing occurred between three components: (1) mafic, (2) felsic and (3) previously formed hybrid magmas. Near the contact of the intrusion the granophyric magma display brittle deformation indicated by the presence of sharp and blocky enclaves separated by mafic veins. The complexity of the mingling/ mixing increases towards the center of the intrusion, where chaotic hybrid rocks dominate the lithology. New input of magma locally increases the host temperature which significantly changes the rheology of both the felsic and basic magma. Repeated reheating episodes due to multiple magma injections decrease the viscosity of the granophyres and promote chemical diffusion. Compared to previous studies on the petrology of the Austurhorn intrusion our 65 bulk rock samples show linear trends suggesting mixing between the mafic and silicic end-members as well as mixing between different hybrid magmas. Textural observations in the field and bulk rock analysis suggest that hybrid rocks, in case of Austurhorn with andesitic composition, are formed by several mafic replenishment events into the basal part of an already partially crystallized felsic magma chamber.

P77

Eroded Neogene Silicic Central Volcanoes in Northeast Iceland Revisited

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We report on a geological expedition to NE Iceland in August 2011. A comprehensive sample suite of intrusive and extrusive rocks, ranging basaltic to silicic compositions, was collected from the Neogene silicic central volcanic complexes in the region between Borgarfjörður eystri and Loðmundarfjörður. The area contains the second-most voluminous occurrence of silicic rocks in Iceland, including caldera structures, inclined sheet swarms, extensive ignimbrite sheets, sub-volcanic rhyolites and silicic lava flows. Yet it is one of Iceland's geologically least known areas (c.f. Gústafsson, 1992; Martin & Sigmarsson, 2010; Burchardt et al., 2011).

The voluminous occurrence of evolved rocks in Iceland (10-12 %) is very unusual for an ocean island, with a typical signal of magmatic bimodality. The "Bunsen-Daly"compositional gap is a long-standing fundamental issue in petrology (e.g. Bunsen, 1851; Daly, 1925; Barth et al., 1939). The Bunsen-Daly Gap is very difficult to reconcile with continuous fractional crystallization as a dominant process in magmatic differentiation (Bowen, 1928), implying that hydrothermal alteration and crustal melting may play a significant role. Our aim is to unravel the occurrence of voluminous evolved rhyolites in NE Iceland, which has for long been a challenge to our understanding of magmatic processes.

We will use a combined petrological, textural, experimental and in-situ isotope approach. We plan to perform major, trace element and Sr-Nd-Hf-Pb-He-O isotope geochemistry, as well as U/Pb and Ar/Ar geochronology on rocks and mineral separates. In addition, high pressure-temperature partial melting experiments aim to reproduce and further constrain natural processes. Using the combined data set we intend to produce a comprehensive and quantitative analysis of rhyolite petrogenesis, and of the temporal, structural and geochemical evolution of the silicic volcanism in NE Iceland. The chosen field area serves as a good analogue for volcanoes such as Askja and Krafla where a close interaction of basaltic and more evolved magma has led to explosive eruptions. In turn, this research may add to our understanding of active central volcanoes in Iceland.

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P78

From plagioclase ultraphyric basalts to architecture of the Icelandic crust

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Plagioclase ultraphyric basalts (PUBs) are common in many oceanic tectonic settings and are particularly abundant as discrete flow groups throughout the stratigraphy of Iceland where useful as regional marker horizons. Their petrogenesis, however, is rarely studied and thus remains uncertain. With up to 45% plagioclase macrocrysts PUBs provide records of complex crustal plumbing systems.

We have investigated the ~10 Ma old Grænavatn Porphyritic Group, originally mapped by G.P.L Walker, consisting of 5-10 PUB lava flows that attain a maximum thickness of ~90m west of Reyðarfjörður, East Iceland. It is traceable for >50km along strike, but tapers out to the north, south and up-dip to the east. Modal proportions of plagioclase macrocrysts vary both vertically and laterally within single lava flows. Occasionally the plagioclase macrocryst mode increases from the base (25%) to the top (45%) of flows whereas the pyroxene macrocryst mode (1-6%) displays the opposite distribution, indicative of plagioclase flotation and pyroxene sinking. Moreover, on the scale of the whole group (9 flows) the abundance of plagioclase macrocryst decreases up-section while pyroxene macrocrysts are only present in the lower part.

From crystal sizes and shapes four plagioclase populations are identified; (1) single, zoned euhedral macrocrysts (~5mm) with overgrowth rims, (2) unzoned, anhedral glomerophyric macrocrysts (4-10mm) in cumulate clusters up to 3cm, (3) subhedral microcrysts (0.5-1mm) often elongated, and (4) 5-50μm lath-shaped groundmass.

Plagioclase macrocryst cores of types 1 and 2 (An78-90) are more primitive than overgrowth rims and groundmass (An50-70), and therefore in disequilibrium with the host melt. The microcrysts of type 3 are of intermediate composition (An74-80). Clinopyroxene macrocrysts are also more primitive (Mg# 78-85) relative to groundmass crystals (Mg#70-76). A preliminary study of melt inclusions in plagioclase macrocrysts suggests typical tholeiitic basalt compositions (5-7 wt% MgO) with Mg# of ~50. Detailed textural and chemical mapping of zoned macrocrysts cores reveals complex histories with resorption, overgrowth and stages with entrapment of melt inclusions. Chemical traverses display oscillatory, continuous normal and reverse zoning (ΔAn1-3). Further, we observe discontinuous reversely zoned mantles (ΔAn4-5) on macrocryst cores and discontinuous normal zoned overgrowth rims (5-30μm) of albitic composition (ΔAn10-15).

Our preliminary observations suggest that macrocrysts cores (types 1+2) grew in a staging magma chamber in the lower-middle crust (>12-15km depth) that was highly dynamic and periodically promoted entrapment of melt inclusions and oscillatory zoning. The reversely zoned mantle on plagioclase macrocryst cores is explained by decompression and rapid ascent of crystal-laden melt into an upper crustal magma chamber (1-5km depth). The compositions of macrocryst rims and ground mass plagioclase imply that the final stage of PUB emplacement involved mixing of yet more evolved melt with the resident sub-volcanic melt and An-rich plagioclase in the upper crust, triggering fissure eruptions. Sorting driven by crystal-melt density contrasts in the sub-volcanic plumbing system led to an up-section decrease in modal contents of both plagioclase (early high - due to flotation) and clinopyroxene (late low - due to sinking) as the flow group was erupted. PUBs hold a potential key to understand the dynamics of magma storage, transport and evolution within the oceanic crust.

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Author Index

AUTHOR INDEX

AUTHOR INDEX

AUTHOR INDEX

Photo: Fredrik Holm

NORDVULK

THE NORDIC VOLCANOLOGICAL CENTER, INSTITUTE OF EARTH SCIENCES, UNIVERSITY OF ICELAND

NORDVULK is a nordic research center specializing in volcanology and related fields. The center is co-financed 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, an institute of more than 60 staff members. Within the Nordic countries the Institute of Earth Sciences prominent in disciplines such as volcanology and plate tectonics, and furthermore holds special expertise in climatology, glaciology, sustainable environments and geothermal processes.

NORDVULK was established to enhance Nordic research and educational collaboration in dynamic geology, focusing on volcanology and plate tectonics. The NORDVULK fellowships for young researchers provide nordic geoscientists with an opportunity to participate in studies of such active processes during their early carrier (PhD stdies or Post Doc level). NORDVULK furthermore offers opportunities for established senior researchers within the Nordic countries, as either short term hosting (sabbaticals) or 4-year contracts.

NORDVULK'S RESEARCH PROGRAMME

The current research programme at NORDVULK is focused on volcanic processes and eruptive products, crustal structures, tectonic processes, and environmental effects of eruptions. The activities include among others seismology, structural geology, geodetic measurements of crustal deformation, geophysical studies of crustal structures, physical volcanology, petrology and geochemical studies, distribution of volcanic products, geo- and tephrochronology, morphology, water-rock geochemistry, geochemical variations within volcanic and seismic zones, environmentally related effects of volcanic eruptions, and paleoclimatology based on soil, sediment and ash profiles.

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Positions are available to nordic citizens or residents for a 1 or 2 year initial period, with the possibility of extension up to three years in total. Candidates are required to hold a degree in geoscience. Nordic PhD students in geoscience are particularly encouraged to apply for the research fellow positions. It is the intention that a research stay at NORDVULK can be incorporated as part of the requirements towards earning a PhD degree at a Nordic home university. The employment period preferably starts June 1, allowing time for an initial field season. Salaries are according to Icelandic regulations. NORDVULK covers project related expenses, one trip to the applicants home country per year, as well as annual expences for attending international conferences and/or summer schools.

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AUTHOR INDEX




AUTHOR INDEX

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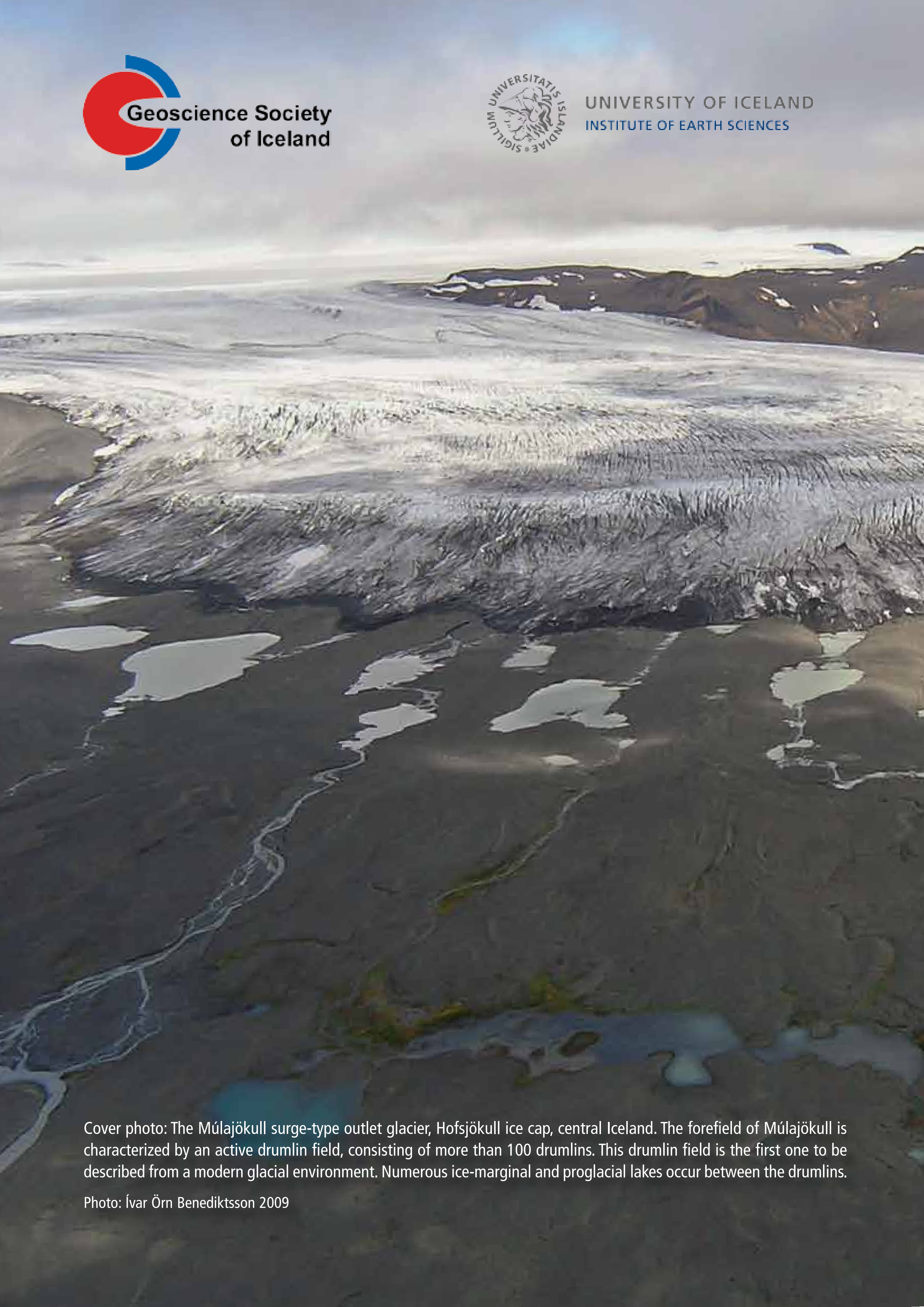

Cover photo: The Múlajökull surge-type outlet glacier, Hofsjökull ice cap, central Iceland. The forefield of Múlajökull is characterized by an active drumlin field, consisting of more than 100 drumlins. This drumlin field is the first one to be described from a modern glacial environment. Numerous ice-marginal and proglacial lakes occur between the drumlins.

Photo: Ívar Örn Benediktsson 2009