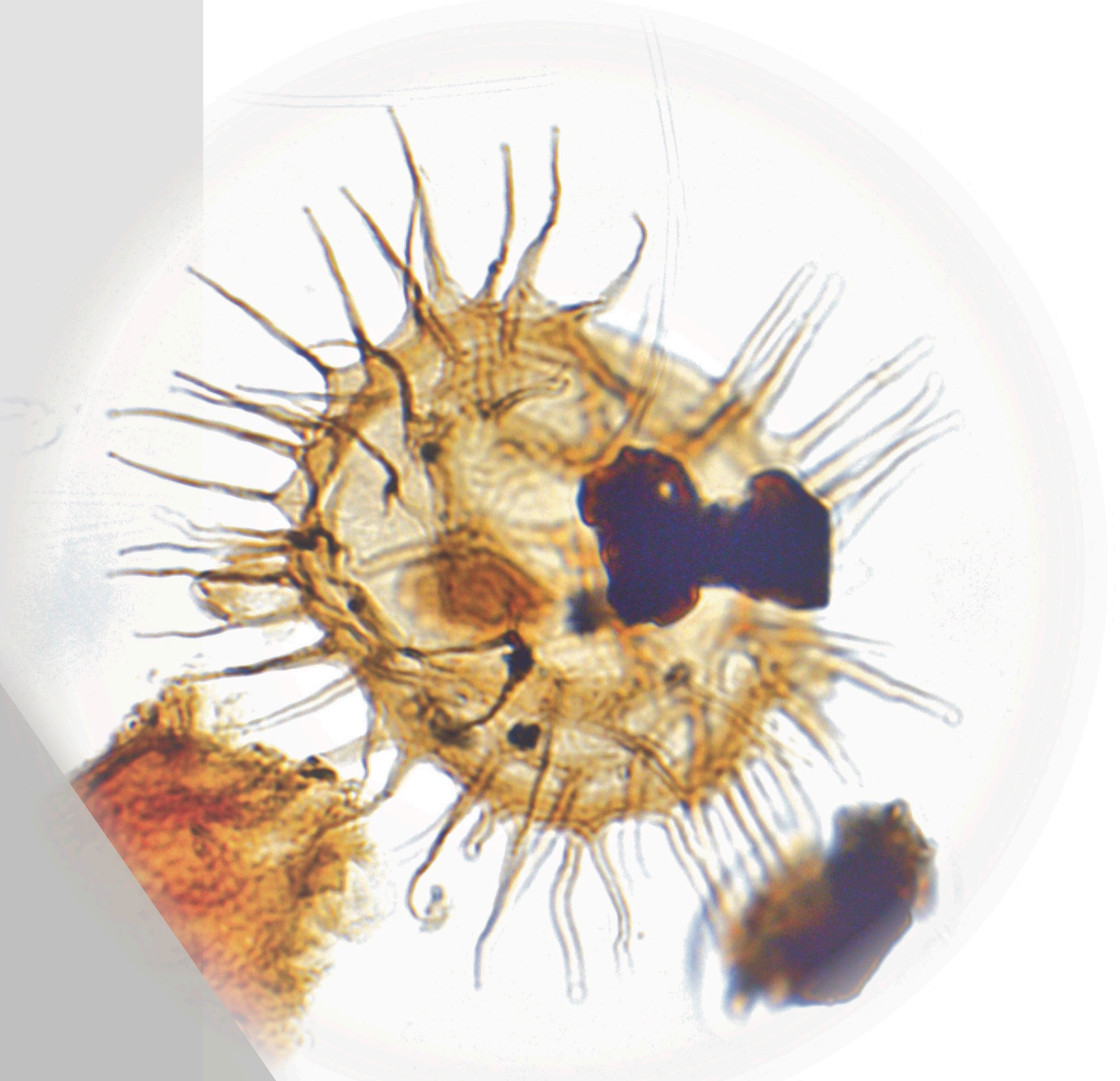
CEED

ANNUAL REPORT 2020



UiO : The Centre for Earth Evolution and Dynamics
University of Oslo

Above: *CEED members and guests gathered on the 6th of March 2020 for a scientific symposium at the Natural History Museum, University of Oslo. This was six days before the University of Oslo and the rest of the Norwegian society closed down due to the Covid-19 pandemic. Photo:* ***Carmen Gaina.***

Front cover: *Dinoflagellates identified in rock clasts collected from the Lusi eruption crater, Indonesia. A palynological study, conducted on a suite of erupted clasts, reconstructs the local stratigraphy. Some of these clasts originate from the deep (~ 4.5 km) organic-rich formation, that was exposed to anomalously high temperatures (higher than 230°C). Magmatic intrusion from the neighbouring Arjuno-Welirang volcanic complex induced the ongoing generation of large amounts of hydrocarbons, as demonstrated by palynological analysis, vitrinite reflectance, and chlorite and carbonate Raman microthermometry. This study was published in Scientific Reports (Nature) by CEED PhD student* ***Alexandra Zaputlyaeva*** *(graduated in December 2020), as one of the results of ERC Starting grant LUSI LAB (PI CEED Researcher Dr.* ***Adriano Mazzini****). Lusi represents a modern analogue of the paleo hydrothermal vent system that released large amount of volatiles to the atmosphere. CEED has been studying this system for better understanding the environmental impact of volcanism. Report cover design:* ***Fabio Crameri****, CEED.*

Back cover from the top:

1. ***Adriano Mazzini*** *on the SENECA expedition to the Dry Valleys of Antarctica. SENECA: SourcE and impact of greeNhousE gasses in AntarctiCASourcE and impact of greeNhousE gasses in AntarctiCA).*
2. *The Bygdø formation at Bygdø, Oslo seen from the air. Field work and drone photo by* ***Henrik H. Svensen***
3. ***Morgan Jones****, Anna Sartell (UNIS), Teresa Moszka (UNIS),* ***Lars Eivind Augland*** *and Valentin Zuchat (UiO) on the way to field work in Barentsburg and Festningen, Svalbard. Photo:* ***Sverre Planke***

PRIMARY OBJECTIVE:

Develop an Earth model that explains how mantle processes drive plate tectonics and trigger massive volcanism and associated environmental and climate changes throughout Earth history

SECONDARY OBJECTIVES:

(1) Build a consistent global plate tectonic model for the past 1100 Ma

(2) Explore how palaeogeography and True Polar Wander have influenced the long-term climate system

(3) Develop models that link surface volcanism with processes in the deepest mantle

(4) Develop models that link subduction processes in arcs and collision orogens with the mantle

(5) Understand the role of Volumeinous intrusive and extrusive volcanism on global climate changes and extinctions in Earth history

(6) Develop models for mantle structure, composition and material properties

(7) Understand similarities and differences between the Earth and the other terrestrial planets

(8) Develop tools and databases that integrate plate reconstructions with geodynamic and climate modelling

CEED is dedicated to research of fundamental importance to the understanding of our planet, that embraces the dynamics of the plates, the origin of large scale volcanism, the evolution of climates and the abrupt demise of life forms.

This ambitious venture shall result in a new model that explains how mantle processes interact with plate tectonics and trigger massive volcanism and associated environmental and climate changes throughout Earth history.

ACHIEVEMENTS IN 2020

CEED produced **111** publications in international journals, and **seven** books / book chapters. This includes **12 papers in high-impact journals, three of them** with CEED personell as the **first autor**

Five PhD students sucessfully defended their PhD projects: **Björn Heyn** (31.01)**, Dmitrii Zastrozhnov** (01.07)**, Eivind Straume** (18.07)**, Joost van den Broeck** (23.11), and **Alexandra Zaputlyaeva** (04.12)

Professor **Clinton (Clint) Conrad** was awarded the Evgueni Burov Medal by the International Lithosphere Program (ILP)

Stanford University compiled an overview of the world's most important researchers based on how often they are cited by others, and in which journals these citations appear. Professor **Trond H. Torsvik** is on the list of the two percent highest ranked in the field of *Geochemistry & Geophysics*

CEED conferred **the Else Ragnhild Neumann Award for** the third time. The 2020-award went to **Ágnes Király**, CEED

On 1st of March 2021, the Researchers **Sara Callegaro** and **Ágnes Király** received the CEED prize for young scientists for their acheivements in 2019 and 2020, respectively

CEED organization

Scientfic Advisory Board

Professor **Anny Cazenave**, LEGOS-CNES Toulouse, France

Professor **Claudio Faccenna**, Università Roma TRE, Italy

Professor **Per Barth Lilje**, Department of Astrophysics, UiO

CEED

Centre leader: Professor **Carmen Gaina**

Deputy Centre leader: Professor **Trond H. Torsvik**

Admin. leader: Dr. **Trine-Lise K. Gørbitz**

46 Professors, Adjunct Professors, Researchers and Research Associates

12 Postdocs

15 PhD fellows

6 Technical-administrative staff members

10 Master students

1 Professor emerita

2 Professor emeritus

In total:

75 paid staff members and 47 man-years representing 18 nationalities

Centre for Earth Evolution and Dynamics (CEED) was officially opened on 1st of March 2013. Our research includes the dynamics of tectonic plates and Earth history, convection in the mantle, structure of the deep Earth and the origin of mantle plumes and possible connections with large scale volcanism, climate changes through geological time, mass extinctions, and research on planets from our Solar System. To ensure that our scientific vision is effectively met, the activities have been carried out mainly within six research themes, each lead by a Team leader :

The Deep Earth (Team leader Reidar Trønnes, deputy Team leader Chris E. Mohn)

Earth Modelling (Team leader Clint Conrad, deputy Team leader Agnes Kiraly)

The Dynamic Earth (Team leader Valentina Magni, deputy Team leader Grace Shephard)

Earth Crises (Team leader Henrik Svensen), deputy Team leader Morgan T. Jones)

Earth and Beyond (Team leader Stephanie Werner, deputy Team leader Agata Krzesinska)

Earth Laboratory (Team leader Pavel Doubrovine, deputy Team leader Evgeniy Kulakov)

Photo on the left side from upper left:

*1. Dr. **Bjorn H. Heyn** with his main supervicor and the adjudication committee. From the left: Prof. Torgeir B. Andersen CEED, Prof. Allen McNamara, Michigan State University, main supervicor Prof. Clint Conrad, Dr. Bjorn H. Heyn, Prof. Anne Davaille, Paris-Sud University*

*2. Dr. **Dmitrii Zastronov** at his PhD party, flanked by his supervisors Professor Sverre Planke (left) and Professor-Jan Inge Faleide (right) at a reception organized by VBPR*

*3. Dr. **Eivind O. Straume** and his main supervisor Professor Carmen Gaina at a reception at CEED after his PhD defence*

*4. Dr. **Joost van den Broeck** flanked by two of his supervisors, Professor Carmen Gaina (left) and Dr. Valentina Magni (right) at a small gathering at CEED after his PhD defence*

5. Dr. Alexandra Zaputlyaeva and her main supervisor Dr. Adriano Mazzini at a small gatehring at CEED after her PhD defence

The Researchers ***Sara Callegaro*** *(to the left) and* **Ágnes Király** *(to the right) receivd the CEED Young Scientist prize for 2019 and 2020, respectively. The prizes were conferrerd by CEED`s Director* ***Carmen Gaina*** *during a celebration of CEED`s 8-years anniversary on the 1st of March 2021. Photo:* ***Trine-Lise K. Gørbitz***

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From the Director

CEED started 2020 with an active role in the 34th Nordic Geological Winter Meeting held at the University of Oslo in January 2020. More than 500 scientists from all Nordic countries attended the conference and CEED scientists organised and led 3 out of 19 sessions, with «Geodynamics, astrogeology and planetology» topic as a new flavour for this conference.

Despite the promising beginning, most group activities, expeditions, field work and mobility programmes had to be postponed or cancelled, one by one; the pandemics had a major impact on the "soul" of geoscientific research by limiting the possibilities to collect field data, visit and work with international teams and access necessary infrastructure.

While doing scientific research, one needs to be creative and patient, and luckily, every researcher has in her/his drawer a sample collection, data and ideas waiting to become published results. Therefore, in the pandemic year 2020, CEED continued to flourish and disseminate its results through publications, online courses, seminars and conferences, and to prepare the new generation of geoscientists.

As a clear demonstration of its scientific maturity, CEED researchers excelled in 2020 by publishing the highest number of articles (more than 10% of total publications) in high impact journals (*see pages 10-11*). Importantly, CEED Early Career Researchers (ECRs) were lead authors of 4 out of the 12 high-impact articles; one of these articles was authored by a CEED-only team (*Heimdal et al., 2020 published in Proceeding of National Academy of Sciences*), and two of them by ECRs-only teams (*Crameri et . al. a, b*, both published in *Nature Communications*). From the total number of papers published by CEED researchers in 2020, almost 25% were led by CEED ECRs, a truly remarkable achievement by a centre of excellence deemed to nurture the new cohort of scientists.

CEED research spans an incredible range of topics meant to contribute to an Earth model that can explain links between mantle structure and associated processes, and plate tectonics and massive volcanism responsible for a continuous changing Earth's paleogeography. In addition, CEED is ascertaining itself as the Norwegian leading group in comparative planetary sciences, which in turn brings fresh knowledge about the Earth's evolution as a young planet, and possible scenarios for an Earth devoid of water and atmosphere.

Two studies led by CEED Master student, Rebecca Karlsson, and PhD candidate Sruthi Uppalapati and their CEED colleagues from Earth and Beyond and Earth Modelling teams, used numerical modelling to explore scenarios of extreme plate tectonics on Venus. Their results may explain how the heterogeneous crust of present day Venus may have formed, and give an insight into the role of mantle convection modes for crust preservation through time on different planets, including the Earth (*Karlsson et al. , 2020 and Uppalapati et al., 2020, see page 54*).

Understanding the cyclicity of plate tectonics, named the "Wilson cycle" on Earth, is one of the primary scientific goal of our centre. Through the work of PhD student Joost van den Broek (*van den Broek, 2020*) an additional stage has been added to the classical Wilson cycle: the microcontinent formation. Joost's PhD work shed light on the re-distribution of continental crust due to rifting and ocean basin formation in the subduction tectonic setting (*van den Broek and Gaina, 2020*, *see page 38*). The precursor of the North Atlantic Ocean, the Iapetus Ocean, separated Baltica from Greenland/North America during an older Wilson cycle episode, and left geological hints in today's Scandinavia. By using this preserved information and a wealth of published data, postdoctoral fellows Drs. Hans Jorgen Kjøll and Boris Robert told the stories of Baltica margin formation and the analogy of the opening of the Iapetus Ocean with the Tethys Ocean, another ancient ocean whose remains are scattered in the Alpine-Himalayan mountain chain (*Kjøll, 2020 and Robert et al, 2020*, respectively, see page 60).

CEED's umbrella project, **Water Planet**, established since 2017, was continued in 2020 through intensive research activities that resulted in publications and new external projects. Due to the pandemics, planed seminars and staff mobility had to be postponed or cancelled, but CEED's contribution to this subject is nevertheless significant. For example, in a highly-cited paper, an international team including CEED Professor Clint Conrad, suggests that groundwater played a significant role in the Cretaceous sea-level variations (*Sames et al., 2020, see page 27*). This is an important result that brings to attention an important, yet poorly accounted, water reservoir, whose dynamics influences eustasy today, and did so in the geological past.

PhD student Eivind Straume, who completed his PhD thesis on global paleobathymetry (*Straume, 2020*), published a study where he modelled the evolution of oceanic gateways formed in the Northern Hemisphere for the last 65 million years (*Straume et al., 2020, see page 37*). His new model is used for simulating the dynamics of oceanic currents in the North Atlantic region at the time of climatic tipping points (*Straume et al., in review*).

Lastly, the water theme and its importance for geothermal energy was discussed in several publications resulting from an international project in Iceland where CEED Adjunct Professor Sverre Planke played an important role (*Kastner et al., 2020; Reiser et al., 2020; Millet et al., 2020*). This theme will also be explored in another geothermal energy promising region in the Romanian Carpathian mountains during the project Geysir-Baia Mare that started in 2020 (*Gaina et al., 2020*).

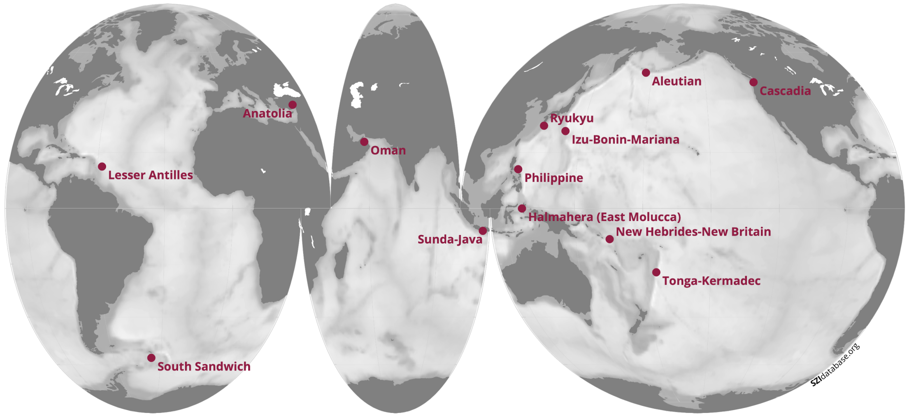
The year 2020 deprived us of the possibility to do intensive field work and meet our peers at conferences and research visits. But we continued our hard work in deciphering Earth and other planet mysteries, and CEED scientists saw their accomplishments rewarded by national and international grants and other recognition. CEED scientists were successful in proposing and getting approved new drill sites in the Scandinavian region by the prestigious International Ocean Discovery Programme (IODP) and International Continental Drilling Programme (ICDP); field campaigns are scheduled in 2021 (*see pages 46-47*). The project MAPLES (MAgma PLays with sedimEntary rockS), a Young Talented Researcher project granted to Dr. Sara Callegaro in 2019, was successfully started in 2020, and another postdoctoral fellow, Dr. Ágnes Király was awarded this prestigious Norwegian Research Council Grant in 2020 for her project ANIMA – ANIsotropic viscosity in MAntle dynamics. A particular mention and congratulations go to CEED Professor Clint Conrad, who received the Evgueni Burov Medal from the International Lithospheric Programme for his praiseworthy mid-career achievements.

Year 2020 was a global turning point, and it also brought changes to my professional life. To cite a close mentor of mine, leading a centre of excellence is enormously rewarding as it offers the opportunity to work with incredibly talented and dedicated people, including very bright and dynamic young researchers, and it is the most privileged position one can wish for in the academic world. I thank everyone who trusted and supported me in this role. In 2021 I will embark on a new quest where I can use this incredible experience for catalysing new endeavours that can equally benefit science and society. CEED, to be led by our founding Director T. H. Torsvik for its remaining two years, will remain my spiritual home.

Research Highlights 2020

1 Nature Communications

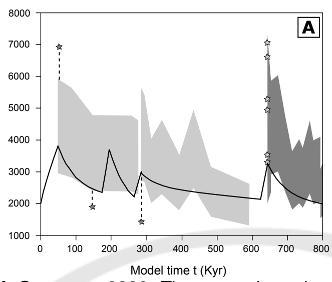
«The transdisciplinary subduction zone initiation database reveals that most events during the past 100 Ma were predated by collision events along a pre-existing subduction trench, horizontally forced, and proximal to a pre-existing subduction zone»



Fabio Crameri, Valentina Magni, Mathew Domeier, Grace E. Shephard, Kiran Chotalia, George Cooper, Caroline M. Eakin, Antoniette Greta Grima, Derya Gürer, **Ágnes Király,** Elvira Mulyukova, Kalijn Peters, **Boris Robert** & Marcel Thielmann. **2020.** A transdisciplinary and community-driven database to unravel subduction zone initiation. **Nature Communications, 11,** 3750, https://doi.org/10.1038/s41467-020-17522-9

2 PNAS

«This study explores the effects of thermogenic carbon release from CAMP using carbon cycle modeling, and shows that it represents a credible source for the negative CIEs observed around the T-J boundary»



Thea H. Heimdal, Morgan T. Jones, and Henrik. H. Svensen. 2020. Thermogenic carbon release from the Central Atlantic magmatic province caused major end-Triassic carbon cycle perturbations, **PNAS**, https://doi.org/10.1073/pnas.2000095117

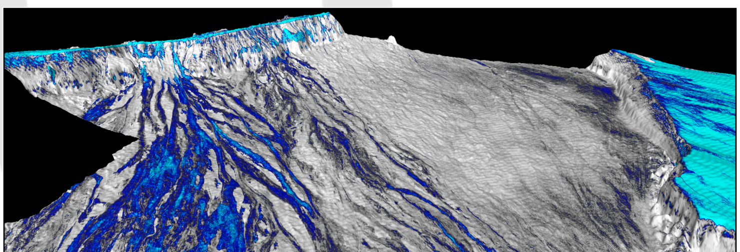
3 Nature Geoscience

«Laboratory Martian simulation experiments, reveal that in the red planet mud propagates like lava, similarly to the Hawaiian eruptions on Earth, forming the so-called pahoehoe flows. Many structures believed to be related to magmatic activity, may be in fact the result of sedimentary volcanism»

Petr Brož, Ondřej Krýza, Lionel Wilson, Susan J. Conway, Ernst Hauber, **Adriano Mazzini,** Jan Raack, Matthew R. Balme, Matthew E. Sylvest & Manish R. Patel. **2020.** Experimental evidence for lava-like mud flows under Martian surface conditions, **Nature Geoscience**, https://doi.org/10.1038/s41561-020-0577-2

4 Nature Communications

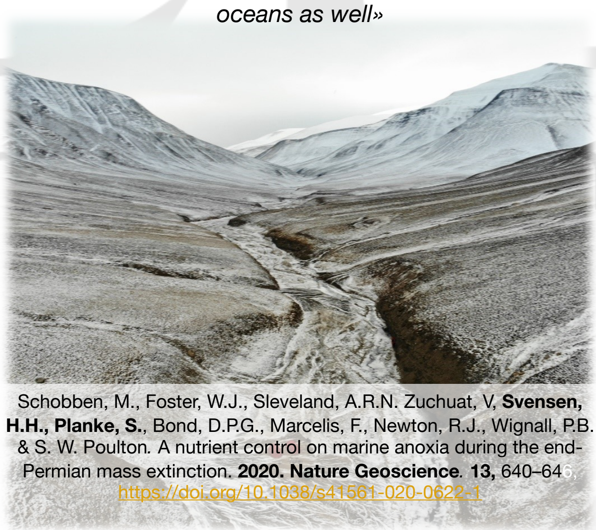
«In this paper we use 3D seismic data to document that meltwater discharge is an important sedimentary processes for construction of large-volume glacial fans, such as the North Sea Fan offshore mid-Norway»



Bellwald, B., **Planke, S.**, Becker, L.W.M. *et al.* Meltwater sediment transport as the dominating process in mid-latitude trough mouth fan formation. 2020. **Nature Communications, 11,** 4645, https://doi.org/10.1038/s41467-020-18337-4

5 Nature Geoscience

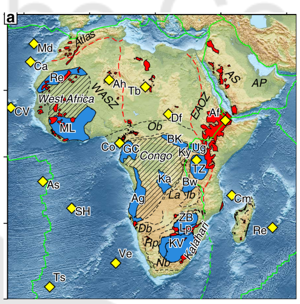
«This paper demonstrates the dramatic consequences initiated by large scale volcanism, with a severe effect not only on land, but in the oceans as well»



Schobben, M., Foster, W.J., Sleveland, A.R.N. Zuchuat, V, **Svensen, H.H., Planke, S.**, Bond, D.P.G., Marcelis, F., Newton, R.J., Wignall, P.B. & S. W. Poulton. A nutrient control on marine anoxia during the end-Permian mass extinction. **2020. Nature Geoscience. 13,** 640–646, https://doi.org/10.1038/s41561-020-0622-1

6 Nature Communications

«Here we show, using waveform tomography with a large, newly available dataset, that cratonic lithosphere beneath Africa is more complex and fragmented than seen previously»

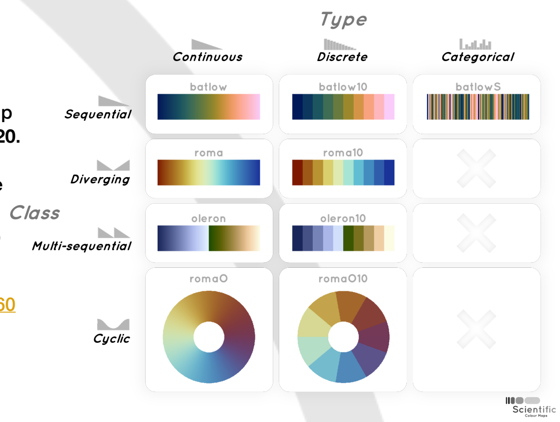


Nicolas Luca Celli, Sergei Lebedev, Andrew J. Schaeffer & **Carmen Gaina. 2020.** African cratonic lithosphere carved by mantle plumes, **Nature Communications, 11,** https://doi.org/10.1038/s41467-019-13871-2

7 Nature Communications

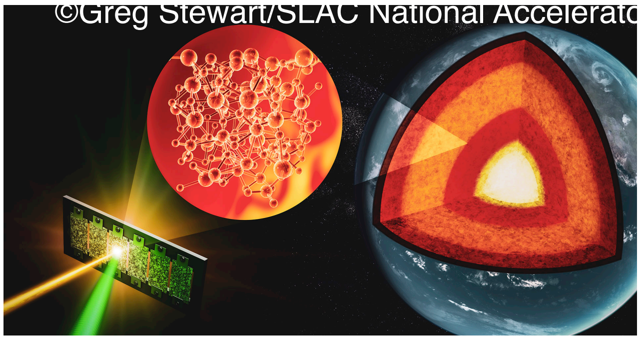
«While scientifically-derived colour maps are key to display data fairly and make it accessible to all interested readers, applying the suitable colour-map type and class allows for a more effective presentation of specific data sets.»

Fabio Crameri, Grace E. Shephard & Philip J. Heron, P.J. **2020.** The misuse of colour in science communication. Nat Commun 11, 5444.. https://doi.org/10.1038/s41467-020-19160-7



8 PNAS

«This article presents the first in situ structural measurements of dense liquid silicates at the conditions of the early Earth's deep magma ocean; the results support the long-lasting assumptions that dense silicate glasses are good structural analogues of the silicate liquids.»

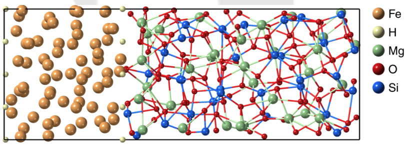


Guillaume Morard, **Jean-Alexis Hernandez**, et al. **2020.** In situ X-ray diffraction of silicate liquids and glasses under dynamic and static compression to megabar pressures, **PNAS**, https://doi.org/10.1073/pnas.1920470117

9 Nature Geoscience

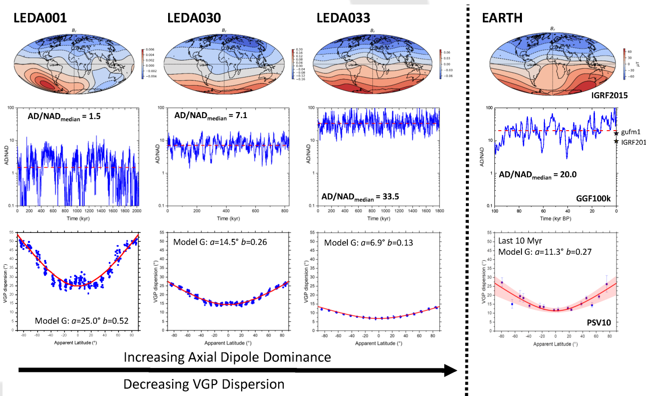
«A simulation of hydrogen partitioning between silcate melt (right hand side of top picture) and Fe melt (left hand side of top picture) showing that hydrogen strongly prefers to be in the Fe melt phase (lower picture), and so majority of the Earth's water should be in the core»

Yunguo Li, Lidunka Vočadlo, Tao Sun, **John P. Brodholt. 2020.** The Earth's core as a reservoir of water. **2020. Nature Geoscience**, https://doi.org/10.1038/s41561-020-0578-1



10 Nature Communications

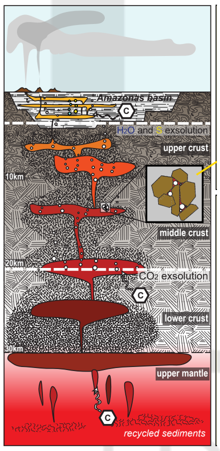
«Biggin et al. (2020) defined a power law relationship between geomagnetic secular variation and relative strength of the axial dipole term in the total field, used this relationship to estimate average levels of axial dipole dominance, and showed that a dipole-dominated geometry, has been a remarkably stable characteristic of the Earth's magnetic field through large parts of geologic time»



Andrew J. Biggin, Richard K. Bono, Domenico G. Meduri, Courtney J. Sprain, Christopher J. Davies, Richard Holme & **Pavel V. Doubrovine. 2020.** Quantitative estimates of average geomagnetic axial dipole dominance in deep geological time. **Nature Communications, 11,** 6100. https://doi.org/10.1038/s41467-020-19794-7

11 Nature Geoscience

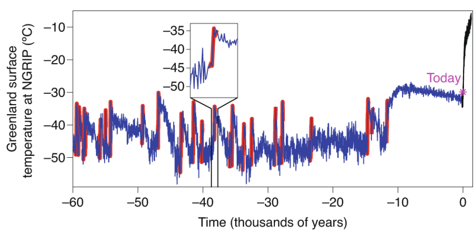
«Abundant CO_2 in gas exsolution bubbles within melt inclusions was found by Raman spectroscopy in basaltic rocks of the Central Atlantic Magmatic Province (CAMP), linked to the End-Triassic mass extinction. Part of the CO_2 released by CAMP magmas came from the mantle and/or the deep crust, adding to the already voluminous shallower carbon,thermogenically produced from volcanic basins»



Manfredo Capriolo, Andrea Marzoli, László E. Aradi, **Sara Callegaro,** Jacopo Dal Corso, Robert J. Newton, Benjamin J. W. Mills, Paul B. Wignall, Omar Bartoli, Don R. Baker, Nasrrddine Youbi, Laurent Remusat, Richard Spiess & Csaba Szabó. **2020.** Deep CO2 in the end-Triassic Central Atlantic Magmatic Province, **Nature Communications, 11,** https://doi.org/10.1038/s41467-020-15325-6

12 Nature Climate Change

«This Perspective uses observations and climate models to place contemporary Arctic change into the context of past abrupt Greenland warmings»



Eystein Jansen, Jens Hesselbjerg Christensen, Trond Dokken, **Kerim H. Nisancioglu,** Bo M. Vinther, Emilie Capron, Chuncheng Guo, Mari F. Jensen, Peter L. Langen, Rasmus A. Pedersen, Shuting Yang, Mats Bentsen, Helle A. Kjær, Henrik Sadatzki, Evangeline Sessford & Martin Stendel. **2020.** Past perspectives on the present era of abrupt Arctic climate change. **Nature Climate Change 10,** 714–721. https://doi.org/10.1038/s41558-020-0860-7

The origin, structure and dynamics of deep mantle domains, with a view to chemical exchange between the early molten mantle and the core, continued to be a main focus during 2020. In the remaining CEED term, we aim to consolidate our growing insights in this field. This wider objective is part of the more limited sub -theme 1.2 in the 2011 CEED proposal (Composition, mineral physics and origin of the LLSVPs). The subthemes 1.1 and 1.3 are partly related to 1.2 and have largely been addressed by the the Dynamic Earth and Earth modelling groups (Absolute reference frames and links to the deep mantle, temporal stability of the LLSVPs and triggering mechanisms for mantle plumes from the LLSVP margins). The three annual reports from 2017- 2019 presented our efforts to understand the origin and dynamics of various domains in the lower mantle, and their links to the chemical exchange between the core and the molten mantle. Here we review geochemical evidence for the existence of early refractory domains and present the results of a few specific ongoing projects.

Chemical exchange between the core and molten mantle

The cooling of large terrestrial planets like Venus and Earth, causing chemical exchange between the early silicate magma ocean (MO) and the protocore, and subsequently between the basal magma ocean (BMO) and the core, has important consequences for the chemical and mineralogical evolution of the lower mantle and core. The chemical exchange equilibrium:

$$2\,Fe^{metal} + SiO_2^{silicate} = Si^{metal} + 2\,FeO^{silicate}$$

is displaced towards the product (right) side with increasing temperature and reversed during planetary cooling (Trønnes 2019a and references therein). Consequently, a hot protocore with core-mantle boundary (CMB) temperatures of 5000-6000 K had likely high Si and low O content relative to the present core with a CMB-temperature of about 4000 K. Planetary cooling, which is still ongoing, would have promoted transfer of FeO (and Fe_2O_3) from the MO, BMO and the solid mantle to the core and SiO_2 in the opposite direction. A preservation of the molten mantle oxidation state necessitates oxide exchange, rather than elemental exchange of O and Si. Elemental loss of O from the MO, for example, would cause Fe-oxide reduction with accompanying Fe-metal alloy sinking into the core. Similarly, metallic Si diffusing from the core to the MO would be oxidised by accompanying Fe-oxide reduction, causing sinking of the precipitated Fe-metal into the core. The chemical effect of FeO-SiO_2 exchange between the MO or BMO and the core is elevated Si/(Mg+Fe) and Mg/Fe ratios of the molten mantle, promoting and prolonging the early crystallisation of $MgSiO_3$-rich bridgmanite and suppressing ferropericlase crystallisation.

Whereas liquid state FeO-SiO_2 exchange between the MO-BMO and the core would be efficient, the corresponding exchange involving the currently solid lowermost mantle is limited by the low diffusion rate of major elements in the ferro-magnesian minerals, and especially in bridgmanite. A long-lived BMO might have persisted into the Proterozoic, or possibly even the Phanerozoic, leaving ample time for the exchange. Even today, the outer convecting core is undersaturated with oxygen (Trønnes et al. 2019a).

Early refractory domains (ERD) of bridgmanitic compositions

The Hadean solidification of the MO and parts of the BMO started with extensive crystallisation of $MgSiO_3$-rich bridgmanite (bm) above and below a neutral buoyancy level at about 1800 km depth in the Earth (Figure 1.1; Trønnes et al. 2019a,b). The convection pattern in the rapidly rotating and mostly molten Earth is expected to cause planar equatorial outflow and columnar polar inflow (CEED 2019 Ann. Rep.; Maas and Hansen, 2019; Trønnes 2020a). Therefore, the early bridgmanitic cumulates would probably have formed two neutrally buoyant hemispheric shells penetrated by inflow along the rotation axis. After rapid solidification

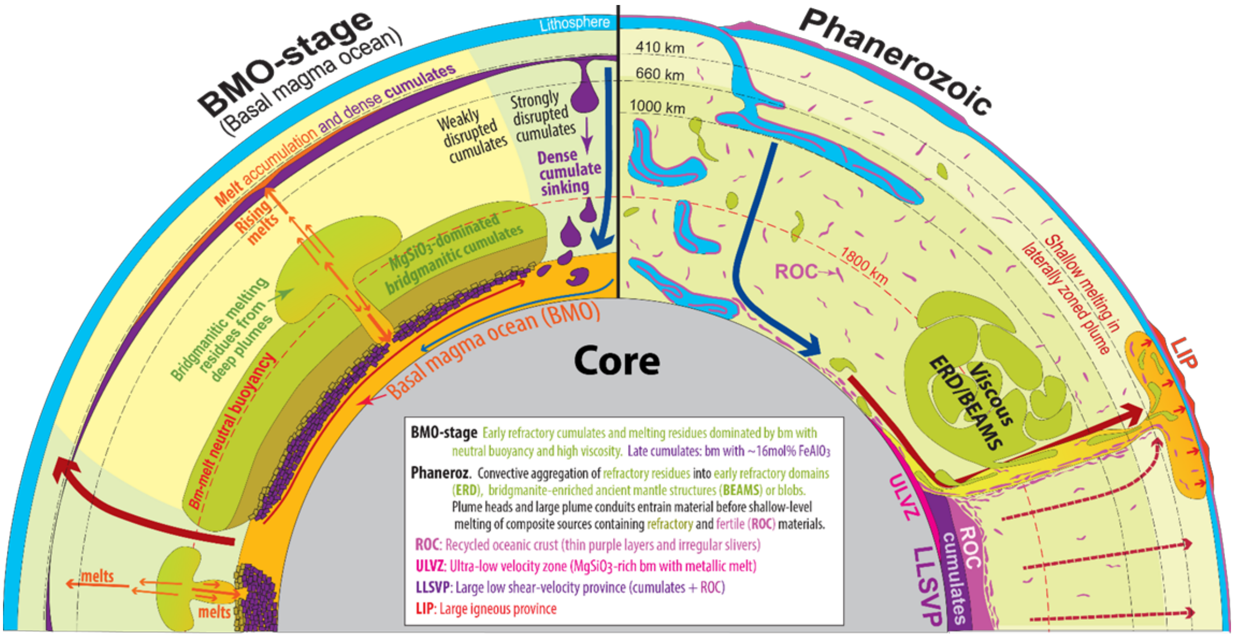


Figure 1.1. Schematic cross-sections of the Earth during an intermediate BMO stage (left) and during the Phanerozoic (right). The initial $MgSiO_3$*-dominated bridgmanitic cumulates will accumulate at a neutral buoyancy level, probably in the 1700-2200 km depth range. Additional residues from extensive partial melting above the basal magma ocean at a slightly later stage would also rise and accrete to these early refractory domains (ERD). In the solid mantle the ERDs are expected to be neutrally buoyant at slightly shallower levels in the middle of the lower mantle, and convective aggregation of the highly viscous bridgmanitic domains may lead to Mm-sized BEAMS (Ballmer et al. 2017). Very low concentrations of U and Th, and suitable diffusion rates for He and Ne in bridgmanite, make the ERDs/BEAMS favourable reservoirs for He and Ne with primordial-like isotopic composition. Such high-viscosity refractory domains will tend to resist convective shearing and mixing with the surrounding mantle but may be partially entrained into deep-rooted, vigorous plumes.*

of the MO above the neutral buoyancy level (in about 5-50 My), the global convection pattern of the mostly solid mantle would likely change into two antipodal outflow columns in the equatorial plane and a sheet-like longitudinal (circumpolar) inflow. The redistributed early bridgmanitic domains, neutrally buoyant in the middle part of the lower mantle, would then be mostly confined to two ring-shaped zones peripheral to the antipodal equatorial outflow columns (Trønnes 2020a). Additional accretionary contributions to such refractory bridgmanitic domains would be residues from extensive partial melting in hot plumes rising from the ceiling of the BMO. Ballmer et al. (2017) emphasised the feasibility of convective aggregation of such early refractory and high-viscosity material into Mm-sized "bm-enriched ancient mantle structures" (BEAMS). Figure 1.1, which is an updated version of Figure 1.2 in the CEED 2017 Annual Report, illustrates the Hadean origin of the early bridgmanitic cumulates and residues and their present distribution as early refractory domains (ERD) or BEAMS.

The geophysical signals from such neutrally buoyant ERDs are expected to be weak. CEED-based seismic tomography compilation efforts by the Dynamic Earth Researcher Grace Shephard (Shephard et al. 2020) are promising, but not yet conclusive (see also CEED 2019 Ann. Rep.). The geochemical evidence from the short-lived ^{146}Sm to ^{142}Nd decay system (half-life of 103 My) for ERD material entrained into deep-rooted and vigorous plumes is still somewhat tenuous, mostly due to the very limited $m^{142}Nd$-range, which is only about 0.25%

of the m^{143}Nd-range (Figure 1.2, lower panel; Trønnes 2020b). The subtle deviations from the homogenised terrestrial composition in the ^{142}Nd/^{144}Nd ratio, expressed as μ^{142}Nd (Figure 1.2), requires measurement with high accuracy and precision. Although the development of the Thermo-Finnigan "Triton" mass spectrometer about 20 years ago facilitated a significant improvement of such measurements, the analytical uncertainty envelope may still conceal potential anomalies. Positive μ^{142} Nd anomalies in the 62 Ma Baffin Island basalts generated in the Iceland plume head, 123 Ma Ontong Java basalts and in the present-day Loihi seamount and Ofu basalts from the Hawaiian and Samoan plumes, respectively (Rizo et al., 2016; Horan et al, 2018; Figure 1.2) may therefore be only the first Nd-isotopic evidence for deep-rooted plume entrainment of ERD material.

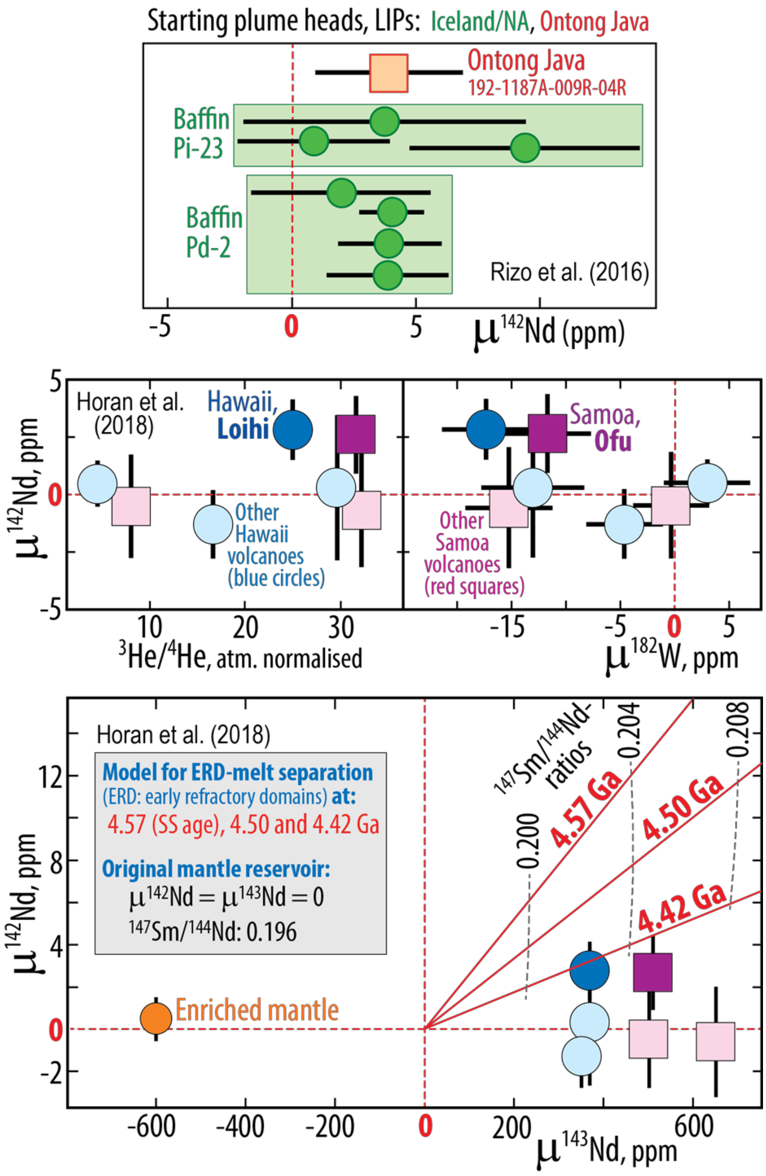


Figure 1.2. Evidence for early refractory domains, based on ^{146}Sm-^{142}Nd decay systematics (half-life: 103 Ma). The m-values for the ^{142}Nd/^{144}Nd, ^{143}Nd/^{144}Nd and ^{182}W/^{184}W ratios (R) are $m(R) = 10^6[(R/R_{standard}-1)]$. The corresponding e-value, commonly used for e.g. the ^{143}Nd/^{144}Nd ratio, is $e(R) = 10^4[(R/R_{standard}-1)]$, therefore: $e^{142}Nd = m^{142}Nd/100$. Each symbol with 2s error bars in the middle and lower panels represents an average with error bars of 3-5 samples from the same volcanic system. The ^{3}He/^{4}He ratios are normalised to the atmospheric ratio. SS: Solar system.

Sm and Nd are both incompatible in bm and partitioned into coexisting melt, but because Sm is five times more compatible than Nd, the resulting high Sm/Nd-ratio in bridgmanitic ERDs will develop high μ^{142}Nd during the Hadean. The model for separation of melt from ERD material, followed by radiogenic ingrowth of Nd in μ^{142}Nd-μ^{143}Nd space, shown in the lower panel of Fig. 1.2, indicates that the refractory bridgmanitic cumulates and/or residues, sampled by the Loihi Seamount (Hawaiii) and Ofu (Samoa) basalts, formed 150-250 Ma after Solar system initiation at 4.57 Ga (U-corrected Pb-Pb dating of Ca-Al-inclusions in carbonaceous chondrites give an accurate age of 4567 Ma).

As shown in the middle panel, the positive μ^{142}Nd values of Loihi seamount and Ofu are matched by high ^{3}He/^{4}He ratios and negative μ^{182}W values. Samples from Reunion, not reproduced here, display an analogous positive correlation between μ^{142}Nd and ^{3}He/^{4}He ratios (Peters et al., 2018). The negative μ^{182}W values are most likely a result of core metal contamination of the deepest parts of the plume roots, via the ultra-low velocity zones (e.g. Mundl et al., 2007; Mundl-Petermeier et al., 2020). Even if the He- and W-isotopic signals are found in the same plume basalt, their sources may well be decoupled. Based on ab initio determination of diffusion rates for He and Ne in bridgmanite, we have developed a model for plume entrainment of ERD-material in the mid-lower mantle (Trønnes et al., 2018; in prep.). The matching He- and W-isotopic signals seem to characterise deep-rooted and vigorous plumes, facilitating the entrainment of tiny fractions (0.1-0.3%) of core metal (Mundl-Petermeier et al. 2020) via the ULVZ root zones, as well as larger fractions of ERD material from a wider depth range in the middle of the lower mantle.

The importance of Ca-perovskite in the LLSVPs and ULVZs

Multifaceted ab initio atomistic simulations to determine the melting curve of Ca-perovskite ($CaSiO_3$) through the lower mantle pressure range have revealed a strongly increasing thermal stability with increasing pressure (based on results from a CEED Master project (Guren et al. in prep.). This finding is in accordance with the results from experimental melting investigations on natural basaltic and peridotitic compositions, as well as compositions in the system MgO-SiO_2. Some of the preliminary results were presented in the CEED 2017 Annual Report. The highly residual character of Ca-perovskite (cpv) during partial melting of basaltic and picritic lithologies and during fractionation of evolved BMO melts, combined with its high density, may have profound implications for the geochemistry and distribution of heat producing elements in the lower mantle. This is because the heavy large-ion lithophile elements, and especially U, Th and the lanthanides are highly compatible in cpv, with mineral-melt partitioning coefficients exceeding 10 (Corgne et al. 2005).

The continued bm-crystallisation at the BMO-ceiling will steadily enrich the residual melt in Al, Ca and Na, setting the stage for precipitation of cpv and the Al-Na-rich Ca-ferrite structured phase. The latter mineral has an appropriately low density to accumulate along with moderately Fe-enriched bm at the BMO-ceiling, whereas the high density of cpv would have made it sink into the hot (and dense) BMO-melt to dissolve again. Our BurnMan calculations demonstrate that cpv has similar density to bm with 16 mol% of the combined Fe-components $FeAlO_3$ and $FeSiO_3$ (Trønnes et al. 2019b). This is also our estimated bm-composition for the base layers of the LLSVPs, based on the density excess inferred from normal-mode, free-air gravity, tidal tomography and mineral physics constraints (Ishii and Tromp, 1999, Lau et al. 2017; Trønnes et al. 2019a). The strong Fe-partitioning to melt relative to the ferromagnesian minerals, bm and ferropericlase, implies that the BMO melt density will likely exceed that of the minerals throughout most or all of the BMO solidification. At the stage when bm with 16 mol% combined Fe-components would crystallise and accumulate at the BMO ceiling, significant amounts of cpv would also co-precipitate there. If these cumulates were later swept into the root-zones of the two antipodal outflow columns in the equatorial plane, the excessive ^{4}He production in cpv would *exclude* the resulting LLSVP base layers as candidate reservoirs for primordial-like He. Similarly, accumulations of recycled oceanic crust (ROC) of basaltic or picritic compositions would also contain large proportions of Ca-perovskite and be unsuitable primordial-like He reservoirs.

A third reservoir which has been suggested as the source of the coupled high ^{3}He/^{4}He ratios and negative m^{182}W anomalies, is the core, via the ULVZs. The high density and highly residual nature of cpv during partial melting of basaltic to picritic lenses or slivers of ROC, however, might concentrate cpv in the ULVZs, *excluding also these domains* as possible sources of primordial-like He. Dense ROC slivers are expected to sink slowly in the lateral D" flow towards the LLSVP margins and their relatively low solidus temperatures (Pradhan et al. 2015; Liu et al. 2016; Tateno et al. 2018) may cause partial melting in the hottest areas near the ULVZ surfaces at the LLSVP margins. Our new ULVZ-model (based on results from a CEED Master 0roject, Guren et al. in prep.) involves partial melting of ROC-slivers with differential sinking of immiscible metallic and dense silicate melts and residual cpv, combined with ascending Fe-depleted bm, silica and possibly even small amounts of the the Ca-ferrite structured phase, which is the first phase to disappear during progressive melting. This model prescribes dense cpv as the main ULVZ-mineral. The interstitially distributed silicate melt may be denser than or close to neutral buoyancy with cpv, whereas the denser immiscible metallic melt might slowly trickle through to the core. However, despite their limited thickness (generally <40 km), the ULVZs are likely to have vigorous convection with average convective velocity exceeding the melt percolation velocity (Hernlund and Jellinek, 2010; Lay, 2015). Our model favours the core and the hydraulically linked ULVZs as the source reservoirs for tiny contaminating metallic fractions producing the negative m^{182}W anomalies observed in deep-rooted plume basalts (Mundl-Petermeier et al., 2020). Due to the high densities of cpv and interstitial metallic melt, combined with convective vigour, the ULVZs may be continuously replenished from above and and from below and represent "partially open windows" between the core and the D" zone. Deep-rooted plume sampling of such CMB "mixing pots" can also explain the elevated ^{129}Xe/^{136}Xe ratios measured in gas-rich olivine inclusions in Iceland and in CO_2-dominated springs in the Eifel area.

Silicate liquids and glasses under dynamic and static compression to Mbar pressures

Sampling the physical properties of liquid silicates at the conditions of the lower mantle is crucial for understanding early differentiation events and the present-day core-mantle boundary. However, the high temperatures (> 4000 K) required to melt silicates at 100 GPa make conventional experimental approaches in diamond anvil cell extremely difficult. In the framework of a large international collaboration, we carried out novel laser-driven shock experiments combined with ultrafast X-ray probes at the Linac Coherent Light Source (LCLS) X-ray free electron laser facility (Menlo Park, CA, USA). In particular, we performed ultrafast X-ray diffraction to measure the structure of shock-compressed $MgSiO_3$ glass and orthoenstatite up to ~300 GPa and 8000 K.

As is typical for such experiments at the nanosecond scale, we found that neither bridgmanite nor post-perovskite form in shocked $MgSiO_3$ glass and shocked enstatite. Instead, we observed a dense disordered (amorphous or liquid) structure, persisting both below and above the equilibrium melting line. This structure is similar to the dense glass obtained in statically compressed $MgSiO_3$ glass at 300 K and validates the widely-used assumption, never demonstrated at high-pressure, that silicate glasses are good structural analogues of silicate liquids. Moreover, temperature measurements in plate-impact experiments (microsecond scale) indirectly suggests that these high-pressure polymorphs may form at longer time-scales. The absence of bridgmanite or post-perovskite crystallization from the dense amorphous phase at nanosecond-scale thus also constrains the crystallization of those phases to occur between ten and a few hundred nanoseconds, which is two order of magnitude lower than the crystallization kinetics of stishovite in SiO_2, revealing fundamental differences between these two systems possibly due to the presence of Mg cation affecting the structure of the Si-O-Si network. These findings were published by CEED Postdoc **J-A. Hernandez** and collaborators in Morard et al. (2020) and Hernandez et al. (2020).

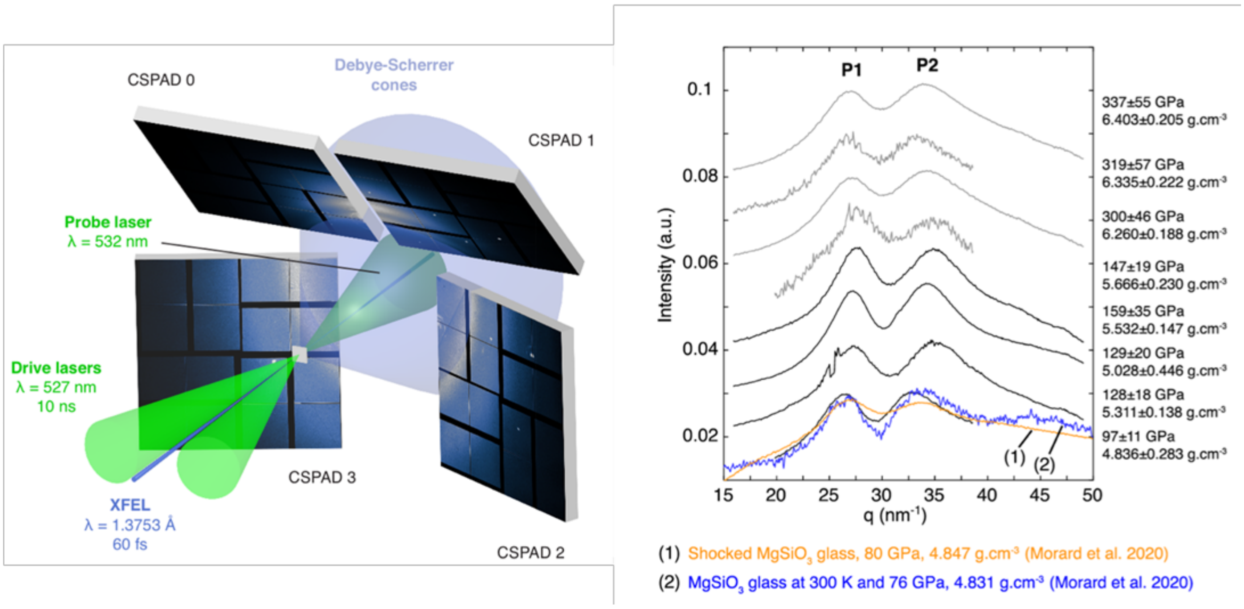


Figure 1.3. *Left: The experimental setup. Two drive lasers generate a shock wave that increase both pressure and temperature into the sample (small grey square). During the few nanoseconds of the compression, an ultrafast and intense X-ray pulse (blue beam) is used to probe the structure of the shocked sample by X-ray diffraction. The diffraction signal is recorded on four different detectors (CSPADs). Right: Integrated diffraction spectra of* $MgSiO_3$ *enstatite shocked up to 337 GPa in the liquid state (black and grey lines). As shown by the blue and orange lines, the spectra are similar to the ones obtained in shocked* $MgSiO_3$ *glass and in statically compressed* $MgSiO_3$ *glass at 300 K. Figures from Hernandez et al. 2020.*

Magma Oceans in Terrestrial Planets.

In a computational effort spanning several years we model the evolution of the terrestrial global magma ocean from its formation until its full crystallization. The major components of the starting composition, whose proxy is called pyrolite or bulk silicate Earth, lie in a six-dimensional chemical space: Na_2O – CaO – Al_2O_3 – FeO – MgO – SiO_2. During the cooling of the magma ocean, Fe-bearing bridgmanite is the first mineral phase that crystallizes. Ab initio molecular-dynamics simulations by CEED Adjunct Professor R. Caracas and collaborators suggest the neutral buoyancy at middle depths in the global magma ocean (Caracas et al., 2019) contribute to the separation of a dense basal magma ocean. The densification of the magma with depth is almost entirely due to more efficient packing at the atomic level (Solomatova and Caracas, 2019; Kobsch and Caracas, 2020). The presence of volatiles rendered the melts more buoyant, enhanced convection and turbulence, and thus promoted the chemical exchanges of the magma ocean with the early atmosphere (Solomatova and Caracas, 2020). Deep Earth members also collaborated with other CEED teams, among other studies they have contributed to the PhD project of **Krister Karlsen** (Earth Modelling) and common publications.

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The Earth Modelling Team employs a variety of modeling techniques to understand the geodynamics of Earth's lithosphere and mantle, with an overall goal toward deciphering the relationship between mantle dynamics, plate tectonics, and the Earth's surface environment over Earth history. In 2020 the group was active in a wide variety of projects including: plumes originating from the edges of thermochemical piles in the lower mantle and impinging on continental lithosphere near the surface, tectonic plates interacting with mantle convection, viscosity anisotropy influencing a variety of geodynamic processes, analogue modeling of subduction processes, reconstructions of long-lost seafloor, seismological imaging of Scandinavia, and glacial isostatic adjustment in Greenland. We have also contributed to broader efforts in education, methodological advances in geodynamic modeling, and scientific visualization.

Most of the world experienced new challenges in 2020, and the Earth Modelling team was no exception. We travelled less, set up home offices, and communicated by Zoom, but nevertheless we had a productive year. Some projects required major changes (e.g., the MAGPIE fieldwork in Greenland had to be postponed), but our computer models were not constrained by the year's events, and we published some important papers. In addition, we enjoyed some exciting events:

- Björn Heyn defended his PhD in January.
- Clint Conrad was awarded the Evgueni Burov Medal in May.
- Ágnes Király was awarded the Else-Ragnhild Award and an NRC grant in December.
- Fabio Crameri published two papers in Nature Communications.

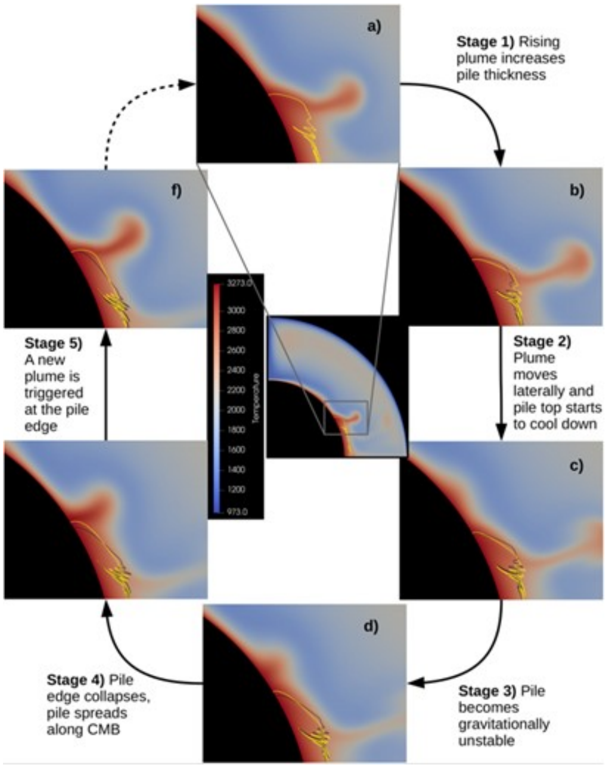
The Earth Modelling Team has continued to further the overall goals of CEED. For example, the observation that plumes rise from the margins of the LLSVP zones is a foundational aspect of CEED. Björn Heyn's PhD research, completed in 2020, now explains the physical process by which this occurs (Figure 2.1 next page). Another fundamental goal of CEED is to understand the link between tectonics and the deep mantle. This year, PhD student **Krister Karlsen** used plate tectonic reconstructions to show that tectonic plate motions at the surface have likely released significantly more heat from the Pacific side of the plate, compared to the African side (Figure 2.4 below). Such variations have likely caused hemispheric temperature variations within the mantle of up to ~150°C during the past 400 million years. This hemispheric dichotomy may explain the dramatically different tectonics of the two hemispheres and represents a fundamental component of recent Earth history. As we look forward to an exciting 2021, here is a brief synopsis of the Earth Modelling Team's most important activities from 2020.

Plumes throughout the mantle: from initiation to interaction with lithosphere

Seismic imaging of the Earth's mantle shows that mantle upwellings, also known as mantle plumes, most likely originate at the core-mantle boundary. In particular, plumes seem to preferentially rise from margins of the large low shear velocity provinces (LLSVPs), which are thought to be piles of dense and viscous material that are stable at the base of the mantle.

Former PhD student **Björn Heyn** (defended his PhD thesis on January 31, 2020) has shown how the presence of such thermochemical piles can initiate the formation of plumes at their margins by a cycle of viscous drag and gravitational collapse of the thickened pile (Figure 2.1). This interaction results in an almost periodic behavior (Heyn et al., 2020a). He also showed that plume formation is accompanied by short-wavelength deformation of the core-mantle boundary associated with stresses trapped outside the pile margin (Heyn et al., 2020b).

Such depressions of the CMB may be detectable by seismic waves, which could eventually help us better understand the phases of this newly-discovered plume cycle.



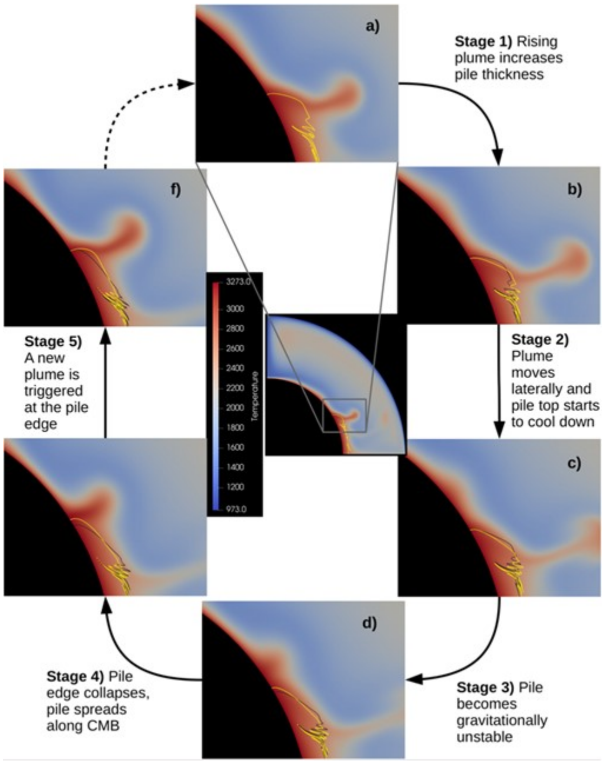


Figure 2.1. Cycle of plume formation at the CMB. Models showing temperature (colors) for different stages of the plume cycle. Plumes that rise from the CMB typically do so from the edge of the LLSVPs (yellow outline, grey outline is from previous step). As they rise, they pull the dense LLSVP upwards (b) but later drop it (d) as the upwelling diminishes. The spreading LLSVP then initiates the next plume (f).

Following his PhD defence, CEED Postdoc **Björn Heyn** has worked to understand the interaction between plumes and the lithosphere. This project, funded by the European Space Agency (ESA), focuses on the heat flux and the lithosphere thinning associated with the arrival of the plume. Preliminary results indicate that significantly elevated heat flux is only possible if the plume is able to erode the base of the lithosphere considerably. This erosion happens via small -scale convection caused by the hot rising plume material, and results in drips of cold lithosphere sinking through the upper mantle. Thus, the factors that control the lithosphere thinning, such as the viscosity of the asthenosphere and/or lower lithosphere, or the plume excess temperature, also control the heat flux anomaly at the surface (Figure 2.2).

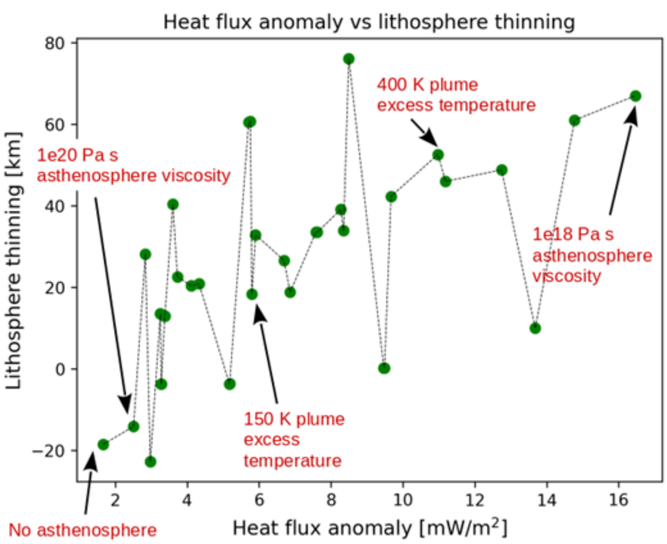


Figure 2.2. Relationship between heat flux and lithospheric thinning. Models (green dots) with different parameter show that greater lithospheric removal leads to larger heat flux anomalies at the surface.

How long do plume heads take to rise through the mantle?

While there have been some recent estimates of slab sinking times through the mantle, few constraints exist for plume head rise times. Yet, both are important for understanding time-scales of material cycling in the mantle.

Adjunct Professor **Bernhard Steinberger** and collaborators use a new approach to constrain plume rise time based on the observation that hotspots, caused by mantle plumes, seem to preferentially occur above the margins of Large Low Shear Velocity Provinces (LLSVPs).

They asked the question: For which plume head rise times can this correspondence between plumes and LLSVP margins be maintained for the locations where plume heads started rising through the mantle? Because flow in the high-viscosity lower mantle tends to divert plume heads *towards* the LLSVPs (Figure 2.3), we find that plumes with longer rise time end up the further away from the LLSVP margins. A good correspondence between eruption location and LLSVP margins can only be maintained for rather short head rise times of about 30 million years or less (Torsvik et al., 2020).

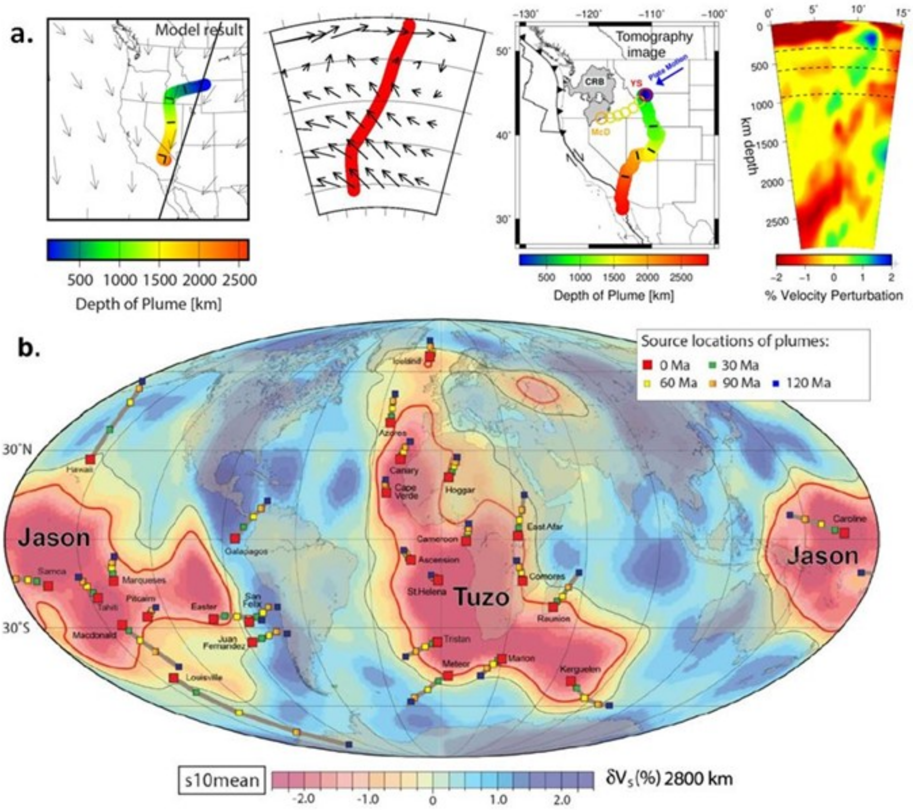


Figure 2.3 a) Modelled conduit (left; 90 Myr plume head rise time) and tomographic observation (right) of the Yellowstone plume. Arrows indicate large-scale flow model, near the bottom of the mantle and along the cross section (following the black line in the top left panel) b) Predicted location from where the plume head initially rises in the bottom of the mantle, as a function of plume head rise time. From Torsvik et al., 2020.

Seismic tomography offers means to “ground truth” such plume models, but model resolution is often too low to reliably image plume conduits. The best continental-scale resolution so far has been achieved through USArray, allowing the Yellowstone conduit to be modeled. This recent results suggest that in order to reach a conduit tilt that is comparable to tomographic observations, the plume head would need to detach from the base of the mantle before (about

90 million years) the Columbia River Basalts emplacement. This means that either the Yellowstone plume reached the surface earlier, or that the plume head took comparatively longer to reach the surface. An unusually long rise time could be due to a comparatively small plume head or that the Yellowstone plume rose in an area of downward regional flow associated with a history of subduction (Steinberger et al., 2019).

This plume model was also used to address the question of whether there is a plume beneath West Antarctica. Since this location is rather far from LLSVPs, an origin along the LLSVP margin would be unlikely regardless of head rise time (Bredow and Steinberger, 2021). A plume in this region should produce low sublithospheric mantle viscosity, which in turn would allow for faster uplift following melting of the West Antarctic Ice Sheet. In the future, this rapid uplift might counteract a marine ice-sheet instability feedback that could otherwise produce several meters of sea level rise over the next few centuries.

Surface Heat Loss History and Mantle Cooling Patterns

Heat loss through Earth's surface is highly variable in both space and time, with thick continents providing good insulation to Earth's interior and thin seafloor allowing more rapid heat transfer. Using models for how the continents and oceanic plates have moved for the past 400 million years, CEED PhD student **Krister Karlsen**, with CEED collaborators **Clint Conrad**, **Mat Domeier** and **Reidar Trønnes**, reconstructed the history of heat loss from Earth's interior (Figure 2.4). He found that heat loss was up to 25% higher in the past than it is today. This implies faster cooling than expected from projections based on the present-day planetary heat budget. He also found that the Pacific side of the world has lost heat at a much faster rate than the African side. This is partly due positioning of continental landmasses, including the supercontinent Pangea, on the African side for most of the past 400 million years. By contrast, the oceans on the Pacific side offered "poor insulation" that led to ~50°C more cooling of the Pacific mantle compared to its African counterpart. This extra heat lost from the Pacific side may have been trapped there by Rodinia, an older supercontinent that covered the Pacific mantle about one billion years ago (Karlsen et al. 2020b).

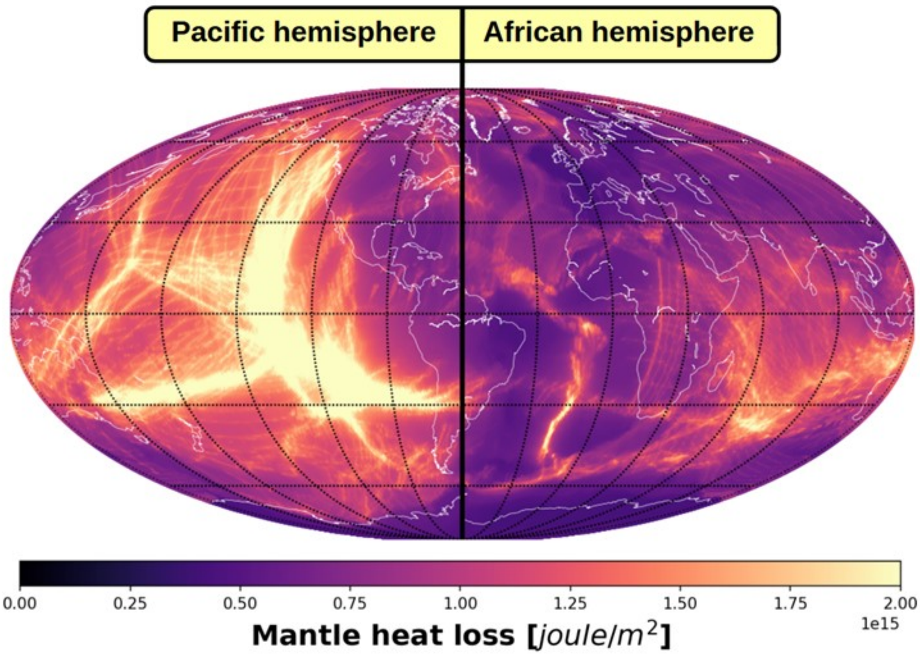


Figure 2.4. Accumulated surface heat loss over the past 400 Myr, calculated based on the plate tectonic reconstructions and paleo-seafloor age grids after Karlsen et al. (2020a).

The MAGPIE Project

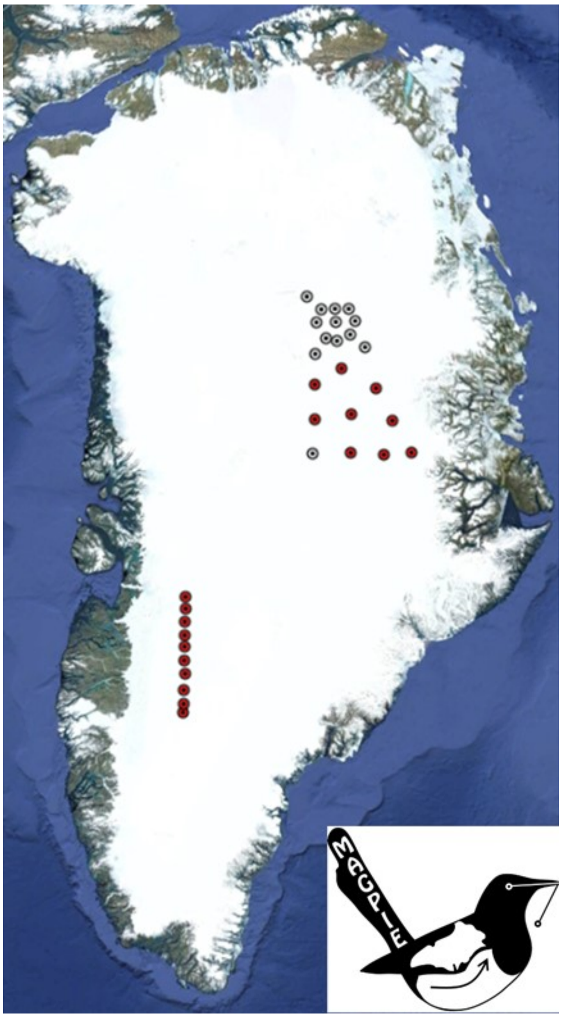


Figure 2.5. Plans for the 2020 MAGPIE field season. Data was collected from the locations of grey dots in 2019; our plan was to augment this data by visiting the red dots during 2020. Unfortunately, corona-related closures forced us to postpone these plans.

During 2020, several Earth Modelling Team members continued work on the **NFR**-funded **MAGPIE project** (Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution, 2019-2023). However, due to travel restrictions we had to make a few adjustments to our planned activity. Early in the year, CEED Adjunct Professor **Kate Selway** developed detailed plans for summer fieldwork in Greenland (Figure 2.5), which included magnetotellurics surveys out of RAVEN and SUMMIT stations in southern and central Greenland, respectively. In March 2020, several countries closed their borders, including Denmark, Norway, and Australia, making our planned fieldwork impossible. We had to cancel the 2020 field season but we hope to return to these sites in a future field season.

Work nevertheless continued with MAGPIE during 2020. CEED PhD student **Florence Ramirez** is developing a method to estimate mantle viscosity, and its uncertainty, using geophysical observations of seismic wave speed (e.g., from a seismic survey) and/or electrical conductivity (e.g., from magnetotellurics surveys). Both types of observations place useful constraints on viscosity because they constrain the temperature and water content of the upper mantle, and both of these properties greatly influence rock viscosity. Kate Selway used a similar approach to model the mantle viscosity beneath Svalbard (Selway et al., 2020) using magnetotelluric data collected as part of a CEED project in 2016 that involved several CEED scientists (A. Minakov and J.I. Faleide). This work highlighted the advances that can be made in estimating mantle viscosity from geophysical data but also some of the current limitations, which will be improved through the MAGPIE analysis.

Understanding the viscosity structure of the upper mantle is critically important for understanding glacial isostatic adjustment (GIA), which describes ongoing ground uplift following deglaciation. To develop better models of GIA, CEED PhD student **Maaike Weerdesteijn** is adapting the mantle convection code ASPECT for use in GIA problems. Because the ASPECT code was developed to handle large viscosity variations, it will be especially useful for modelling GIA deformation in regions with complex viscosity. Indeed, CEED professor **Clint Conrad** helped to demonstrate this year that GIA uplift patterns are affected by viscosity heterogeneity that lies in close proximity to regions of major deglaciation (Hartmann et al., 2020).

Advances in Understanding Earth Composition from Magnetotelluric Data

Observational geophysical data are often of most use when they can be interpreted quantitatively in terms of Earth composition and temperature. Such interpretations allow the geophysical data to be applied to geological questions such as mantle dynamics, subduction processes and mineral exploration. CEED Adjunct Professor **Kate Selway** has been working on improving the geological interpretation of mantle electrical conductivity, as measured by magnetotelluric (MT) data. Together with her PhD student Sinan Özaydin at Macquarie University(Sydney, Australia), she helped develop the open-access software Mantle Analysis Tool for Electromagnetics (MATE) (Özaydin and Selway, 2020). MATE links experimental petrology, experimental mineral physics, and geophysical data to enable researchers to determine which mantle compositions and geotherms are compatible with MT observations (Figure 2.6). Using similar methodologies, Kate helped produce a new interpretation of enigmatic zones of high electrical conductivity often imaged trenchward of the volcanic arc in subduction zones. Although some earlier interpretations suggested that these conductors are caused by slab melts taking a circuitous path from the slab to the arc volcano, Kate and her colleagues showed that they are likely to be caused by the phlogopite-rich metasomatic products of melting subducted sediments (Förster and Selway, in press).

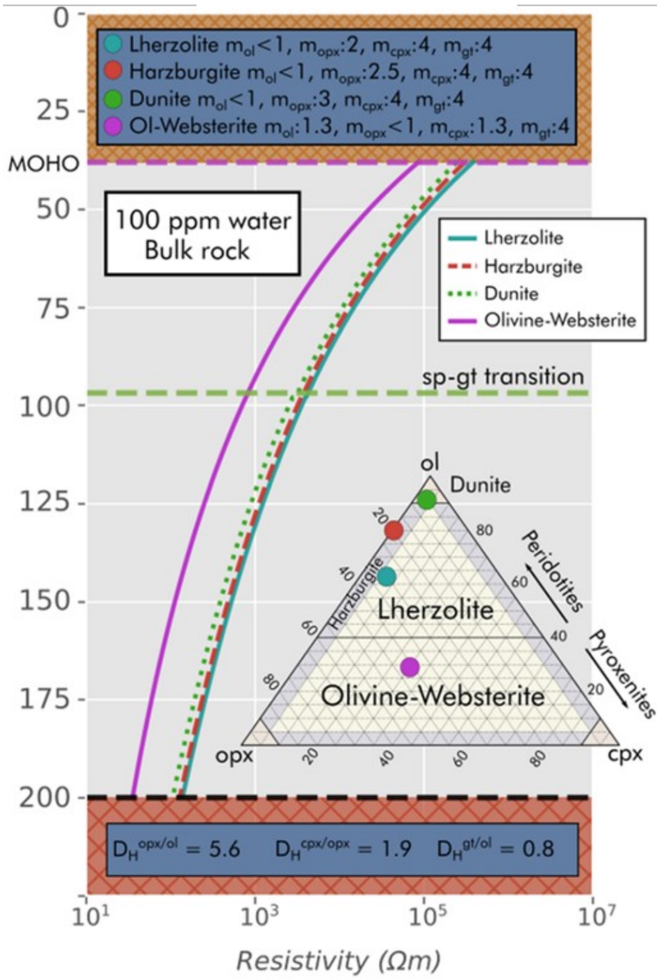


Figure 2.6. *Using the open-source MATE software to calculate the expected resistivity-depth profiles for mantle sections with different typical compositions.*

Seismic structure of the crust and upper mantle in the Baltic Shield

CEED Professor **Valerie Maupin**, with collaborators from GFZ Potsdam and Univ. of Uppsala, has continued the exploitation of the seismological data collected during the ScanArray experiment (2012-2017). This work builds upon the work reported in 2019 concerning a remarkable variation with azimuth of the Rayleigh wave phase velocity that is observed in the south and the north of Scandinavia, but absent in the central part (Mauerberger et al. 2021). This year, Valerie's group confirmed the original hypothesis of a peculiar propagation effect due to the proximity of a major lithospheric step. In addition, they have developed these data into a tomographic model of the S-wave velocity in the crust and upper mantle of Scandinavia, providing in particular a new uniformly sampled map of Moho depth. This map differs significantly from previous ones in the north of Scandinavia. The crustal and upper mantle structure appears to be very different beneath the topographic highs of southern and northern Norway, suggesting that the topography to the north is at least partly related to crustal processes, whereas the mantle plays a major role in the south. Current work is under way to exploit these data for mapping the anisotropy of the upper mantle in the Baltic Shield. Another tomographic study using these data, but based on finite-frequency P- and S- wave travel-time residuals, was pursued this year in cooperation with Istanbul Technical University PhD student Nevra Bulut. Questions related to the validity of merging datasets from different seismological experiments in a tomography study of this type resulted in a methodological study (Maupin, 2021). This study demonstrates a simple trick to combine data recorded asynchronously without biasing the resulting tomographic models.

The eight seismological stations of the Norwegian Broadband Pool installed for our Kongsberg project have been running and collecting data for the whole of 2020. Data collected in 2018-2019 were exploited in a master thesis defended in June by CEED MS student **Mathilde Opshaug** (Opshaug, 2020). She analyzed the P-Receiver functions (RFs) at these 8 temporary seismic stations located in a 100x100 km region around Kongsberg (Norway) and compared them to those obtained at the permanent Kongsberg seismometer KONO, where anomalous signals have been detected previously. RFs are used in particular to measure Moho depth and analyze crustal structure beneath seismological stations. The 4 stations located furthest away from KONO showed normal RFs, while those located closer, but also to the northeast along the boundary of the Oslo Graben, showed complex waveforms for waves coming from northeast (Figure 2.7). We interpret this anomaly as resulting from crustal heterogeneities such as a laterally varying lower crustal layer or a complex Moho topography. The analysis will be redone with more data in 2021, as data stacking is important to improve the quality of the RFs. A joint interpretation is planned with colleagues from Uppsala University in Sweden who have collected seismological data at sites complementary to ours to the northeast and to the southwest.

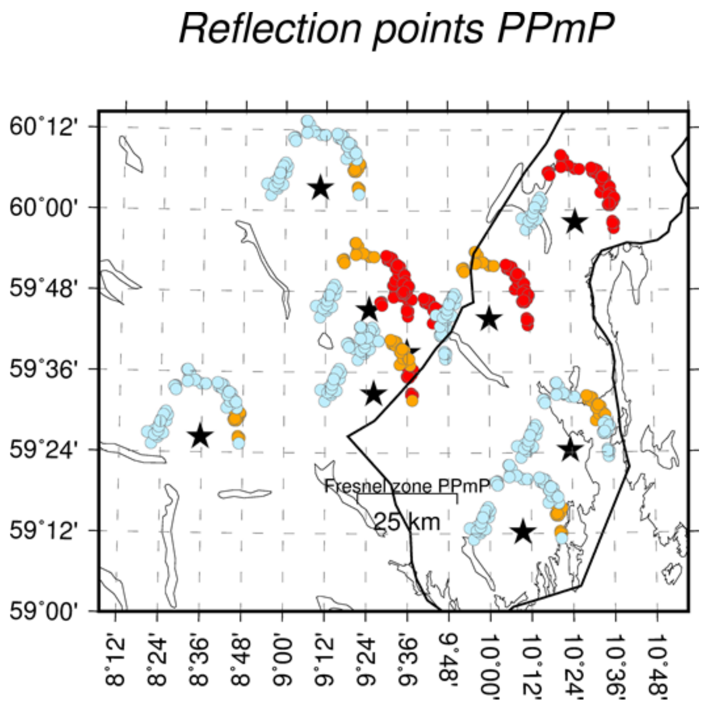


Figure 2.7. Location of the 8 temporary seismic stations of the Kongsberg network and of the permanent KONO station (black stars), and of the reflection points on the Moho of crustal multiple PPmP phases. The red dots show reflection points where this phase is anomalous, the orange dots show where the phase is possibly anomalous, and the light blue dot show where it is normal. The Oslo Graben is delineated with a black thick line. The Oslo fjord can be seen on the right side of the map (from Opshaug, 2020).

Aquifer-Eustasy and Sea Level Change

It is well known that cycling of water between the oceans and the continental ice sheets caused large changes in sea level during the past several million years. However, cycles of sea level change have also been observed during the hotter Cretaceous "greenhouse", which was thought to be inhospitable to great ice sheets. CEED professor **Clint Conrad** and collaborators have explored the possibility that greenhouse sea level changes may result from cycling of water between the oceans and the continental aquifers (Sames et al., 2020). This "aquifer-eustasy" results from climate change that affects the relative aridity of continental interiors. Based on the sea level record, we estimate that seawater exchange with aquifers produces sea level change during greenhouse times of up to ~70 m over timescales of a few hundreds of thousands of years (Figure 2.8). This would make aquifer-eustasy the dominant mechanism for sea level change during greenhouse periods.

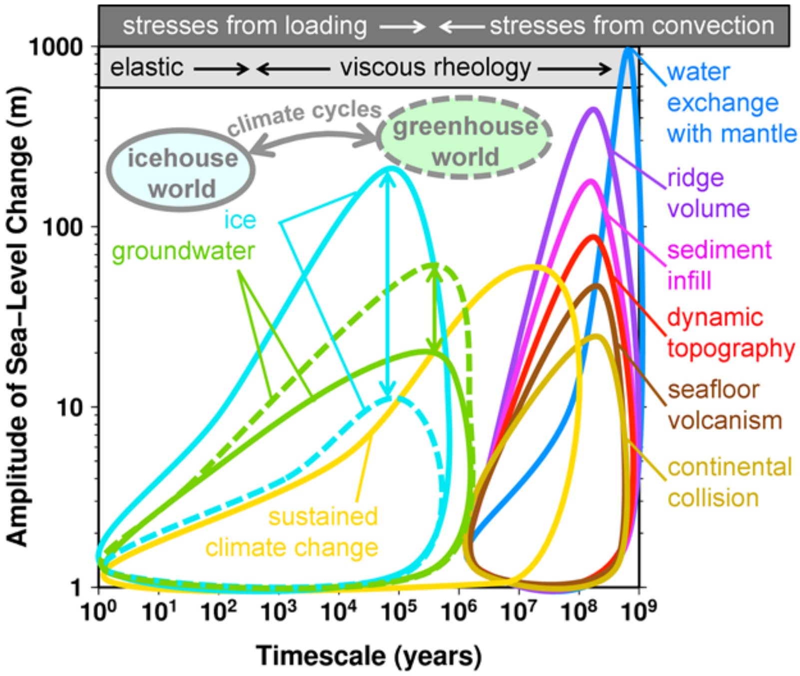


Figure 2.8. Timescales and amplitudes of mechanisms that cause sea level change. On longer timescales (millions of years and longer), sea level change occurs mostly via mechanisms that< affect the volume of the ocean basins. On shorter timescales, cycling of water between the oceans and continental sources control sea level change. Continental ice sheets (light blue lines) are the most important source during icehouse times, while groundwater (green lines) is most important for greenhouse climate states (Sames et al., 2020)

Mediterranean Geodynamics: Subduction zone interactions around the Adria Plate

During the Cenozoic, the southern part of Europe was influenced by convergence between Africa (and Adria) and Eurasia. As a result of the convergence, multiple subduction zones have been active in the Mediterranean area, which exhibit two distinctly different styles. Subduction zones that are more or less parallel to the convergence (e.g., the Alps) are slow, magma poor, and produce little or no trench retreat. By contrast, subduction zones that are more or less perpendicular to the convergence (e.g., the Apennines) are characterized by rapid trench retreat and back-arc basin opening. In the last 30-35 Myrs, while Alpine subduction has ceased and become structured, multiple fast retreating subduction zones were simultaneously active around it. CEED researcher, **Ágnes Király** has conducted analogue laboratory experiments that extend our understanding on how these subduction zones communicate and affect their surroundings. In a paper (Király et al., under review in *Global and Planetary Change*), written with collaborators from Italy and Australia, they show that the outward-dipping double subduction of Adria produces wide-spread mantle flow (Figure 2.9) that contributes to the deformation, uplift, and magmatic activity of the nearby tectonic plates.

This research received particular interest in connection of the Adria-Array project, which aims to gain new (mainly seismological and geodetic) data from the surroundings of Adria to better understand its role in the geodynamics of the Mediterranean. CEED researcher **Ágnes Király** has been invited to present this work at the Adria-Array workshop, and, together with Carmen Gaina, became secondary proposer on the COST action proposal for Adria-Array.

Orphan Slabs

In an open-access publication of one of his PhD students, Antoniette Greta Grima, CEED Researcher **Fabio Crameri** identifies the possibility for sunken oceanic plates to break off also at upper-mantle transition zone depths and not only in the shallow uppermost mantle. The potential occurrence of this so-called "slab orphaning", which provides a geodynamic link between slab penetration and deflection at the upper-mantle transition zone (Figure 2.10), will need to be considered across disciplines. This includes tectonic reconstructions that have, up to now, associated observed separated slab portions in the deep mantle to shallow breakoffs only.

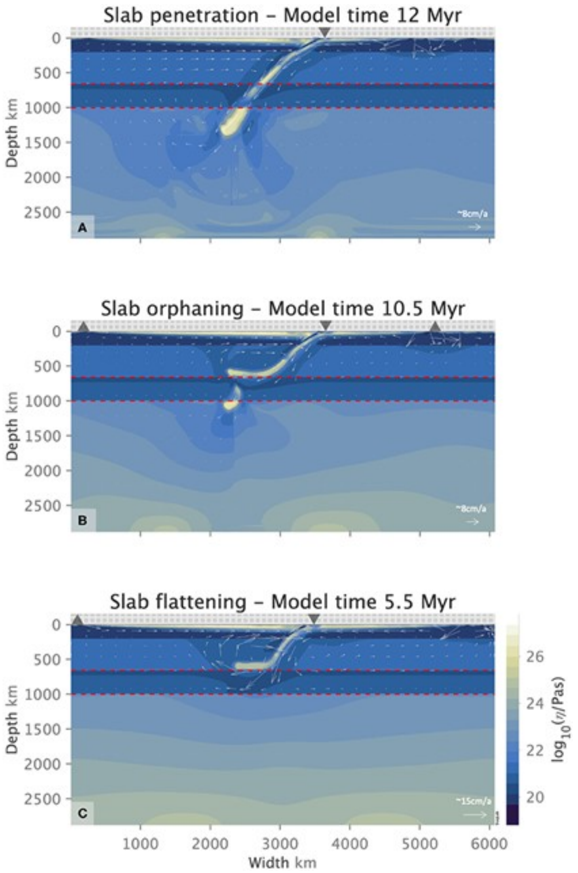


*Figure 2.10. Deep slab dynamics. Comparison of A penetrative, B orphaning, and **C** flattening behavior for a subducted slab. Flow arrows indicate the sense of flow direction and its relative magnitude for each figure.*

Data visualization and conceptual representation

CEED Researcher **Fabio Crameri** and his colleagues further provides the scientific community with a simple guide for the scientific use of colour (*Crameri et al., 2020b*). They show how scientifically derived colour maps report true data variations, reduce complexity, and are accessible for people with colour-vision deficiencies (Figure 2.11). This open-access publication significantly impacts the whole scientific community, with already over 60 thousand accesses, as it highlights ways to identify and prevent the widespread misuse of colour in science.

Researcher **Fabio Crameri** further supervised a BSc student to successfully develop a more-accurate representation of the Earth's interior to counteract the current widespread misconception of a red-hot, molten mantle (*Scherrer, 2020*). The new design takes its form as a scientific poster that is aimed to be exhibited in museums on still or motion screens. It additionally makes the imaginary spatial and temporal scales of mantle deformation more tangible to

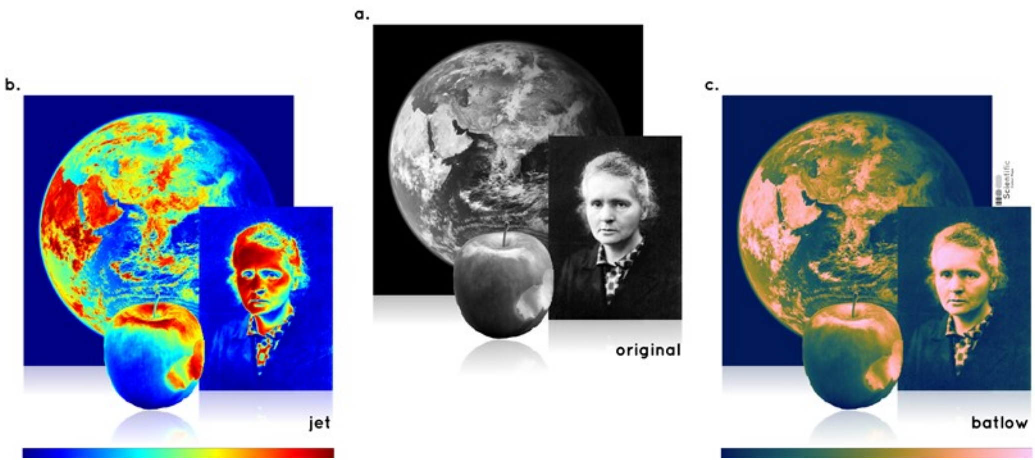
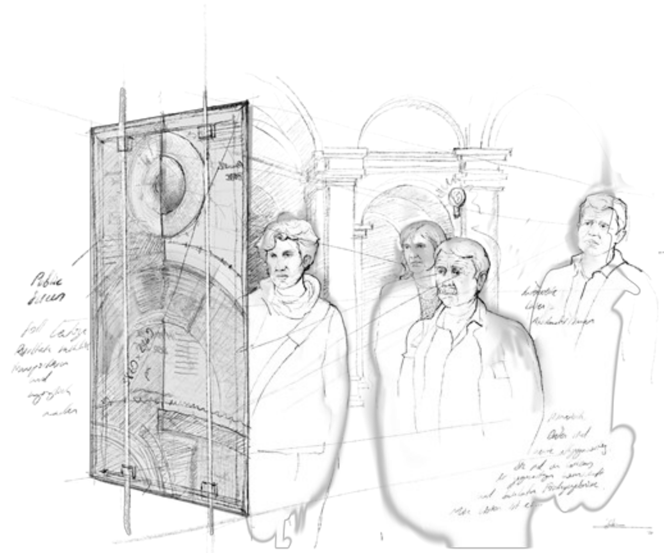


Figure 2.11. The superiority of scientifically derived colour maps. By knowing what something looks like in advance, the distortion by unscientific colour maps, like jet or rainbow, becomes instantly obvious. The look of scientific data is, however, usually unknown a priori, which makes the distortion of an unscientific colour map less apparent. Marie Skłodowska-Curie, the Earth from space, and an apple are shown ***a*** *in their original images and* ***b*** *in distorted and* ***c*** *in undistorted colour versions. Inferring the true picture from an unscientifically (e.g., jet) coloured data set is incomparably harder than from a data set represented in a perceptually uniform and ordered colour map, like batlow (Crameri et al., 2020b).*

Figure 2.12. Exhibition concept. The developed design to accurately and tangibly represent the Earth's interior. Sketch by Stefan Scherrer.



the viewer (Figure 2.12).

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3. Dynamic Earth: Plate motions and Earth history

The Dynamic Earth Team aims to explore plate motions and Earth's history in the framework of Plate Tectonics and the Wilson Cycle. The mission of our team (which comprises around 18 members, including adjunct and Emeritus positions) is to explore the links between the lithosphere and the convecting mantle and quantify how paleogeography and true polar wander have influenced the climate system. In 2020, Dynamic Earth members and their collaborators published about 30 articles on a variety of topics, including: regional and global tectonic reconstructions and the link to climate change, the architecture of rifted margins, global paleobathymetry, subduction zone initiation, microcontinent formation, and collisional processes. The Dynamic Earth team members are also involved in a number of collaborative projects with the other CEED teams, GEO department as well as national and international collaborations. Two new projects were granted from the RCN: NOR-R-AM2 (PI Gaina), and EEA grants (Geothermal potential of Baia Mare region-Romania, PI Gaina). 2020 also saw the graduation of two Dynamic Earth PhD candidates: Eivind O. Straume, on 18.09.2020, and Joost van den Broek on 23.11.2020.

The Dynamic Earth team continued to contribute to the understanding of Earth's structure and evolution by studying various processes within the Wilson Cycle: from the continental rifting stage, and the characterization of passive margins and oceanic basins, to the ocean closure and the formation of microcontinents in subduction zones.

Wilson Cycle - margins, rifting, orogenesis

The study of plate boundaries and their evolution is an overarching theme of most of this team's research. In addition to global tectonic plate reconstruction models, a lot of effort is put into the understanding of how tectonic plates deform in response to changes in plate boundaries and active tectonics. Researchers **Sergei Medvedev** and **Alexander Minakov** analyzed how lithospheric plate geometry controls the pattern of tectonic stresses with numerical experiments of the North Atlantic realm that looked at the influence of the high geopotential of the synthetic Iceland plume and variable topography-related local curvature of the plate. They show that local curvatures of the lithosphere may facilitate local bending and rise of corresponding stresses and that the geometry of the model plate may control stress and deformation pattern (Medvedev and Minakov, 2020).

Margins - Plate boundaries and kinematic reconstructions

In a new study on the Barents Sea region, Researchers **S. Gac, A. Minakov, G. Shephard,** Professor **J.I. Faleide,** and Adjunct Professor **S. Planke** (Gac et al., 2020) used numerical models that couple kinematic models of the Greenland plate with mechanical models in order to constrain the timing of contractional deformation in the Barents shelf. Late Cretaceous -Cenozoic contractional structures are widespread in the Barents Sea. While the exact dating of the deformation is unclear, it can only be inferred that the contraction is younger than the early Cretaceous. One likely contractional mechanism is related to the Greenland Plate kinematics at Paleogene time. A thin sheet finite element modelling approach was used to compute deformation within the Barents Sea in response to the Greenland-Eurasia relative motions during the Paleogene. The analytical solution for the 3-D folding of sediments above basement faults was used to assess possibilities for folding. The results show that the Greenland plate's general northward motion promotes growing anticlines in the entire Barents Sea shelf. Numerical models suggest that the fan-shaped pattern of cylindrical anticlines in the Barents Sea can be associated with the Eurekan deformation concurrent to the initial rifting and early seafloor spreading in the northeast Atlantic. The main contraction phase in the SW Barents Sea coincides with the timing of continental breakup, whereas the peak of deformation predicted for the NW Barents Sea occurred at later times. Svalbard has experienced a prolonged period of compressional deformation. The study concluded that the Greenland plate kinematics in Paleogene time is a likely candidate to explain contractional structures in the Barents Sea (Gac et al., 2020).

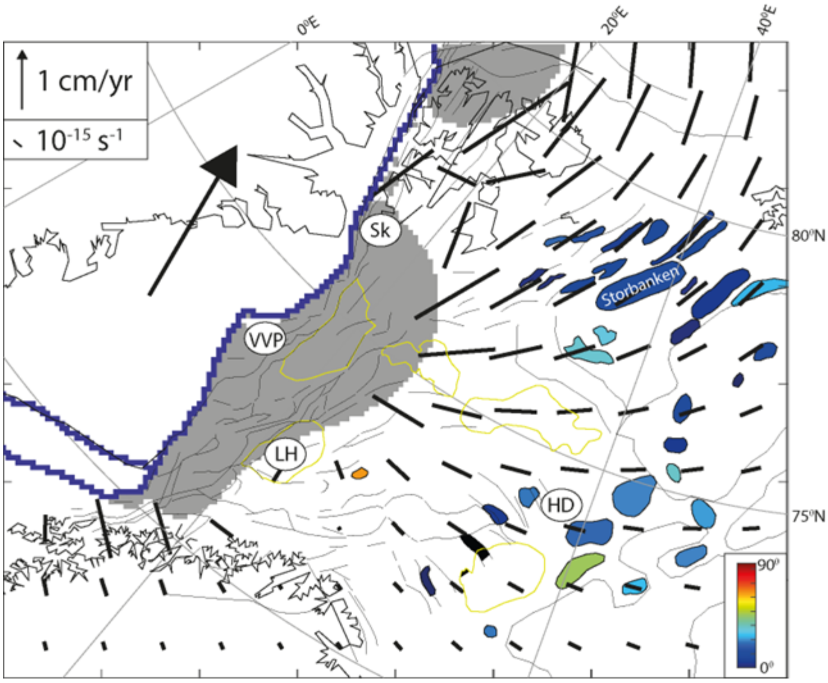


Figure 3.1. Predicted favoured folds (black streaks) in the Barents Sea shelf during the latest Cretaceous-Eocene Greenland-Eurasia relative plate motions. The grey areas represent zones with Coulomb stress larger than 50 MPa. The rainbow shades represent the deviation angle (in °) between the modelled fold axes and the observed anticline axes. HD: Haapet Dome, LH: Loppa High, Sk: Sørkapp, VVP: Vestbakken Volcanic Province (Gac et al., 2020).

Rifting - The Norwegian passive margin

One of the main research focus of Researcher **M. Abdelmalak** and Professor **J.I. Faleide** is on the mid-Norwegian margin, a margin that experienced several post-Caledonian extensional episodes followed by break-up and seafloor spreading between Greenland and Norway in the earliest Eocene. This margin is known as a type example of volcanic passive margins characterized by (1) thick volcanic wedges of seaward dipping reflector sequences (SDRs) emplaced along the proto-breakup axes, (2) massive emplacement of sill and dyke intrusions in the sedimentary basins, and (3) presence of high-velocity/density lower crustal bodies (LCB). Despite widespread consensus on these geophysical observations, an understanding of the rifted structure and evolution up to the onset of magmatic breakup remains incomplete and debated in the outer and distal parts of the mid-Norwegian margin and similar volcanic passive margins worldwide. A key question related to the mid-Norwegian margin is whether the final phase of extension evolved similarly to magma-poor margins (like the Iberian margin) in continuous extension from necking to breakup, or if it evolved in a fundamentally different polyphased manner consisting of discrete pulses of extension and final magmatic weakening.

Recently, a new generation of long-offset 2D seismic reflection lines and 3D seismic data, together with new well data, has permitted a significant improvement in the regional understanding of the Møre and Vøring basins offshore mid-Norway and the corresponding Faroe-Shetland basins on the UK side. This has enabled much better imaging of the deep Cretaceous sub-basins and sub-basalt structures that can be studied in relation to deep crustal structures and regional tectonic events, as described in details in the next paragraphs.

The Zastrozhnov et al. (2020) paper presents a regional tectonostratigraphic synthesis of the pre-breakup development of the Møre and Vøring basins. They re-evaluate the timing of uplift of the intrabasinal structural highs and establish a series of new isopach maps to illustrate the spatio-temporal evolution of the main depocentres. The late Jurassic-Early Cretaceous extensional event is characterized by a regional unconformity called the Base Cretaceous Unconformity (BCU, Figure 3.2A). The BCU forms the floor of the Møre and Vøring basins and shows great regional variability that reflects the different structural position of the main basin elements as well as regional variations influenced by basin-scale tectonic, thermal and/or isostatic processes and global sea level variation. The Early Cretaceous deposition was mainly focused in the Møre Basin, while the main Cenomanian and subsequent Late Cretaceous-Paleocene depocentres developed principally in the Vøring Basin and migrated sequentially west towards the present continent-ocean boundary (Figure 3.2B). Strain hardening due to Mesozoic lithospheric cooling as well as additional enhancements from

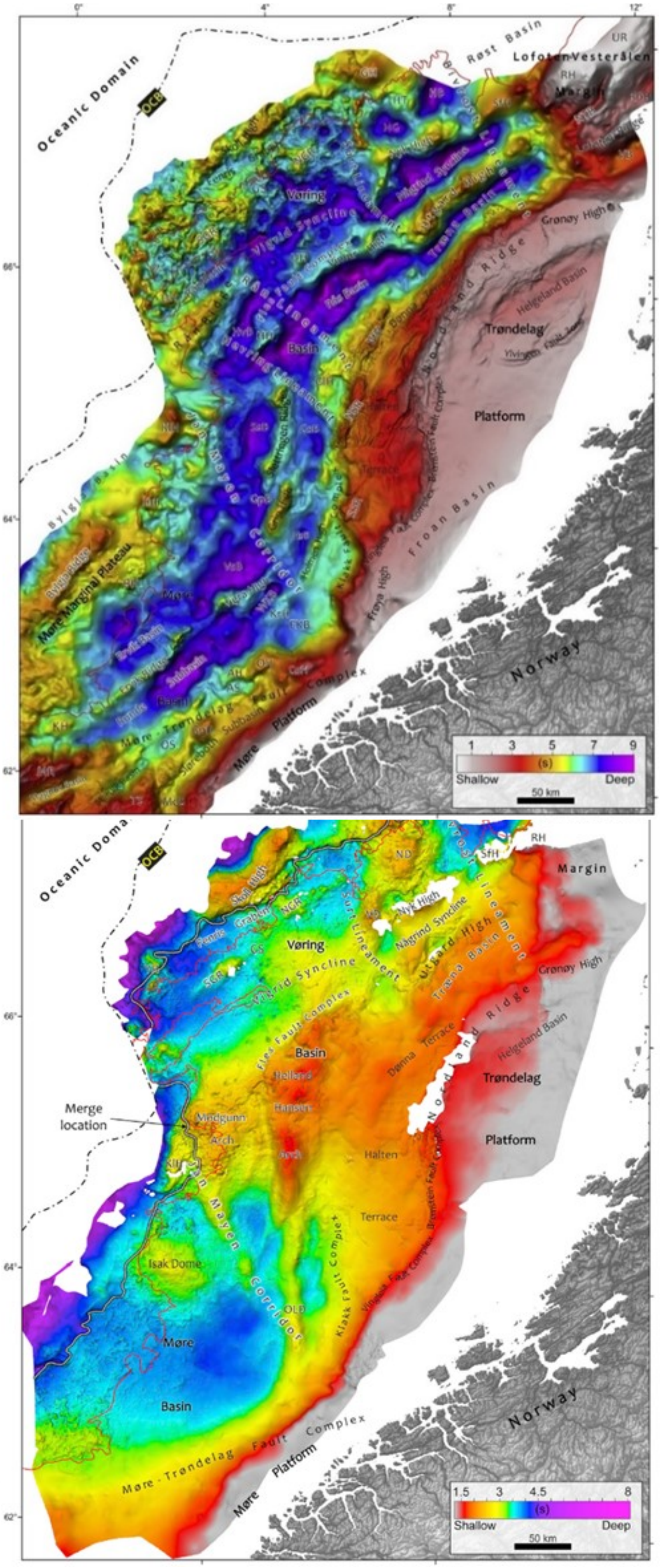


Figure 3.2. Time-structure maps of (A) the Base Cretaceous Unconformity (left) and (B) Near Base Eocene (right) corresponding to the time of breakup (Zastrozhnov et al., 2020).

lateral lower crustal flow may explain the migration of depocentres and/or jumps of the rift axes over time (Fig. 3.3). This may also have partly influenced the location of the final rift and volcanic margin together with the diachronous breakup configuration. Zastrozhnov et al. (2020) conclude that the mid-Norwegian margin formed in a polyphased manner and represents a specific type of passive margin, where basin distribution and development are largely controlled by pre-existing crustal blocks and where the outer domain is underlain by a relatively thick continental crust compared to the extremely thinned crust beneath central parts of the deep Cretaceous basins (Figure 3.3).

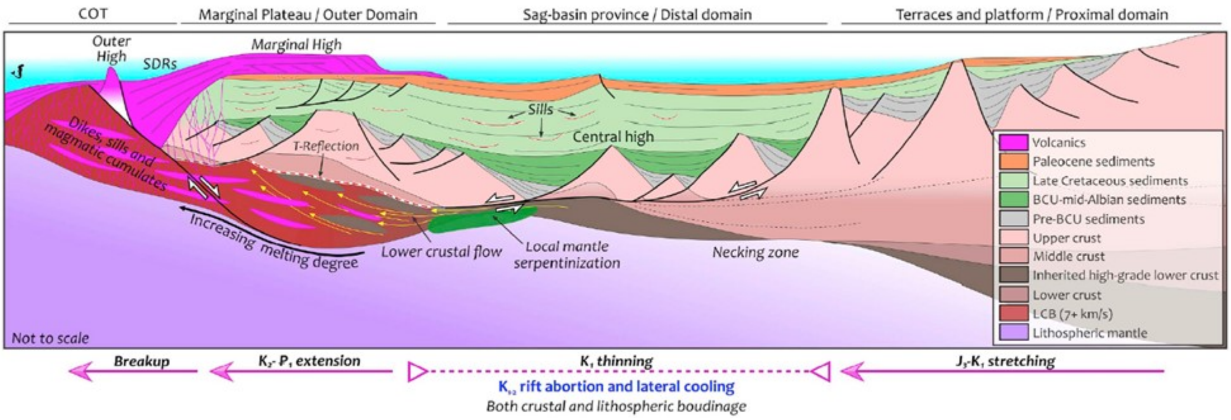


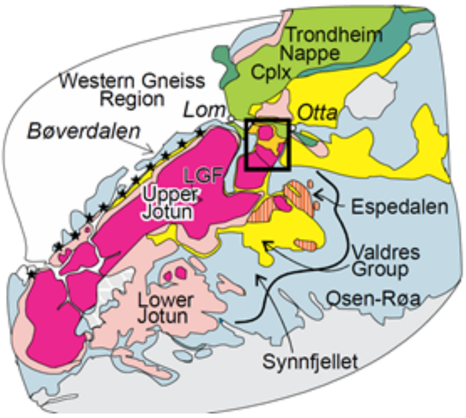
Figure 3.3: Schematic section illustrating configuration and development of the mid-Norwegian margin by the initial seafloor spreading time in the early Eocene. The lower crustal body (LCB) represents a mixture of exhumed high-grade Caledonian crust and breakup-related magmatic material (Zastrozhnov et al., 2020).

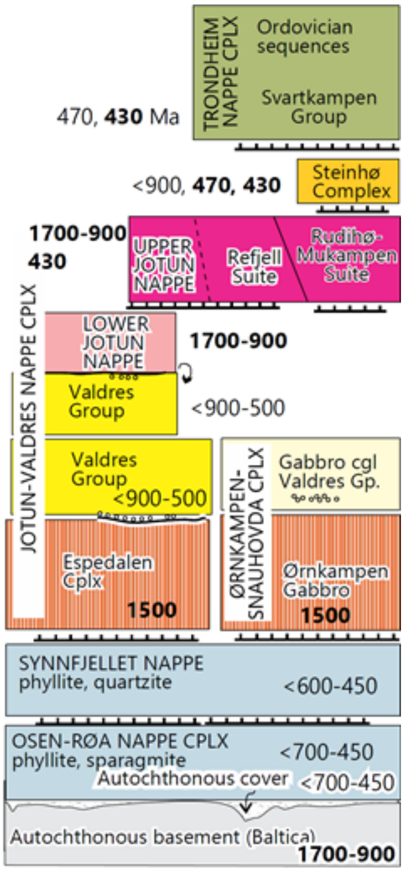
In the Millett et al. (2020) paper the study is extended across the border to cover the Faroe-Shetland and Møre-Vøring basins at the NE Atlantic margin. Focus is on basin structure and prospectivity (source rocks, reservoirs, and traps) and insights from the new extensive 3D seismic data are presented in frontier and underexplored regions. Improved imaging of the areas affected by Paleogene igneous rocks reveals major unknown sub-basalt structures including some regions on the marginal highs where the basalt cover has been entirely removed by erosion, revealing sub-basalt stratigraphy and structures with pre-Cretaceous potential prospectivity. The influence of igneous rocks on both discovered and prospective hydrocarbon systems is also discussed.

Orogenesis - geochronology of Caledonides terrains

The region of northern Gudbrandsdalen (onshore) Norway represents an important geological transition in architectural style and composition of the Caledonian nappes and the meeting point of tectonic elements with diverse geological histories of both Baltic and exotic origins. In the past century this complexity has generated a number of conflicting interpretations. New U-Pb data from F. Corfu and M. Heim (2020) show that: (1) the Ørnakmpen Gabbro low in the tectonostratigraphy is 1497 ± 5 Ma, correlating with the Espedalen Complex of Telemarkian (1550-1480 Ma) affinity; (2) the structurally higher crystalline Rudihøe-Mukampen Suite (RMS) is of Gothian (1700-1600 Ma) affinity and was metamorphosed at high grade between 980 and 900 Ma; (3) these ages and mapping indicate that the RMS is a lateral equivalent of the Upper Jotun Nappe; (4) the overlying, dominantly metasedimentary Steinhø Complex was metamorphosed in the Ordovician at 473 ±3 Ma; (5) both the RMS and Steinhø Complex were intruded by trondhjemite dykes at 430-427 Ma.

Figure 3.3: Schematic section illustrating configuration and development of the mid-Norwegian margin by the initial seafloor spreading time in the early Eocene. The lower crustal body (LCB) represents a mixture of exhumed high-grade Caledonian crust and breakup-related magmatic material (Zastrozhnov et al., 2020).





These units are structurally overlain by the lowest elements of the Trondheim Nappe Complex, which includes serpentinite lenses and conglomerates, the products of hyperextension, locally with Ordovician fossils. The tectonostratigraphic position of the Svartkampen Group reveals a paradox, because it is also correlation with similar hyperextension assemblages, which underlie the Jotun Nappe Complex and Valdres Group equivalents on the west, in Bøverdalen. The solution of the paradox requires either complex tectonics, or a non-identity of the two assemblages.

Wilson Cycle - oceans, subduction and climatic changes

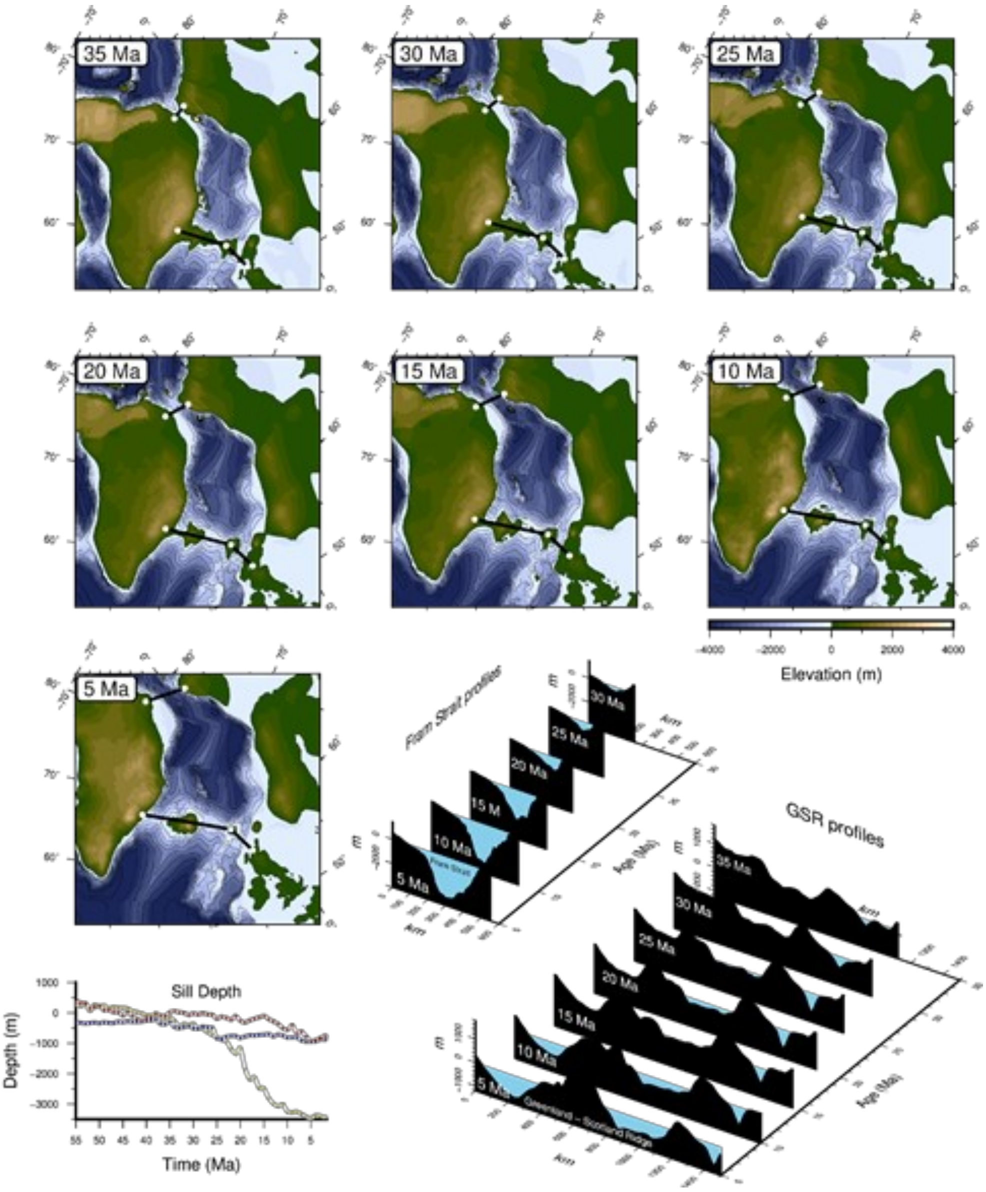
Part of the research in the Dynamic Earth team explores the links between changes in ocean basins and climatic changes. PhD student Chloé Marcilly and collaborators have been working on modelling the long-term climate fluctuations with long-term carbon cycle models that take into account the paleogeography and the position of continents through time. For more recent times, PhD student Eivind Straume and collaborators studied the link between paleobathymetry, ocean gateways, and Cenozoic climate (explained in more details below). The characterization of important tectonic features of ocean basins and their link to geodynamic processes is also a scientific avenue followed at CEED. For instance, PhD student **Lea Beloša** and collaborators study the role of fractures zones in geodynamic processes. In particular, their research focuses on the Jan Mayen Fracture zone region and adjacent submarine volcanoes (like the Vesteris seamount) by using geophysical and geological data to: 1) map volcanic and tectonic features; and 2) identify possible regions of serpentinization. As part of her PhD training, Lea Beloša participated to the research cruise Gloria-Flow M162 that aimed at exploring subsurface fluid flow and active dewatering along the oceanic plate boundary between Africa and Eurasia (the Gloria Fault).

Oceans - Paleobathymetry and ocean gateways

In the Cenozoic (66 Ma – 0 Ma), opening and closing of strategic oceanic gateways linking the major oceanic basins have facilitated ocean circulation changes. This played an important role in the Cenozoic transition from a greenhouse to an icehouse climate. A new CEED paper authored by PhD student **E. Straume,** Professor **C. Gaina,** Researcher **S. Medvedev** and Adjunct Professor **K. Nisancioglu** have re-evaluated the evolution of the Northern hemisphere oceanic gateways (i.e. the Fram Strait, Greenland–Scotland Ridge, the Central American Seaway, and the Tethys Seaway) and embedded their tectonic histories in a new global paleobathymetry and topography model for the Cenozoic time. In particular, the NE Atlantic region is significantly updated from previous models by including a new model of dynamic support from the Iceland mantle plume through time.

The new CEED model can be used to test if the Northern Hemisphere gateways played an important role modulating ocean circulation and climate. To do so, this study provides a set of realistic global bathymetric and topographic reconstructions for the Cenozoic time at one million-year intervals which are well suited as input for paleo-ocean circulation and climate models (Figure 3.5)

Figure 3.5. Cenozoic paleobathymetry of the Atlantic – Arctic oceanic gateways and W-E profiles of the Fram Strait and Greenland – Scotland Ridge (GSR) showing their evolution from 35 Ma to 5 Ma. The sill depth reconstructions show the minimum elevation along the extracted profiles for every million-year since continental breakup between Greenland and Eurasia at 55 Ma. Sill depths for the Fram Strait = yellow, Greenland – Iceland – Faroe Ridge = red, and the Faroe – Shetland Channel = blue (Straume et al., 2020).



very warm with tropical sea surface temperatures (SSTs) of around 45°C (Figure 3.7c) and sea levels were so high that they have only since been exceeded in the mid-Cretaceous. The Cambrian radiation was one of the most significant evolutionary transitions seen in the fossil record but the evolutionary diversification that followed during the Mid-Ordovician (~470-455 Ma), known as the Great Ordovician Biodiversification Event (GOBE, Figure 3.7b) saw a huge increase in the number of different complex animal forms. This was followed by a mass extinction at 445-444 Ma and the only known mass extinction occurring during icehouse conditions. The end Ordovician glaciation (Hirnantian) is one of only three glacial episodes known in the most recent half billion years but it is noteworthy that the Hirnantian glaciation lasted only for perhaps less than a million years.

During the Early Ordovician, CO_2 levels were high (~3500 ppm at 490 Ma) with SSTs around 45^o C. CO_2 levels were steadily falling to about 460 Ma and then flattening out with CO_2 level at around 2500 ppm whilst SSTs was reduced to about 28^o C (Figure 3.7c). CO_2 levels and SSTs are strongly correlated (Pearson correlation, r=0.92), but more interestingly, the diversity of global articulate brachiopods (Figure 3.7b) show a strong negative correlation with temperature and CO_2. The negative correlation is probably factored by global cooling during the Ordovician that reduced SSTs to temperatures that challenged life to evolve faster and more substantially than before. Cooler oceans would store more dissolved oxygen and there is a strong temporal link between GOBE and increased O_2 concentrations since the mid-Ordovician (Figure 3.7b). Oxygen levels may therefore have played an important role in regulating Ordovician biodiversity and we find a strong positive correlation between atmospheric O_2 and the diversity of global articulate brachiopods (r=0.86).

Plate tectonics plays an intricate role in shaping the long-term climate by controlling the distribution of continents and oceans (palaeogeography), mountain building, arc-volcanism, topography and weathering. Plate tectonics also has a major effect on the hydrosphere because the variation in seafloor spreading is the most important driver of sea-level rise and falls. In turn, that also affects the biosphere and biodiversity, which is strongly influenced by continental flooding, intercontinental connectivity, the link between latitudes of the various continents and their overall average temperature, habitat, and oceanic-atmospheric circulation. Although the GOBE was probably driven by a combination of biological and environmental factors, global cooling during the Ordovician must have been the prime factor, by reducing SSTs to temperatures that challenged life to evolve faster and more substantially than before. Global Ordovician cooling was driven by decreasing atmospheric CO_2 (Fig. 3.7c) that probably reflects a combination of causes in this extraordinarily dynamic period in Earth evolution. These include reduced sourcing and increased silicate weathering due to the advent of land plants as well as the progressive exhumation of low-latitude collisional arcs. Ultimately, long-term CO_2 sinks are largely controlled by palaeogeography, and the general increase in the concentration of continents in the tropics during the Ordovician (Fig. 3.7a) appears to have increased the overall global weatherability.

The circum-Arctic region

The Arctic is one of the key domains of interest for CEED research, and is particularly relevant within numerous Dynamic Earth projects, collaborations and initiatives that resulted in publications about the North Atlantic and Norwegian margin, central Arctic, the High Arctic LIP (HALIP), Svalbard and the Barents Shelf. In 2020, several field campaigns and teaching at Svalbard were cancelled due to the pandemic, nonetheless, there were several new and continuing projects.

One of the most significant developments in 2020 was the successful renewal of the international collaborative INTPART-funded project "NOR-R-AM 2" (Changes at the Top of the World through Volcanism and Plate Tectonics. A collaboration between Norway-Russia-North America) for 2020-2023. This follows the "NOR-R-AM" project which ran from 2017-2019 (PI **Gaina, Faleide, Minakov, Corfu, Shephard**). Other existing external projects with Dynamic Earth members include the ESA funded 3-D Earth (**Gaina, Minakov, Medvedev**) that was extended until 2021 and includes a Greenland focus and collaboration with colleagues from the Earth Modelling team (**Conrad and Heyn**), CEED-MOD and ArcEx and (**Faleide, Medvedev, Gac, and Abdelmalak**). Dynamic Earth members are also developing the International Summer School course "A Changing Arctic" which ran from 2014-2018. Related to this course, (PI **Shephard, Gaina**) received funding from UArctic and UiO:Norden to create a Massive Open Online course. A new UNIFOR project was funded - "Ice-Age Volcanism on Svalbard: Timing and Geodynamic Significance (PI **Minakov**). **Shephard** was also elected as IASC Marine working group representative, Association of Polar Early Career Scientist (APECS) Council, local APECS Norway chapter President, and the UArctic Geology co-Leader, and is a collaborator on a new UiO:Norden project related to exploration and museum collections "Collecting Norden".

More of Dynamic Earth research in a nutshell

The thermal maturity of sedimentary basins as revealed by magnetic mineralogy: We used magnetic mineralogy as indicator of thermal maturity of sedimentary basin in an increasing burial depth case example and in sill intruded sedimentary basin.

***Abdelmalak, M. M.**, and Polteau, S., 2020, Basin Research, v. 32, no. 6, p. 1510-1531.*

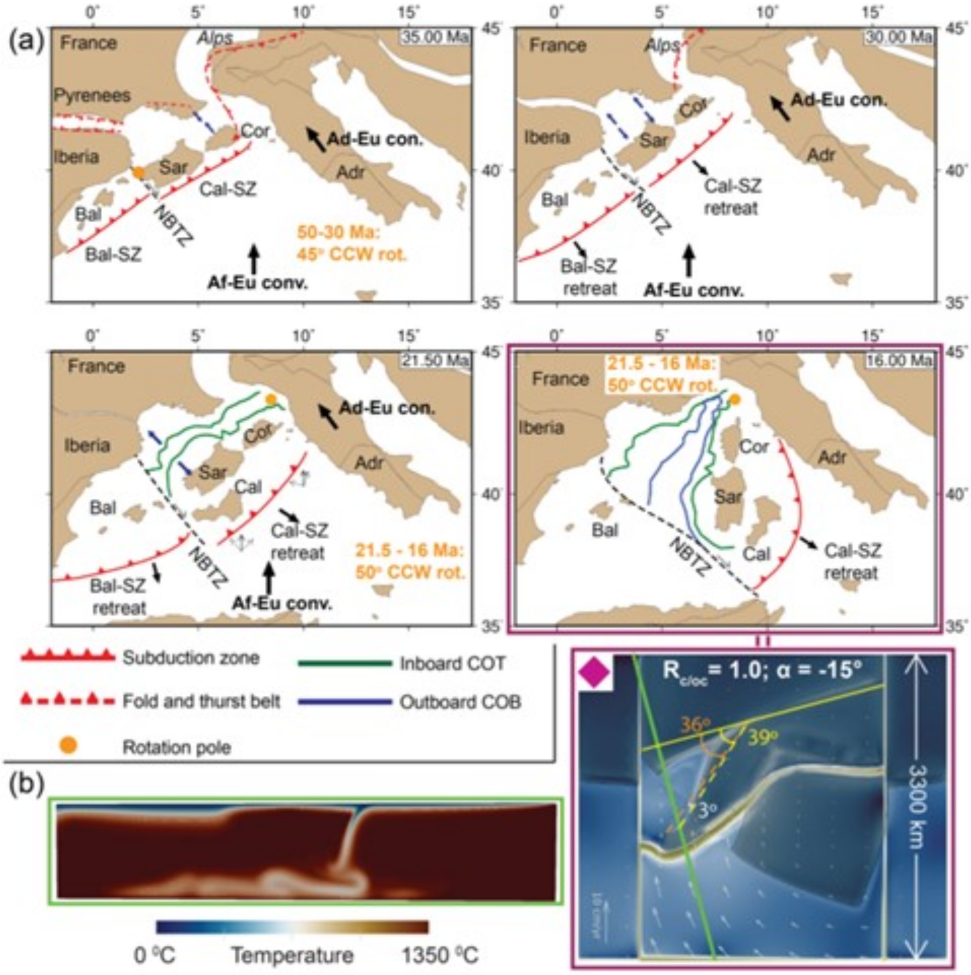
Crustal structure and erosion of the Lofoten/Vesterålen shelf, northern Norwegian margin: We show that (1) crustal thickness of the Lofoten/Vesterålen shelf is greater than old study suggested, and less affected by continental breakup and (2)Extensive erosion episodes are likely to be detrimental to petroleum potential.

***A.J. Breivik, J.I. Faleide**, R. Mjelde, E.R. Flueh, Y. Murai, Tectonophysics 776 (2020) 228318*

The tectonized central peak of the Mjølnir Impact Crater, Barents Sea: We investigate the effect of far-field tectonic stresses on the uplifted central peak of the Mjølnir impact crater in the Barents Sea. Reactivation of impact-induced faults and mobilization of impact-shattered rocks by tectonic compression provides a new and robust explanation for the structural rise of Mjølnir's central peak.

Subduction - Microcontinents in subduction zones

Microcontinents and continental fragments are small pieces of continental lithosphere surrounded by oceanic lithosphere that form in extensional settings (Gaina and Whittaker, 2020). They are often found in association with rifted margins, but they can also form in subduction zones when the overriding plate undergoes extension. This is the focus of two papers, van den Broek and Gaina (2020) and van den Broek et al. (2020), which are the result of the PhD work of **Joost van den Broek**.



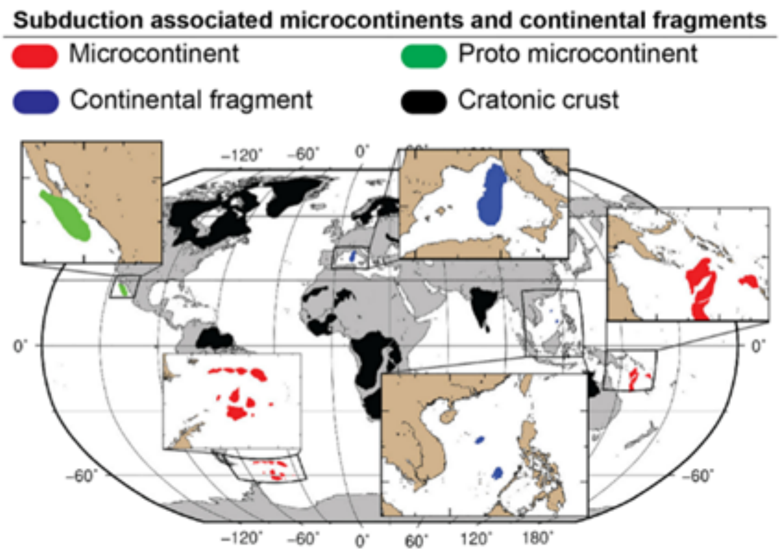


Figure 3.6. On the left: Overview of the extent various microcontinents and continental fragments associated with subduction systems (van den Broek and Gaina, 2020). Above: Tectonic reconstruction of the central Mediterranean subduction zone and vertical section and top view a numerical model that shows the break-up of the overriding plate and the rotation of the slab (van den Broek et al., 2020)

The work by van den Broek and Gaina (2020) analyses available geological and geophysical data of microcontinents and continental fragments adjacent to subduction zones, and attempt to link their formation to the tectonic history of these regions. They find that in all case studies (Fig. 3.6), the microcontinents experienced a long and complex tectonic history within areas with inherited heterogeneities and crustal weakness (such as old suture zones). These inherited structures can be reactivated during extension and can have an important role in the formation of microcontinents. Although a common triggering mechanism for their formation is difficult to identify, it seems to be linked with rapid changes of complex subduction dynamics.

These findings have been the starting point for the numerical study of PhD student **J. van den Broek,** Researcher **V. Magni,** and Professor **C. Gaina,** and Adjunct Professor **S. Buiter** (2020), in which they performed 3-D numerical models of subduction with the aim of investigating the role of inherited weak zones together with the effect of rapid changes in subduction dynamics on continental fragment formation. The models show that indeed both a region of weakness and a change of trench retreating velocity, in this case caused by a large rotation of the slab, are important ingredients for the formation of microcontinent and continental fragments in collision zones.

Climate changes - Ordovician paleogeography and climate change

New palaeogeographical longitude-calibrated maps for the earlier Ordovician (480 Ma) and the later Ordovician (450 Ma) were published by Cocks & Torsvik in 2020. The maps (Figure 3.7a) shows the distribution of lands and seas but also include the global distributions of benthic trilobites and brachiopods. The Ordovician saw some of the most varied climates and sea level variations of the whole Phanerozoic. At the beginning of the Ordovician, the Earth was

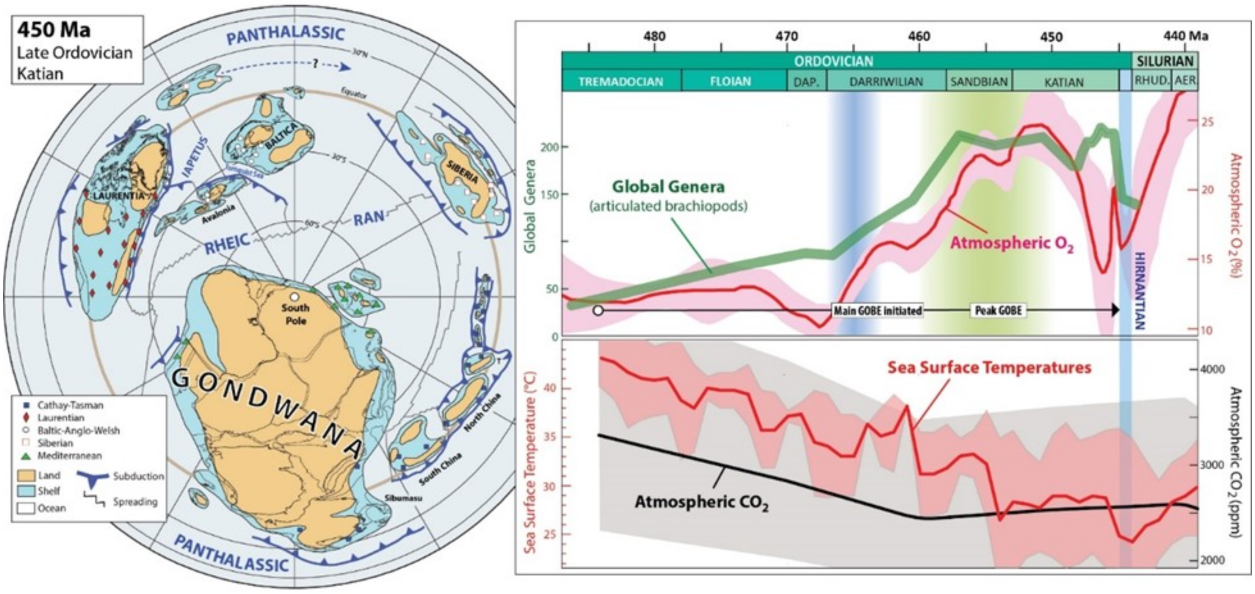


Figure 3.7. (a) Late Ordovician (Katian) lands and oceans at 450 Ma with representative sites of the various brachiopod provinces. (b) Ordovician and Early Silurian stages, a global genera diversity curve from articulate brachiopods and modelled atmospheric O_2 with 95% confidence envelope. (c) Sea surface temperatures and modelled atmospheric CO_2 (GEOCARBSULF model) with 95% confidence envelopes (Cocks & Torsvik 2020 and references therein).

*Corseri, R., **Gac, S.**, **Faleide, J.I.**, Planke, S., Journal of Structural Geology, 2020, 131, 103953*

A transdisciplinary and community-driven database to unravel subduction zone initiation: We constructed a transdisciplinary database featuring detailed analysis of more than a dozen documented subduction zone initiation (SZI) events from the last hundred million years. Our initial findings reveal that horizontally forced subduction zone initiation is dominant over the last 100 Ma, that most initiation events are proximal to pre-existing subduction zones, and that collision events along pre-existing subduction trenches are often precursors of SZI events.

*Crameri, F., **Magni, V.**, Domeier, M., **Shephard, G. E.**, Chotalia, K., Cooper, G, Eakin, C.M., Grima, A.G., Gürer, D., Király, Á., Mulyukova, M., Peters, K., Robert, B. & Thielmann, M. (2020). Nature Communications, 11(1), 1-14.*

Tectonic history of the Earth: We develop a numerical approach, combining plate kinematics and mechanical models of lithospheric deformation, to predict the Barents Sea plate deformation caused by the Paleogene transpression of Greenland vs. Svalbard. The models predict a fan-like folding pattern in accordance with observed anticlines in the Central Barents Shelf.

*Van der Voo, R. & **Torsvik, T.H**. 2020. In Mandea, M., Korte, M. & Petrovsky, E. (eds.): Geomagnetism, Aeronomy and Space Weather: a Journey from the Earth's Core to the Sun. Cambridge University Press doi:10.1017/9781108290135.003.*

Magnetotelluric Constraints on the Temperature, Composition, Partial Melt Content, and Viscosity of the Upper Mantle Beneath Svalbard.: The first long-period magnetotelluric data have been collected in Svalbard and combined with pre-existing broadband magnetotelluric data to produce a model of the electrical resistivity of Svalbard's upper mantle. This is the first direct evidence of partial melt in Svalbard's asthenosphere from deep geophysical soundings.

*Selway, K., Smirnov, M.Y., Beka, T., O'Donnell, J.P., **Minakov, A**., Senger, K., **Faleide, J.I.** and Kalscheuer, T., 2020. Geochemistry, Geophysics, Geosystems, 21(5), p.e2020GC008985.*

The misuse of colour in science communication.: We present the reasons why widely used colour maps, such as rainbow-like "jet," are problematic (including non-linear changes in lightness, unreadable to those with colour-vision deficiencies) and present free, easy-to-implement scientific alternatives.

*Crameri, F., **Shephard, G. E**., & Heron, P. J. (2020). Nature Communications, 11(1), 1-10.*

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van den Broek, J. and **C. Gaina**, 2020, Microcontinents and continental fragments associated with subduction systems, Tectonics, DOI:10.1029/2020TC006063

van den Broek, J. M., Magni, V., Gaina, C., & Buiter, S. J. H. (2020). The formation of continental fragments in subduction settings: The importance of structural inheritance and subduction system dynamics. Journal of Geophysical Research: Solid Earth, 125.

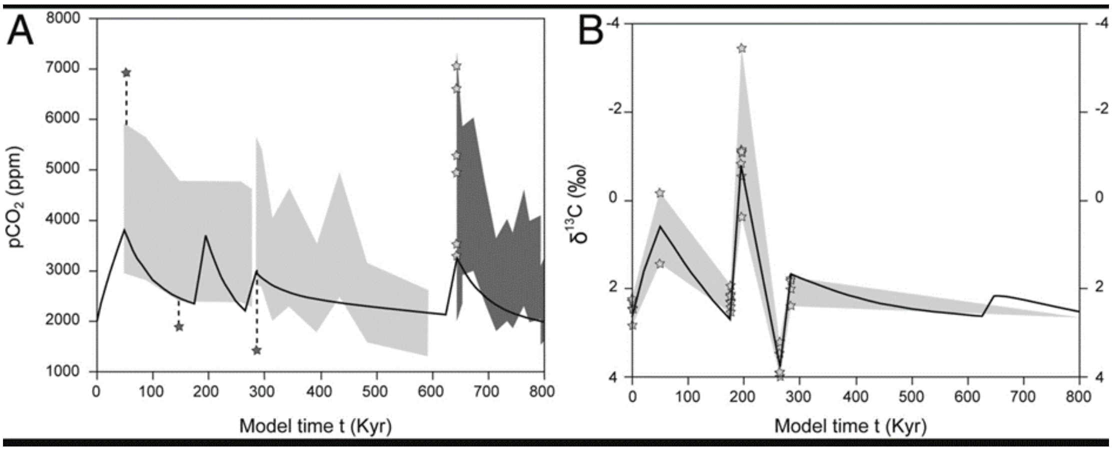
4. Earth`s Crises: LIPs, mass extinctions and environmental changes

In the Earth Crises Team we study volcanically driven effects on the climate system and the biosphere, focussing on large igneous provinces (LIPs). The Earth Crises mission is to investigate the role of volcanism in general, and sediment-derived gases in particular, on the history of life on Earth.

Here we present a selection of the results, updates, and activities from 2020, focussing on the following topics: 1) volcanic and thermogenic triggering of the end-Triassic crisis, 2) the Danish tephra record from the North Atlantic igneous province (NAIP), 3) the end-Permian mass extinction and the Arctic geochemical record, 4) successful proposals related to onshore and offshore drilling of Paleocene-Eocene strata, 5) active Earth degassing systems, and 6) update and projects from the CLIPT stable isotope lab. In addition, we have published papers on topics related to demise of the vast Irati-Whitehill Sea as part of a collaboration with Brazilian colleagues (Bastos et al., 2020), and weathering and temperature reconstruction across the PETM as part of **Ella Stokke**'s PhD project (funded by the The Ashlantic project) (Stokke et al., 2020a; 2020c). Moreover, we have published on the links between LIP volcanism and environmental changes (Svensen et al., 2020). The Earth Crises group activities also extend to planetary studies investigating eruptions and fluid migration systems on Mars (Brož et al., 2020a, 2020b). Another highlight from 2020 is the startup of **Sara Callegaro**'s NFR-funded young outstanding researcher project called MAPLES (Magma plays with sedimentary rocks: Element exchange between magma, sedimentary host-rocks, and the environment). Furthermore, **Adriano Mazzini** (CEED researcher) participated in fieldwork in Antarctica (Dec. 2019-Feb. 2020) as part of the PNRA-SENECA project, aimed at quantify the rapidly increasing regional gas emissions from permafrost thawing in the Dry Valleys region.

Volcanic and thermogenic triggering of the end-Triassic crisis

The Central Atlantic magmatic province (CAMP) coincided with the end-Triassic extinction event and several negative carbon isotope excursions (CIEs). Previous work by the group has shown that sill emplacement in Brazil generated extensive volatiles and triggered degassing due to contact metamorphism of evaporites, organic-rich shales, and hydrocarbons. However, the links between sill emplacement and carbon cycle disruptions requires further testing. A new study led by Postdoc **Thea Heimdal** (Heimdal et al., 2020) explores the effects of thermogenic carbon release from CAMP by using carbon cycle modeling and shows that it represents a credible source for the negative CIEs at the end-Triassic. The new results strengthens the hypothesis that the subvolcanic part of a large igneous province is of major importance for understanding carbon cycle disruptions. This is CEED-only contribution to a high-impact journal, and was led by the early career scientist Thea Heimdal.



The Danish tephra record from the North Atlantic igneous province (NAIP)

A study by PhD student **Ella Stokke** and Researcher **Morgan Jones** in collaboration with Emma Liu (University College London) was published in the open access journal Volcanica (Stokke et al., 2020b). It explores the physical and chemical properties of hundreds of basaltic ash layers found in sediments in Denmark, originating from the NAIP ~55 Ma. The results indicate that these extensive ash deposits were formed by explosive hydromagmatic (water-magma interactions) eruptions in shallow aqueous environments (<200 m water depth). We hypothesize that the prevalence of explosive activity at this time marks the transition of the rift axis of the proto-northeast Atlantic Ocean from subaerial to submarine. These events are calculated to be the largest explosive basaltic eruptions ever documented, suggesting that they would have had a substantial climatic impact.

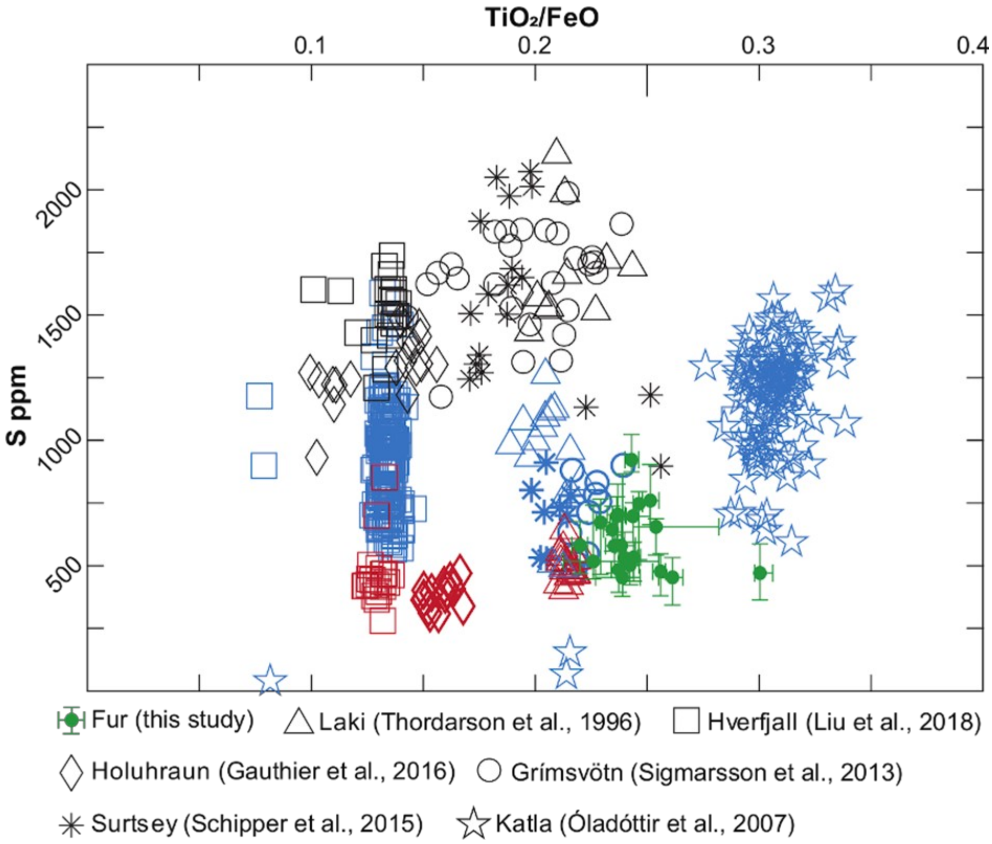


Figure 4.2 (above). A compilation of sulfur concentrations in Icelandic basalts as a function of TiO_2/FeO (Stokke et al., 2020b). Melt inclusions are shown in black, red points indicate fully degassed "dry" eruptions, while partially degassed hydromagmatic matrix glass is shown in blue. The ashes from Fur in Denmark are shown as green symbols. The comparison illustrates the similarity with Icelandic hydromagmatic systems (Stokke e tal., 2020b).

Figure 4.1 (left). Model response of atmospheric pCO_2 (A) and $\delta^{13}C$ of shallow ocean sediments (B; mean value of Atlantic, Indian, Pacific, and Tethys shallow ocean boxes) to a CAMP emission scenario including five pulses of carbon release (Table 1). The increases in $\delta^{13}C$ following each negative excursion and decreases in pCO_2 after each pCO_2 peak reflect organic carbon burial and/or silicate weathering. The gray outlines/star symbols represent the range of observed carbonate $\delta^{13}C$ values and pCO_2 data (Heimdal et al., 2020).

The end-Permian mass extinction and the Arctic geochemical record

In 2015 we successfully drilled the Permian-Triassic boundary in Deltadalen on Svalbard and initiated a multidisciplinary project on two 90 meter long cores. The two first papers were published in 2020, reporting the main findings. Analyses of the core and nearby outcrops include stratigraphic logging and sampling, XRF scanning, petrography, biostratigraphy, isotope geochemistry, and geochronology. The earliest Triassic strata are characterized by dark mudstones and we identified several tephra layers, one with a U-Pb TIMS zircon age of 252.13 ± 0.62 Ma (Zuchuat et al., 2020). High-resolution palaeoenvironmental proxies indicate a transition towards a more arid climate in the earliest Triassic, contemporaneous with prolonged bottom-water dysoxic/anoxic conditions, following an increase in volcanic activity. The $\delta^{13}C$ excursion in organic carbon record signals a large negative carbon isotope excursion (CIE) associated with the mass extinction event, but also records a second, smaller negative CIE above this interval. This younger $\delta^{13}C_{org}$ excursion correlates to similar CIEs in the Dienerian (late Induan) records of other sections, suggesting that the Dienerian crisis may have been global in extent. A second paper looks into the details in the geochemistry of iron and phosphorous and shows how an increased supply of nutrients to the ocean, potentially from volcanic activity, contributed to the mass extinction (Schobben et al., 2020).

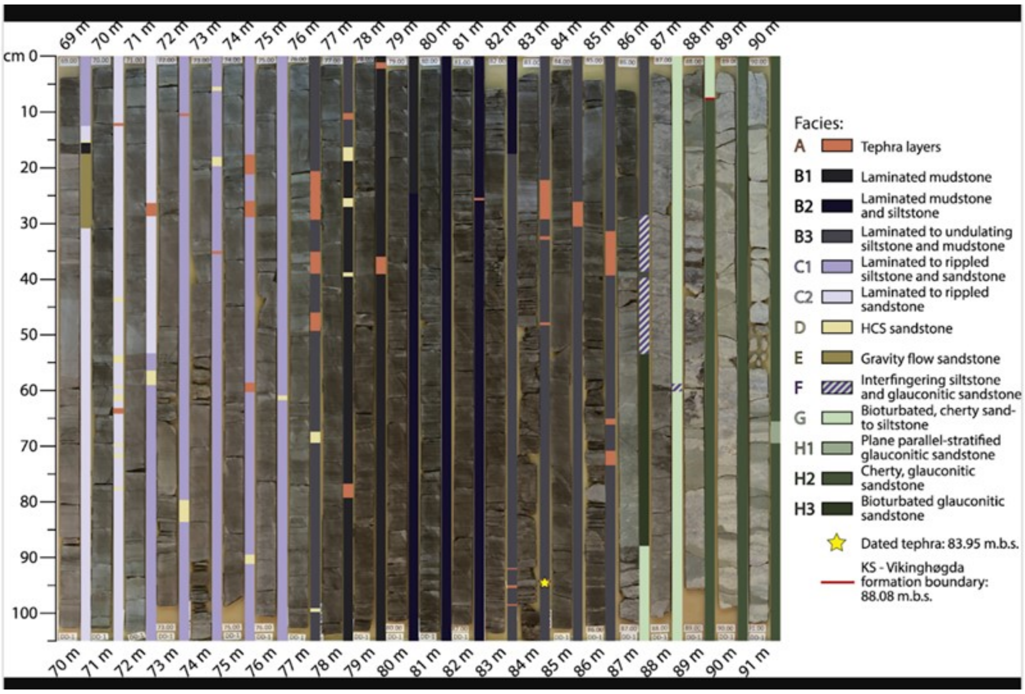


Figure 4.3. *Photographs of the core, sawed and facies coded, between 69 and 91 meter depth. The PT boundary is located between 85 and 87 meters. (Zuchuat et al., 2020)*

Successful proposals related to onshore and offshore drilling of Paleocene-Eocene strata

LIPs often coincide with environmental crises such as global warming and mass extinctions, which has led to the hypothesis that LIPs are the cause of these disturbances. However, this relationship is hampered by a shortage of sedimentary sequences proximal to LIPs that preserve numerous volcanic and climatic proxies. To address this knowledge gap, we have been working on raising funds for drilling expeditions to resolve the climatic forcing of the North Atlantic Igneous Province (NAIP) during the Paleocene and Eocene. These endeavours have been very successful, with two drilling proposals approved for funding in 2020.

The first application used the once-in-a-generation opportunity of the International Ocean Discovery Program (IODP) research vessel *JOIDES Resolution* returning to European waters. The Earth Crises team (**Sverre Planke, Morgan Jones, Henrik H. Svensen, Dougal Jerram**) helped instigate and co-led the proposal and will be shipboard scientists aboard IODP Expedition 396 that will drill a series of cores along the Mid-Norwegian continental margin in August -October 2021. This will be the first IODP drilling in Norwegian waters for over 35 years. **Morgan Jones** led a second application (PVOLC) to the International Continental Scientific Drilling Program (ICDP). The PVOLC project was approved for $725,000 of ICDP funding to cover drilling costs through Paleogene sediments in northwest Denmark, scheduled for 2022. These interdisciplinary projects will be of high impact and great value to a wide range of scientific disciplines.

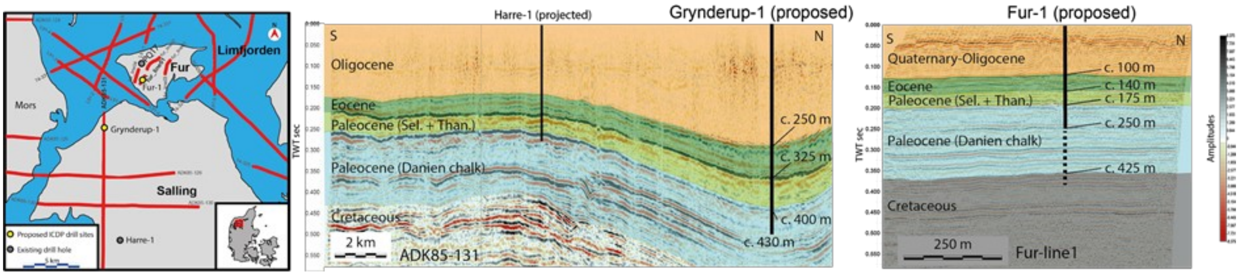


Figure 4.4. Left: Map of Limfjorden showing the Grynderup-1 and Fur-1 drilling site locations scheduled for ICDP project PVOLC in 2022. Right: Vibro-seismic cross sections and anticipated strata at the two drill localities.

Active Earth degassing systems

In the framework of the ERC-LUSI LAB project with PI **Adriano Mazzini**); we have published more than 30 papers dedicated to the Lusi eruption in Indonesia (Figure 4.5). Lusi represents a modern analogue for the palaeo vent systems that released to the atmosphere large amounts of volatiles. In December 2020, **Alexandra Zaputlyaeva** successfully defended her

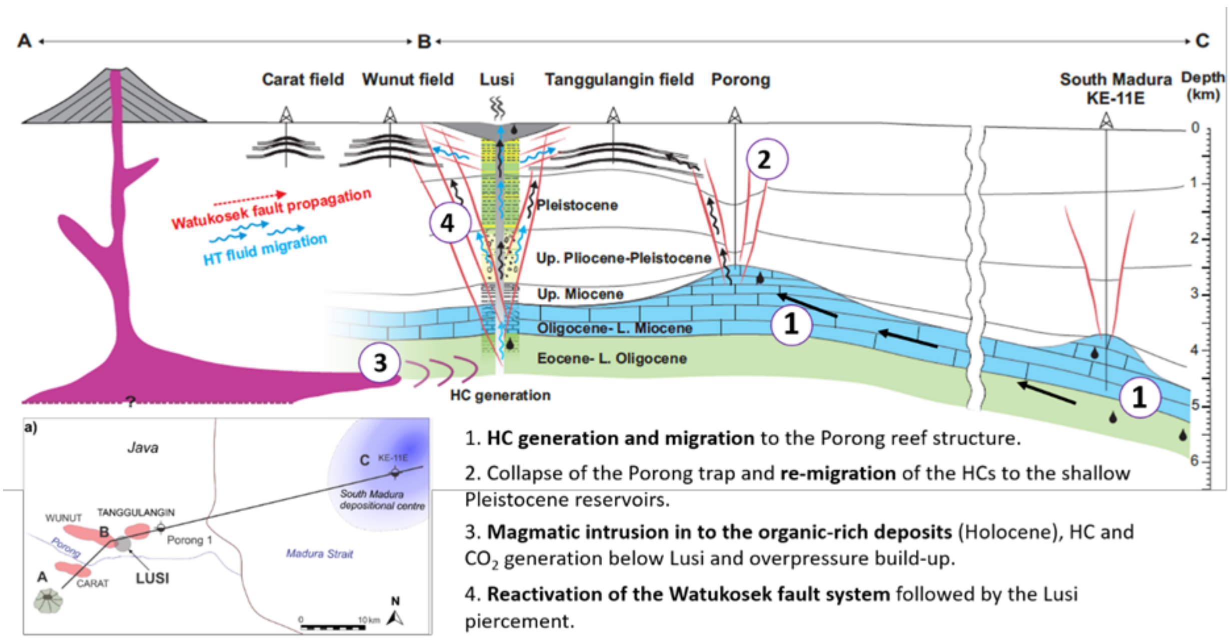


Figure 4.5. Conceptual geological model depicting the development of the petroleum system at the Lusi site and surrounding region. To date, the neighboring volcanic system is fueling the activity of the Lusi eruption.

PhD thesis including a study published in Scientific Reports (Zaputlyaeva et. al 2020). This work investigates the overpressure mechanisms fueling the eruption and the ongoing hydrocarbon generation triggered by the neighboring igneous intrusions and hydrothermal fluids migration in the sedimentary basin. (See also the front page of this report).

Also the HOTMUD project (PI **A. Mazzini**), targets the study of active degassing sites in Azerbaijan and in Lake Baikal where focused degassing is facilitated by the localized dissociation of gas hydrates or by >100 km long tectonic discontinuities (Solovyeva et. al., 2020). Particularly successful investigations have been conducted in the Sea of Galilee (Dead Sea fault, Israel) where fluids sampling and an ad hoc temporary seismic network revealed the geometry of new seismogenic faults that have been likely reactivated by the recent migration of deep overpressured mantle-derived fluids (Gasperini et al., 2020, Haddad et al., 2020).

Update and projects from the CLIPT stable isotope lab

Through 2020, the CLIPT lab has prioritized supporting CEED projects within the Earth Crises Group, providing consultation and stable isotope measurements for the projects utilizing stable isotope analyses. In addition to supporting ongoing projects, we have initiated preliminary paleoclimate studies that apply intra-ring stable isotope methodologies to infer paleoclimate using preserved wood specimens collected from the onset of the Siberian Traps (~250 Ma) and Holocene wood from Lake Baikal, Siberia. The CLIPT lab has also been involved with innovative research that utilizes a multidisciplinary approach to studying human health and the environment, as with the collaboration with Radiumhospitalet studying tumor growth using stable isotopes.

The CLIPT lab has continued in its mission to support the Norwegian sciences on a national level, adding to its user base in 2020 researchers from institutions throughout Norway, including UiB, UiT AMB institute, ARCTOS, NIVA, the University Centre in Svalbard and Havforskningsinstituttet & Norsk Polarinstitutt, Svalbard (See Table 1 on a later page).

In addition to providing analytical support to over twenty-four projects throughout 2020, the CLIPT lab has produced data in support of three published manuscripts (Cui et al., 2020; Jourdain et al., 2020; Stokke et al., 2020a), with three more in review.

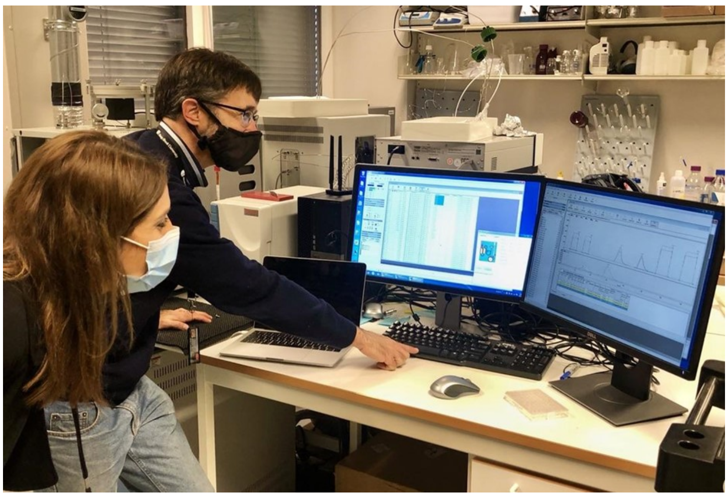


Figure 4.6. CLIPT lab users David Wright and Masters student getting a demonstration on how we measure stable isotopes with the mass spectrometer. Through the use of newly created online video resources, controlled in-person interactions, and stringent lab protocols, the CLIPT lab has continued to provide educational and analytical support for students and researchers in a safe manner.

The Stable Isotope Biogeochemistry lab

We are proud to offer our University of Oslo colleagues 13C, 15N, %C and %N analyses on organic samples. Our research focuses on living and fossil organisms, and how they are chemically linked to the global environment. Using measurements of the stable isotopes of carbon, nitrogen, hydrogen and oxygen, the group is working to elucidate information about metabo-

*Table 5.1. Summary of research projects in the Stable Isotope Biogeochemistry lab (**bold** for CEED members*

VIKINGS project: Stable Isotope Dendroclimatology of the 536 Event (**Henrik Svensen, Anne Jahren, Joshua Bostic**, Frode Iversen, Kulturhistorisk museum; Brian Schubert, University of Louisiana, Lafayette)
Host autophagy mediates organ wasting and nutrient mobilisation for tumor growth: natural abundance $\delta^{13}C$ as a tracer for carbon source (Tor Eric Rusten, Radiumhospitalet; Petter Holland, Radiumhospitalet; **Anne Jahren, William Hagopian**)
Using isotope ratios of edible plants to differentiate sources of carbon used for tumour growth in vivo (Tor Eric Rusten, Radiumhospitalet; Petter Holland, Radiumhospitalet; **Anne Jahren, William Hagopian**)
Spatial variability in $\delta^{13}C$ of terrestrial plants (Anne Jahren, Brian Schubert, University of Louisiana, Lafayette)
An interlaboratory comparison between Geologi Sediment Lab and CLIPT: Comparing elemental composition methodologies for difficult to combust geological samples (**William Hagopian**, Mufak Said Naoroz, Geology)
Fossil Wood from mud volcano: Preliminary $\delta^{13}C$ intra-ring variability investigation (**Adriano Mazzini, Anne Jahren, William Hagopian**)
Holocene mummified wood from Lake Baikal: Preliminary $\delta^{13}C$ intra-ring variability investigation (**Adriano Mazzini, Anne Jahren, William Hagopian**)
Siberian Traps permineralized wood from Lake Baikal: Preliminary $\delta^{13}C$ intra-ring variability investigation (**Henrik Svensen, Anne Jahren, William Hagopian**)
Neoproterozoic climate changes and biotic response: palynological/sedimentological investigation (Wolfram Michael Kürschner, Geology)
A green-blue link made browner: how terrestrial climate change affects marine ecology (Elisabeth Alve, Geologi; Silvia Hess, Geology+ masters students)
Nansen Legacy Project: effects of seasonality and species distribution on contaminant levels in the northern Barents Sea food web (Julia Giebichenstein, IBV; Katrine Borgå, IBV)
BIOS 5412 field and lab class: Toxicants in Ecosystems and Humans: Exposure and Accumulation (Katrine Borgå + undergradate and masters students, IBV)
Food web survey of Sydney harbour (Tom Andersen, IBV; Johanne Stølen, IBV)
Arctic Whales: Contaminants in stranded whales in Norway (Clare Andvik, IBV; Katrine Borgå, IBV; Anjali Gopakumar, IBV)
Festningen Arctic PT boundary stratigraphy : (**Sverre Planke, Morgan Jones, Henrik Svensen**)
VIKINGS project: Volcanic Eruptions and their Impacts on Climate, Environment, and Viking Society in 500–1250 CE (**Kirstin Krüger, Manon Bajard, Eirik Ballo**)
Malawi soils: Land use changes and human induced effects inferred from $\delta^{13}C$ and $\delta^{15}N$ (David Wright, Arkeology)
Nansen Legacy Project: The impact of chemosynthetic carbon sources in marine food webs at Arctic cold seeps (Emmelie Åström, ARCTOS at UiT)
Zooplankton Structure in Lake Mjosa Based on Their Isotopic Signatures (Collin Duinmeijer, IBV; Tom Andersen, IBV)
Nansen Legacy Project: Vertical export and pelagic-benthic coupling in the Northern Barents Sea (Yasemin Vicdan Bodur, UiT)

Table 5.1. continuation

Land-Ocean Interactions: Effects of terrestrial inputs on coastal food-web structure and contaminant trophodynamics in an Arctic fjord system (Maeve McGovern, UiT)
Organic stable isotope analysis (C&N) on marine mammals in the Barents Sea (Kirsteen MacKenzie, Norwegian Polar Institute and the Institute of Marine Research in Tromsø)
$\delta^{13}C$ and δ^{15N} analysis of human serum and urine to differentiate dietary intake of protein (Katrine Borgå, IBV; Jutta Dierkes, UiB)
Using coal $\delta^{13}C$ as a climate proxy (Malte Jochmann and Maria Jensen, The University Centre in Svalbard)

CLIPT Episode 1: Introduction to stable isotopes and the CLIPT lab

From a YouTube wideo demonstrating sample preparation in the CLIPT lab, by ***William. Hagopian.***

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5. Earth and Beyond: Comparative Planetology

Our mission is to understand the similarities and differences between Earth and the other terrestrial planets, with the main hypothesis that the dynamics of Earth and planets can be understood within the same framework, but with different parameters, and that water may be a key factor in determining the style of mantle convection, surface tectonics and volcanism. Therefore, we develop planetary time-scales, surface ages using cratering statistics and study impact cratering and crustal processes to determine planetary evolution.

Planetary Habitability and Martian Surface Evolution

In several studies, we investigated the martian surface composition and the environmental conditions in which the observed mineral assemblages could form. These assemblages are characteristic for different martian epochs and will be studied in upcoming landed missions.

Serpentine and carbonates at Nili Fossae

Both minerals have been detected on Mars by remote sensing and additionally, in situ analysis confirms the presence of hydrothermal carbonates. So far, only infrared spectroscopy from remote-sensing analysis enables precise mineralogical study essential to get insight into the geological context of the martian crust's serpentinization-carbonation. NASA's next rover, equipped with a near-infrared spectrometer will land in the Nili Fossae-Jezero system, which corresponds to such context. Only little is known about the conditions of hydrothermalism leading to formation of serpentine and carbonates on Mars. Variation of protolith, fluid composition as well as temperature may all be key factors at play during serpentinization and carbonation reactions, and exact conditions may have consequences for the H2/CH4 production, which are by-products of these reactions. Efficiency of crustal production of H2/CH4 could be the determinant ingredient for additional greenhouse effect allowing protracted stability of liquid water and, ultimately, habitability of Mars (Fortier et al., 2021). Researcher **Benjamin Bultel** and co-workers (Fortier et el, 2021; Bultel et al., 2020) use geochemical modelling to explore how mineralogy of protolith rock affects reaction, and more importantly, to explore the effect of fluid composition on the mineralogical assemblages formed. This study is complemented by an investigated analogue site (Bultel et al., 2020), the Leka Ophiolite Complex in Norway, within the PTAL (www.ptal.eu) collection. Mafic and ultramafic rocks at this site record complex weathering of serpentinite. The variety of alteration minerals produced allows us to study the effect of the accessory minerals (chromite, brucite, magnetite) on the near infra-red signal. Preliminary results (1, 2; Figure 5.1) suggest that the composition of the crust might be more heterogeneous than postulated for Mars and that H2/CH4 production might be too little to have an effect on climate. Thus, hydrothermalism may contribute less to the warming of martian climate. This challenges the habitability potential of serpentinization-carbonation systems on Mars.

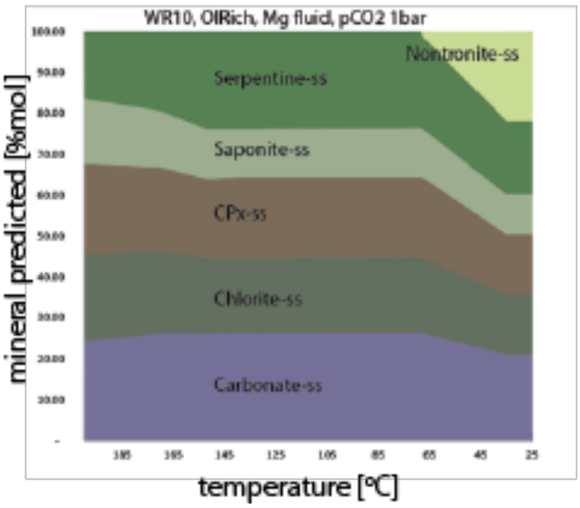

*Figure 5.1. Results of geochemical model. Volume of mineral [% mol] predicted to form as a function of the cooling temperature of the preferred scenario of hydrothermalism in serpentinization-carbonation system on Mars. Parameters are as follow: water-to-rock ratio of 10; Mg-rich fluid (pure water equilibrated with ultramafic rock), pCO2 of 1 bar, protolith: olivine-rich basalt. With these parameters, we reproduced the mineralogical association detected from orbit (*Fortier et el, 2021).

Relationship between salt deposits and paleolakes on Mars

Researecher **Agata Krzesinska** and co-workers (Kretzinska et al. resubmitted; Harrington et al., 2020) have performed extensive detailed mapping in Eridania Basin, Terra Sirenum, Mars. These maps outline chloride salt exposures at greater spatial resolution than previous works. We confirmed that chlorides occur in irregularly shaped topographic lows, as well as high-relief inverted channels. Most chloride deposits on Mars are high-albedo (i.e. appear bright in images, Figure 5.2), but a few salt exposures appear dark. The cause of its dark appearance is under investigation, and may owe to salt mixing with, or being occulted by, regolith. The most interesting finding is the presence of laterally extensive salt beds on Mars, forming unique stratigraphic layers. These beds can be correlated across outcrops, and provide insight into wide-scale basin processes in Mars' past. Because of the salt beds, we know these regions were once saturated with water, even if no other typical morphological features (e.g. channels, delta fans, gullies) are present in surrounding areas. Furthermore, some of the salt beds appear to be layered and even interbedded with other sediments implying episodic deposition or changing environments through time.

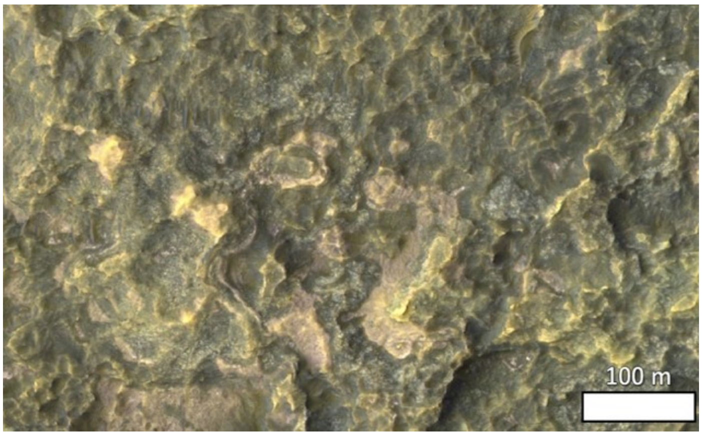

Figure 5.2. IRB false colour satellite HiRISE image of Eridania Basin (-180.0°E, -37.5°S), which was the largest paleolake on Mars. Unlike other paleolakes, it contains multiple evaporitic salt deposits along its ancient shorelines. Chloride salts appear to be forming a stratigraphic layer below the yellow-brown cap rock, and across the outcrops (Kretzinska et al. resubmitted); Harrington et al., 2020 .

Oxia Planum's Terrestrial Analogues

PhD student **Elise Harrington** and co-workers (Harrington et al., 2020) investigated mineralogy, aqueous history and habitability potential of Oxia Planum, a Noachian plain on Mars, and chosen as the final landing site for in-situ studies by ESA's ExoMars 2022 rover. The main scientific objectives of the mission are to understand the mineralogy and aqueous evolution of ancient Mars with relevance to habitability. As shown by spectroscopic investigation by NIR on board of Mars Express, Oxia is covered by vast deposits of Fe,Mg-phyllosilicates, but the exact nature of these deposits is unknown.

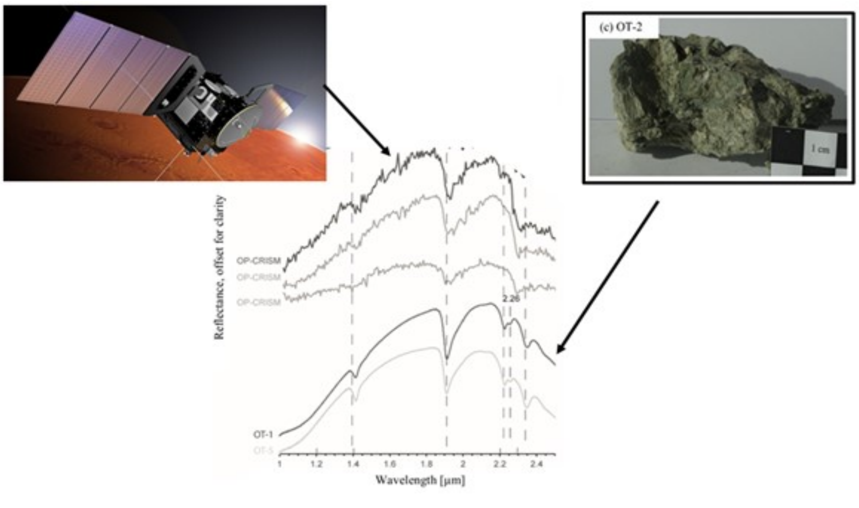

Figure 5.3. NIR spectra collected remotely for Oxia Planum and comparison with laboratory spectra from terrestrial analogue rocks. The comparison enables identification of vermiculite in bedrock of Oxia Planum and allows inference about the oxidation stage of Fe in the clay structure (Harrington et al., 2020).

Therefore, to better understand the mineralogy of deposits at Oxia Planum, we performed a survey of potential terrestrial analogue rocks and conducted mineralogical characterization of these rocks as well as their NIR spectral analysis. Samples from two terrestrial sites appeared to be best fit: 1) vermiculitized chlorite-schists from Otago, New Zealand, which underwent an alteration process without significant oxidation; and 2) basaltic tuffs from Granby, Massachusetts, USA, with Fe-rich clays filling amygdales of supposedly hydrothermal origin. Our research shows that Oxia bedrock clay-rich deposits best spectrally match a well-crystallized trioctahedral vermiculite-saponite. Trioctahedral vermiculite has great potential to store organic matter and the post-deposition geological context of Oxia Planum derived from understanding of environmental conditions in analogue sites is promising for organic matter preservation.

Planetary Interior Dynamics, Tectonics, and Resurfacing

Postdoc **Maelis Arnould**, Researcher **Tobas Rolf, former** Master student **Rebecca Karlsson** and co-workers (Arnould & Rolf, 2020; Rolf & Arnold, 2020; Uppalapari et al., 2020; Karlsson et al. 2020) investigated the effects of composite rheology (co-existing creep mechanisms) in numerical models of mantle dynamics and plate-like behaviour. The presence of dislocation creep locally reduces mantle viscosity and affects the strength of subducting slabs and how they drive surface plate motions (Arnould & Rolf 2020). We extend this work for instance by incorporating grain-size evolution. In parallel, the history-dependence of rheology has been investigated using a strain weakening formulation (Uppalapari et al., 2020). Strain weakening strongly affects the stability field of tectonic regimes (Figure 5.4), but does not strongly change the dynamics of a given tectonic regime. We also investigated the dynamics of lithospheric overturns potentially important for Venus' evolution (Uppalapari et al., 2020) and how they contribute to the resurfacing history of Venus, with and without the present of pre-existing crustal provinces (Karlsson et al. 2020). Finally, the underlying model has been updated to be applicable for modelling icy satellites, for instance via a parameterization of tidal heating, which could be an important driving mechanism for convection in the outer icy shells of these bodies.

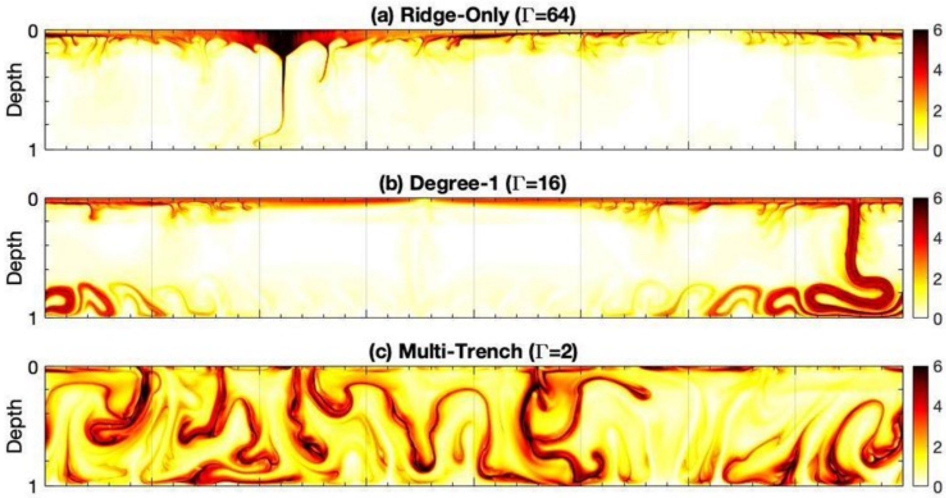

Figure 5.4. Accumulation of strain in mantle convection. Dark regions are more strongly strained and (depending on the choice of the critical strain G) experience a reduction in their plastic strength, which can lead to different tectonic regimes under otherwise identical conditions: (a) ridge-only regime (only spreading ridges, no subduction zones), (b) degree-1 (a single stable ridge + a single stable subduction zone), (c) multi-trench (multiple, time-dependent spreading ridges and subduction zones; Rolf & Arnold (2020).

Asteroids, Meteorites, Comets and the first interstellar object ‘Oumuamua

Adjunct professor **Jane Luu** and co-workers (Luu et al.,2020) present a model to explain the origin of ‘Oumuamua, and the possible link between ‘Oumuamua and the second interstellar comet-like object Borisov. In this study, we follow up for active asteroids using observations from the Nordic Optical Telescope (NOT). These asteroids are particularly interesting because their intermittent (sometimes periodic) mass loss reveals how the small bodies in the solar system are modified on much shorter timescales than previously expected. At the same time, we map the mass wasting and landslide related geological activity on dwarf planet Ceres, the largest “asteroid” in the asteroid belt. We [see CEED public outreach) also had the opportunity to contribute in the classification of two meteorites, which fell in Norway and which have their origin probably in the outer asteroid belt, although they are not from Ceres.

Cratering, the key to the past

Target properties have been since long argued to influence size and shape of a crater despite all other impact conditions are the same. Professor **Stephanie Werner**, Researcher **Nils Prieur** and co-workers have developed automated tools to extract morphometric parameters for fresh craters. We started with the Moon. Typically, the relationship between the crater rim depth dr and diameter Dr shall demonstrate the target influence. Figure 5. 5 shows this relationship for fresh craters, the depth-to-diameter dr/Dr as a measure of diameter Dr, and for a moving averages for those on the lunar mare (in red) and highlands (in black). This enhances the possible differences in dr/Dr caused by the difference in target properties. As a result, one would need to consider this possibility for the age dating technique based on cratering statistics. Future work will show what corrections will be required if measurements on mare and highland units shall be compared.

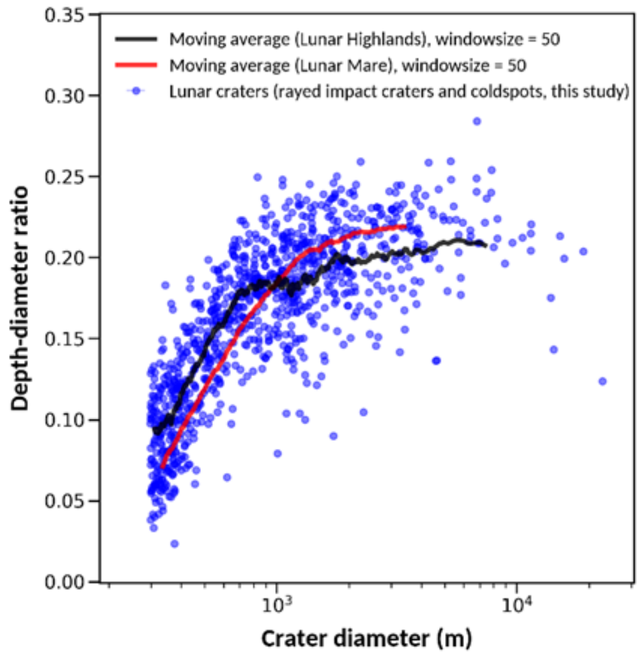

Figure 5.5. Relationship between the depth-to-diameter dr/Dr and Dr. A moving averages (with a window of 50 values) for craters located on the lunar mare (in red) and highlands (in black) enhance the possible differences in dr/Dr (Prieur & Werner, 2020; Prieur et al., 2020).

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The Ariel mission

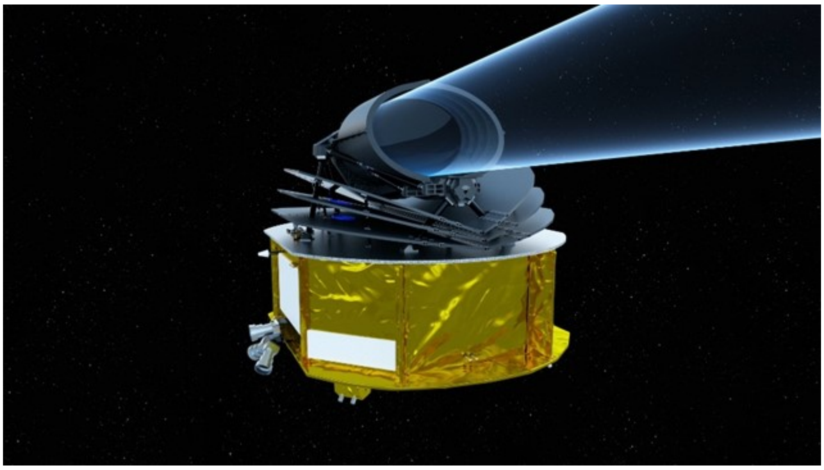
Ariel will survey about 1000 planets outside our solar system during its lifetime. It will unveil the nature, formation and evolution of a large and assorted sample of planets around different types of stars in our galaxy

More than 50 institutes from 17 countries have been working over the past 5 years to develop the science goals and design the instrumentation, which will enable Ariel to survey a diverse sample of around 1000 planets outside our own solar system.

Professor Stephanie Werner, Co-PI in the Ariel Consortium from University of Oslo is excited to be part of the mission: *Ariel will provide a unique set of atmosphere observations of numerous exoplanet very different from those we know in the solar system. We will be able to probe the composition of these planets. Studying planetary systems in this detail will completely change the field of comparative planetology!*

The Ariel consortium

The Ariel mission payload is developed by a consortium of more than 50 institutes from 17 ESA countries – which include the UK, France, Italy, Poland, Belgium, Spain, the Netherlands, Austria, Denmark, Ireland, Czech Republic, Hungary, Portugal, **Norway,** Sweden, Germany, Estonia – plus a NASA contribution.



Artist's impression of Ariel. Image Credit: ESA/STFC RAL Space/UCL/UK Space Agency/ ATG Medialab (https://arielspacemission.files.wordpress.com/2020/11/ariel-telescope.jpg)

The Earth Laboratory group focuses on research in paleomagnetism and its applications to paleogeography, plate tectonics and geomagnetic field behavior. In 2020, the group was active in a variety of projects, which included testing the hypothesis of ultra-fast polar motion during Late Jurassic time, resolving a long-standing controversy between the North American and European Late Jurassic-Early Cretaceous paleomagnetic poles, constraining paleogeography in early Permian time, testing a new tectonic model for the opening of the Neoproterozoic Iapetus Ocean, and probing the morphology of the Earth paleomagnetic field through numerical simulations and analysis of paleomagnetic observables. In addition, we have contributed to broader efforts of CEED in development of plate reconstructions, geodynamic models, and scientific visualization. In 2020, the researchers of the Earth Laboratory group authored seven peer-reviewed articles, two of which were published in Nature Communications.

A paleomagnetic test for ultra-fast polar motion and true polar wander in the Late Jurassic

Although much information about paths of apparent polar wander for continents and other major tectonic blocks has been collected by paleomagnetists since the 1950s, many fundamental questions have yet to be resolved. One well-known example is the controversy over the Jurassic-Cretaceous apparent polar wander path (APWP) for North America. Paleomagnetic data from the North America indicate a vast amount of rapid polar motion in Late Jurassic time, from ~160 Ma to 145 Ma. The over 30° of polar motion that accumulated over a relatively short time interval has been referred to as the Jurassic “monster polar shift” by some workers (e.g., Kent et al., 2015) and may be indicative of an episode of true polar wander (TPW), that is, a rotation of the entire solid Earth relative to the spin axis. However, this rapid TPW event is not supported by paleomagnetic data on the global scale. Notably, the coeval APWPs for Europe and Gondwana, when reconstructed to North America, show much slower polar motion, which is not compatible with the proposed monster polar shift (Figure 6.1a). The inconsistency cannot be explained by errors in relative plate reconstructions and introduces large uncertainties in absolute paleogeography models. We have scrutinized the Jurassic apparent polar wander path (APWP) by virtue of a new paleomagnetic and 40Ar/39Ar geochronology study of Mesozoic coast-parallel dykes exposed in southwestern Greenland. Combined with existing geochronological data, our results show that the age of dyke emplacement was 147.6 ± 5.6 Ma (2σ uncertainty quoted). A primary nature of the characteristic remanent magnetization is supported by multiple positive baked-contact tests and a reversal test. The paleomagnetic pole calculated from 40 site-mean paleomagnetic directions is located at Plat = 69.3ºS, Plong = 5.0ºE (A95 = 4.6º is the radius of the 95% confidence circle), or at Plat = 73.9ºS and Plong = 0.4ºE when reconstructed to North America. Our new high-quality paleomagnetic pole and an updated global APWP (Figure 6.1b) do not support the fast Jurassic polar shift but instead indicate steady polar motion with moderate rates of about 0.7º/Myr. The new pole effectively eliminates the inconsistency between the APWPs for Laurentia and Europe (Figure 6.1a). Our critical reassessment of paleomagnetic data for the Late Jurassic and Early Cretaceous indicates that the monster polar shift is an artifact caused by various deficiencies of paleomagnetic and geochronological data that were originally used to define it. A manuscript describing these findings have been submitted to Gondwana Research by the Researchers **Evgeniy Kulakov** and **Pavel Doubrovine, Petter Silkoset**, Professor **Trond H. Torsvik** and their coauthors.

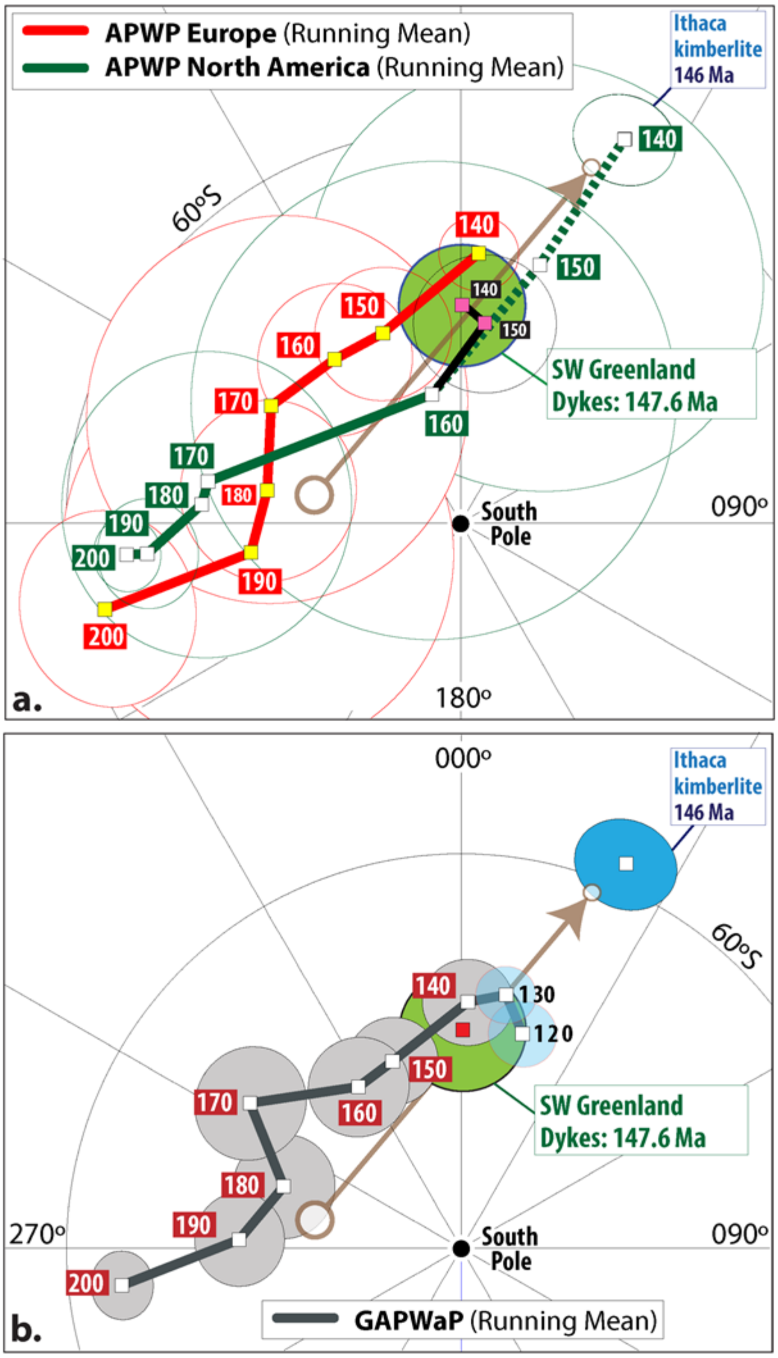


Figure 6.1. (a) Apparent polar wander paths (APWPs) for Europe and North America (Torsvik et al., 2012). The new Greenland pole is shown by the red square with the lime green A95 circle. The Europe APWP and the Greenland pole were rotated to North America. The North American APWP is shown in two versions. The stippled green line between 160 and 140 Ma shows the version that includes the Ithaca 146 Ma kimberlite pole we no longer consider reliable. The solid black line shows the version where we exchanged the Ithaca pole with the Greenland pole. The brown arrow schematically shows the proposed Jurassic monster polar shift. (b) The global APWP (GAPWaP) updated from Torsvik et al. (2012), including our new Greenland pole. Note that the Jurassic monster polar shift is not compatible with the GAPWaP.

Paleogeographic position of the early Permian Tarim large igneous province

The tectonic block of Tarim is one of the principal cratonic components of East Asia, but there is considerable disagreement in the literature on how Tarim was positioned in the Paleo-Asian and Tethys tectonic systems of the late Paleozoic, and different scholars have restored Tarim differently with respect to the supercontinent Pangea. Early Permian magmatic rocks from Tarim have previously been interpreted as remnants of a large igneous province (LIP) and were therefore possibly derived from a mantle plume originating at the core-mantle boundary. In our new study (Wei et al., 2020), Researcher **Mathew Domeier** and his coworkers have reexamined the absolute paleogeographic position of the Tarim block using newly acquired paleomagnetic data from early Permian rocks (~288 Ma) in the Keping area of northwestern Tarim, and using inferences drawn from the plume generation zone reconstruction method. A stable high-temperature component was isolated in 413 samples from 51 sites (basalt flows and intercalated sediments). The directions of this characteristic component pass the fold test and show exclusively reversed polarity, which is consistent with their acquisition during the late Carboniferous to mid-Permian Kiaman Reverse Polarity Superchron. These observation suggest that the high-temperature component is likely a primary magnetization. Using these directions, we have computed a new early Permian pole for Tarim, which is located at 50.1°N, 170.5°E and has the 95% uncertainty radius A95 = 3.6°. Taking the estimated eruption center of the Tarim LIP (41°N, 80°E) as a reference point, this pole restores the LIP to a paleolatitude of ~30° at 288 Ma. Using this paleolatitude estimate, we attempted to fit the LIP to the edge of one of the large low shear-wave velocity provinces (LLSVPs) in the lowermost mantle. Our analysis shows that it is not feasible to reconstruct the Tarim LIP directly above the margins of either the African or Pacific LLSVPs (Figure 6.2), but its reconstructed position could be associated with the Perm anomaly in the deep mantle (Figure 6.2). The suggested link implies that, similarly to the two LLSVPs, the smaller-scale Perm structure may have been stable in its nearly present-day position over the past 300 million years.

A two-stage model for the opening of the Iapetus Oceans in the Neoproterozoic

The Iapetus Ocean opened during the breakup of Rodinia by the separation of the major continental blocks of Laurentia, Baltica, and Amazonia (Figure 6.3). Records of rift-related magmatic activity along those continental margins indicate two distinct phases of rifting, at 750–680 Ma and at 615–550 Ma, respectively (Figure 6.3a). The earlier phase is commonly thought to be a failed rift attempt, whereas the later phase marks the opening of the ocean basin. Based on a compilation of paleomagnetic data for 550-750 Ma, detrital zircon records for Laurentia and Amazonia, and review of other geological observations along the margins involved in the opening of the Iapetus Ocean, Postdoctoral Researchers **Boris Robert**, Johannes Jakob and Researcher **Mathew Domeier** have developed a new plate tectonic model that challenges this concept. Our model calls for the successive opening of two "Iapetan" ocean basins. First, the "Paleo-Iapetus" basin opened between Laurentia and Amazonia at ca. 700 Ma. The later demise of the Paleo-Iapetus mid-ocean ridge and the arrival of a mantle plume at the Laurentian margin around 615 Ma (Central Iapetus Magmatic Province) triggered the opening of the "Neo-Iapetus" basin, leading to the final disaggregation of the supercontinent Rodinia (Figure 6.3b). This scenario better explains the absence of the second rifting phase in western Amazonia, as well as an otherwise enigmatic late Neoproterozoic detrital zircon age fraction in Phanerozoic sediments along that margin. Our new model further proposes that the opening of the Neo-Iapetus Ocean led to the detachment of small

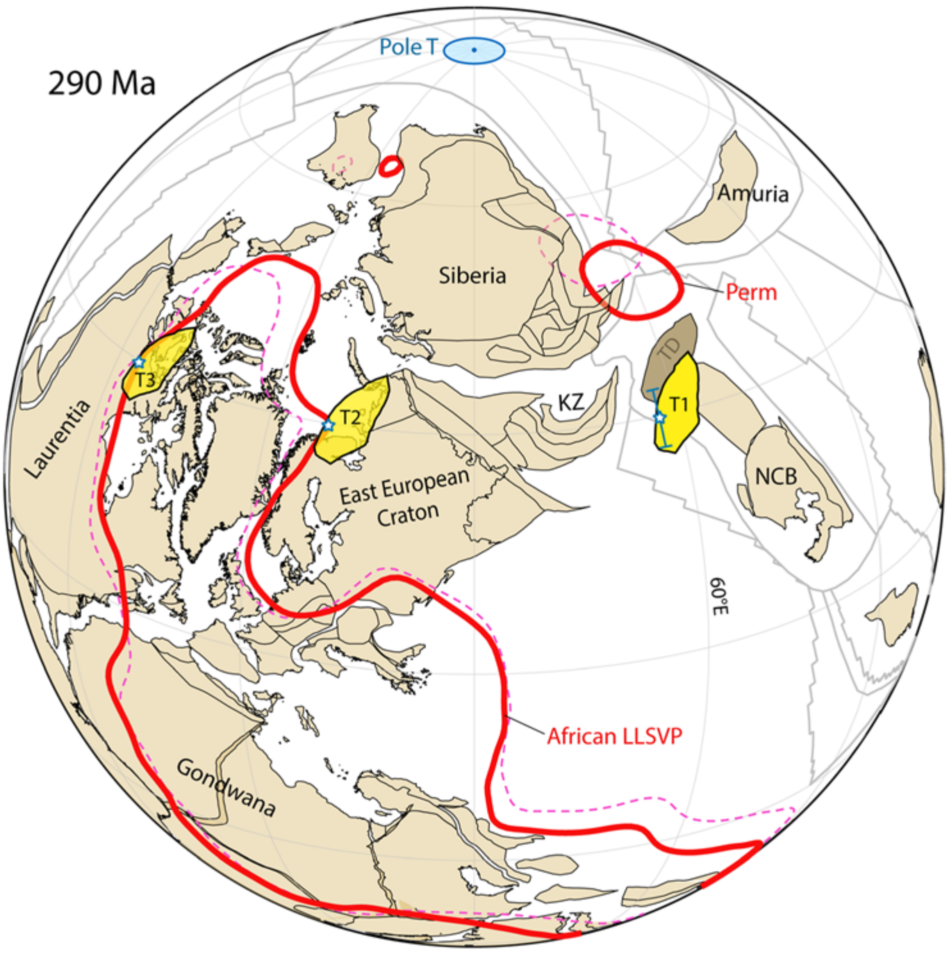


Figure 6.2. Paleogeographic reconstruction at 290 Ma with alternative longitudinal restorations of Tarim (T1-T3) suggested by correlation with the edges of low shear-wave velocity anomalies in the deep mantle (LLSVP and Perm). The blue circle represents the error range (A95) of our new pole from the Tarim LIP. TD is the location of Tarim in Domeier and Torsvik (2014). T1 is our preferred reconstruction of Tarim; T2 and T3 represent excluded restorations of Tarim. Blue star shows the sampling location; red dotted and solid lines represent the boundaries of the LLSVPs (according to Doubrovine et al., 2016) in the mantle and paleomagnetic reference frames, respectively. The locations of Siberia, Kazakhstan (KZ), and the East European Craton are from Domeier and Torsvik (2014).

terranes from Laurentia and their drift toward Amazonia, which was similar in style to the opening of the Neo-Tethys Ocean in late Paleozoic time. The evolution of the Iapetus Ocean realm may thus be a direct, deep-time analog of the tectonic history of the Thetis and Neo-Thetis Oceans. This study was a part of the NFR Young Research Talent project “A model of global tectonics for the last 600 Myr” (PI Mathew Domeier); the results were published in Geology (Robert et al., 2020).

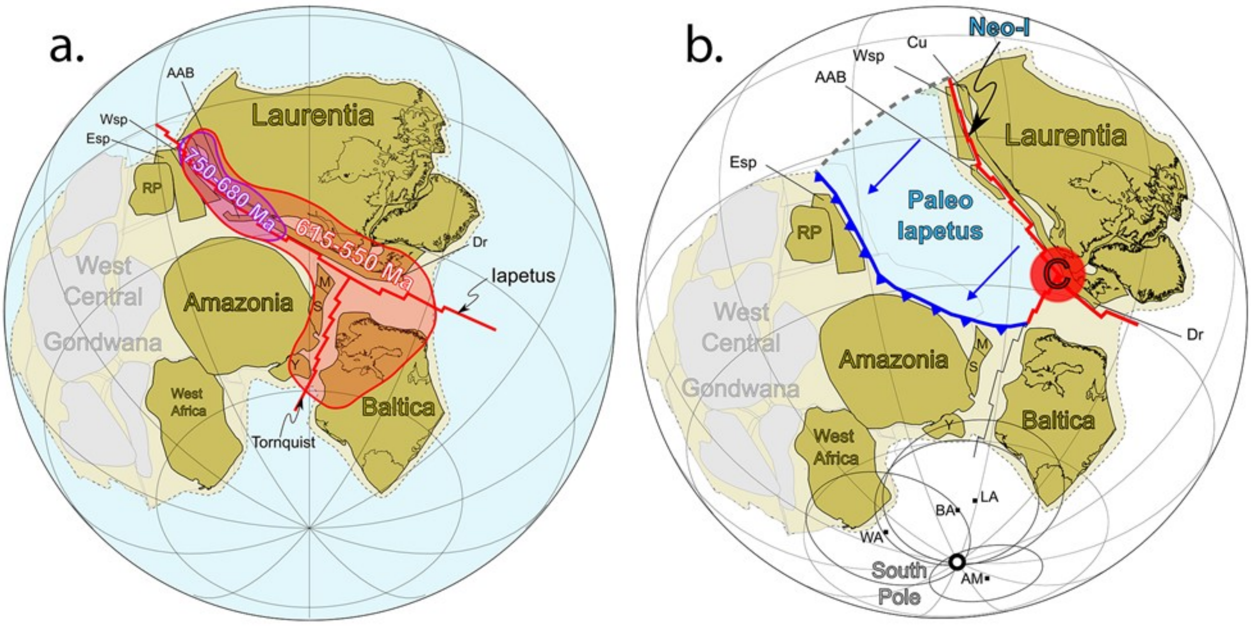


Figure 6.3. (a) Limits of rift-related magmatic pulses at 750-680 Ma (purple) and 615-550 Ma (pink) are shown on the map of pre-breakup configuration of Rodinia. (b) Paleogeographic reconstruction of the Iapetus Ocean at 615 Ma. The reconstruction time corresponds to the initiation of the Neo-Iapetus mid-ocean ridge that followed subduction of the Paleo-Iapetus ridge and emplacement of the Central Iapetus Magmatic Province (the LIP center is shown by the red circle with the letter C). Select paleomagnetic poles for major blocks are shown by black dots with A95 circles around the South Pole (from Robert et al., 2020).

Estimates of geomagnetic axial dipole dominance in deep geologic time

The dominance of the axial dipole contribution over other, higher degree-and-order components is a defining characteristic of the recent geomagnetic field, providing its navigational utility and dictating the shape of the magnetosphere and the efficiency with which it shields the Earth from the solar wind radiation. The geocentric axial dipole (GAD) geometry of the field averaged over time scales of ~105 to 106 years is a cornerstone assumption in paleomagnetism, giving us effective means to constrain paleogeography in deep geologic time. While supported by paleomagnetic data for the last few millions of years of the Earth’s history, the only time period for which the global data coverage is achievable, much less is known about the degree of axial dipole dominance in more distant geologic past. Researcher **Pavel Doubrovine** and his coworkers have developed a novel method for estimating the degree of geomagnetic axial dipolarity in ancient times through analysis of directional dispersion of palaeomagnetic data. Using a large set of diverse tree-dimensional numerical simulations of Earth-like dynamos and empirical models of geomagnetic secular variation based on paleomagnetic observables, we derived a power law relationship between the angular dispersion of virtual geomagnetic poles (VGP) at the equator and the median axial dipole dominance (AD/NADmedian) measured as the ratio between the power of the axial dipole field at the Earth surface and the power of the remaining non-axial dipole terms (Figure 6.4a). An extensive suite of sensitivity tests showed that this power law relationship is robust and provides reliable quantitative estimates for the axial dipole dominance over a wide range of dipolarity states. Applying the power law to published estimates of equatorial angular dispersion suggests that the geomagnetic axial dipole dominance averaged over 107–109 years has remained high, at levels similar to the present state, and was remarkably stable through large parts of geological time (Figure 6.4b). These results challenge a wide-held belief that the degree of dipolarity anticorrelates with the frequency of geomagnetic reversals, and the inferred stability provides an observational constraint to future studies of the geodynamo and paleomagnetosphere. Our results also provide further reassurance as to the reliability of paleogeographic reconstructions constrained by paleomagnetic data under the assumption of GAD morphology for the time-averaged field. This study was published in Nature Communications (Biggin et al., 2020).

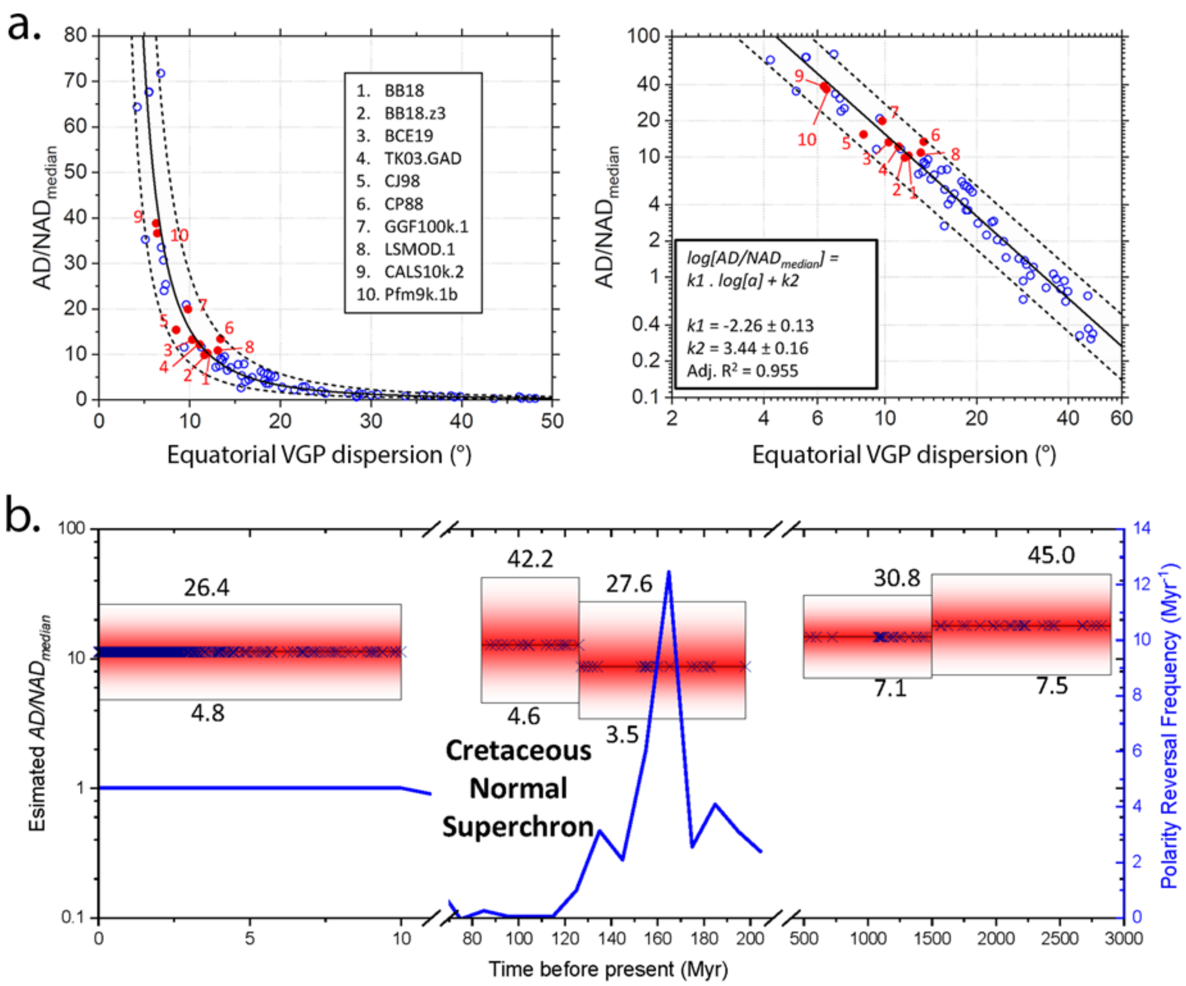


Figure 6.4. (a) Power law relationship between the median axial dipole dominance (AD/NADmedian) and VGP dispersion at the equator. Same data are shown on linear (left panel) and log-log (right panel) plots. Blue open circles are outputs of numerical geodynamo simulations. Red solid circles are predictions observation-based models paleosecular variation for the last 10 Ma. Solid black line is the best-fit power law curve calculated from a linear regression performed in log-space; shaded area with dashed outlines is the 95% prediction bounds. (b) Estimates of axial dipole dominance for the ancient geomagnetic field obtained by application of the power law. Horizontal range of boxes indicates nominal time range; vertical range indicates 95% uncertainties with numerical bounds provided. Crosses show ages for paleomagnetic data sets used to estimate equatorial VGP dispersion (from Biggin et al., 2020).

The National Geomagnetic Laboratory

In 2020, the national geomagnetic laboratory that our group runs and manages (the Ivar Giæver Geomagnetic Laboratory, www.iggl.no) had to operate in a greatly reduced capacity because of the university lockdown caused by the covid-19 outbreak in the spring-summer and overall limited technical support during the larger part of the year (ca. 50% workload compared to 2019). Nonetheless, several research projects were carried out at the laboratory despite these limitations; these projects are listed in Table 6.1.

*Table 6.1. Summary of research projects that used the geomagnetic laboratory in 2020 (CEED members in **bold).***

Ediacaran field behavior and tectonics from the Avalonia zone of eastern Newfoundland, Canada (**Boris Robert, Mathew Domeier**)
Paleogeography of the Tarim Large Igneous Province (**Mathew Domeier**, Bitian Wei, Northwest Univ. Xi'an, China)
Paleomagnetism of Devonian and Carboniferous igneous rocks of the Orkney Islands, Scotland (MSc student Thomas Viken, **Mathew Domeier**)
Paleomagnetism of Mesozoic and Precambrian diabase dikes from southwestern Greenland: Implications for paleogeography and true polar wander (**Evgeniy Kulakov**)
Precambrian paleomagnetism of northern Norway (**Evgeniy Kulakov**, Trond Slagstad, NGU)
The paleogeography of young Rodinia: Paleomagnetic constraints from southern Norway (**Evgeniy Kulakov**)
The shape of Pangea in the early Permian: Paleomagnetic constraints from Morocco (**Mathew Domeier**)
Magnetic characterization of graphene oxide derivatives (Maryam Modarres and Rune Wendelbo, Abalonyx AS)
Magnetic properties of Fe-Co-Ni-Mg-Al high-entropy alloys (Anthoula Poulia and Pavlo Mikheenko, UiO Dept. of Physics + SINTEF)

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Field work in the West Troms region summer 2020, where 1.75 -1.70 Ga gabbroic dykes cut the crystalline basement in a pre-caledonian basement window. Photo: ***Evgeniy Kulakov***

Young CEED: The Subduction Zone Inititation (SZI) database is published

In 2017, at a CEED meeting in Tenerife, a team of international early-career researchers conceived an idea to create a truly open, large-scale and interdisciplinary database – the topic of discussion, how subduction zones initiate. In 2020, researchers **Fabio Crameri, Valentina Magni, Matthew Domeier, Grace Shephard, Ágnes Király,** and **Boris Robert**, along with a team of international interdisciplinary researchers, brought the SZI Database to life. To-date, the project has since led to several conference presentations, a publication in Nature Communications (Crameri et al., 2020a), media coverage, as well as a regularly-updated online database, new definitions and connection, and growing community network – the outcomes of YoungCEED 2018 are of scientific, academic, and even personal value.

Active and extinct subduction zones - the surface point where one tectonic plate plunges, or used to plunge, under another - can be found all over our planet. However, as it turns out, Subduction Zone Initiation (SZI) is a pretty tricky process to understand. SZI occurs over millions of years and we cannot thus see it happening today easily. The rock record of its earliest events (e.g., ophiolites, metamorphic soles, and boninites) have often already been subducted deep into the Earth's mantle or, else, can yield large uncertainties. The potential driving forces are not only limited to the arrival of hot mantle plumes, heavy sediment loading, water or melt intrusions, existing structural weakness or plate boundary, nearby subduction zones, and major mantle downwelling and features. Indirect geophysical evidence can be subject to non-uniqueness or resolution issues. We don't know a lot about the conditions under which subduction zones initiate (even though they constantly do so!) and the existing, extensive research aimed at solving such a key cross-disciplinary problem of the Earth Sciences has now diverged into many, very specialized subdisciplines.

The first YoungCEED initiative aimed to make accessible the extensive data and knowledge on subduction zone initiation (SZI) that, to-date, is veiled within various disciplines, by discipline-specific jargon, and behind pay- and other walls. The interdisciplinary team of 14 people, assembled as part of the initiative to concentrate their diverse expertise in plate tectonics, palaeomagnetism, structural geology, numerical modelling, geochemistry, and seismology. The project kicked-off in 2018, and the following two years of close digital collaboration led to the publication of the brand new transdisciplinary Subduction Zone Initiation Database (Crameri et al., 2020b), the accompanying paper in Nature Communications, and the accessible online platform, www.szidatabase.org.

The value of this project is manifold. First, the SZI Database provides open-access data from direct evidence, plate reconstructions, seismic tomography, and community-based interpretation for, as of now, 13 individual SZI events that occurred during the last around 100 Million years. Second, the invited open-access paper (Crameri et al., 2020a) reviews a wide range of existing literature, presents new and clear universal definitions, key insights into subduction ingredients, and outlines future directions including community participation.

Third, the online platform, SZIdatabase.org, provides key information about SZI, the universal glossary, the specific SZI events in detail, access to the database, paper and other resources, and the online community forum. It is designed to make SZI research accessible and open to feedback and ever-evolving insights from the community.

By looking at common features across multiple SZI events that occurred within the last 100 Million years, some of the following key geoscientific insights are now documented:

- At least 13 unique SZI sites were identified to have started within the last 100 million years.
- These events seem to cluster around two time periods; 6-16 Million years ago, and 40-55 Million years ago.
- Subduction was found to "breed" into other subduction; i.e. truly "spontaneous" SZI is unlikely to have occurred in the recent past.
- Horizontally forced SZI is dominant over vertically forced SZI; tectonic forcing is an important ingredient.
- Well known SZI candidate sites, such as the Puysegur trench near New Zealand, are not considered to have yet developed into a "self-sustaining" zone and thus are not technically SZI events for this database.

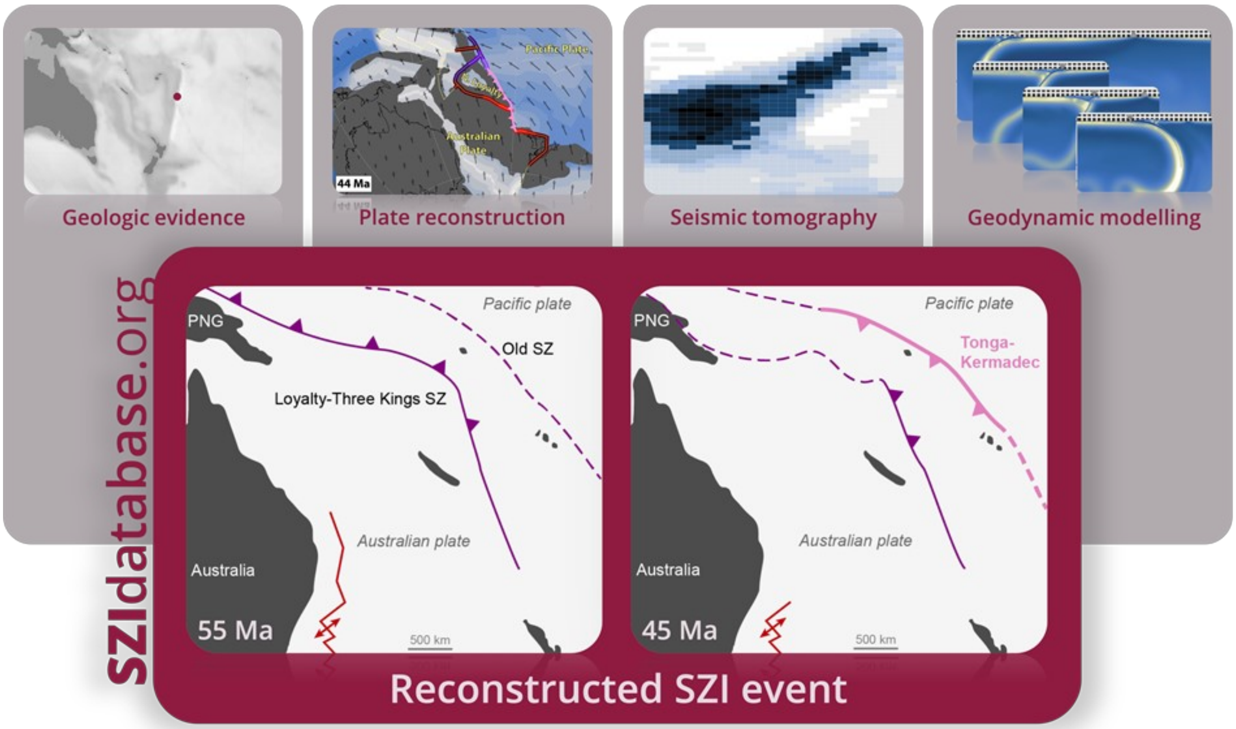

Figure 1 Subduction Zone Initiation (SZI) Database. The transdisciplinary and community-driven SZI database combines direct geologic evidence with plate reconstruction, seismic tomography, and geodynamic modelling that are provided by the various scientific communities to infer individual SZI events, which are eventually provided back to the scientific communities via the interactive online platform www.SZIdatabase.org.

Thanks to the new perspective provided by the data collection, the SZI Database project has already gained wide interest and impacts the field, as researchers employ the universal glossary for accessibility of their own studies. Apart from the constant support of the CEED Director and team leaders, some of the success of the YoungCEED project was achieved by the enthusiastic promotion of team members through various oral and written presentations. The project was first internationally introduced at the EGU General Assembly 2019 in Vienna, which lead to the invited Perspective in Nature Communications and, later that year, at the Ada Lovelace workshop in Siena. The finalised version, the SZI Database 1.0, was then presented online at the shareEGU General Assembly (Magni et al., 2020), as the inaugural presentation of the successful International Virtual Seminar Series in Geophysics and Tectonics (Crameri et al., 2020c), and also in numerous international research group seminars during 2020. In a highly visible EGU GeoLog blog post (Shephard and Crameri, 2020), the SZI Database team further outlines the underlying academic initiative of the scientific project itself, its biggest hurdles towards success, and suggestions for other researchers and academic leaders in charge to facilitate similar projects in the future to not only progress science but also academia. As uncommon this sort of early-career initiative is, it has clearly proven highly successful and is encouraged to be repeated in the future.

The 14 international early-career co-authors as gathered in Drøbak, Norway, for the SZI database workshop. Photo: ***Carmen Gaina***

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The Else Ragnhild Neumann award

CEED awards every year the Else-Ragnhild Neumann Award for Women in Geosciences. It goes to a woman who through PhD or postdoctoral work has made a significant contribution to research in Geosciences.

The committee members for 2020 were Professor ***Anny Cazenave****, LEGOS-CNES Toulouse, France and* ***Brit Lisa Skjelkvåle*** *(the Head of the Department of Geosciences, UiO).*

Requirements for nomination

The nominee should reside in Norway at the time of nomination. Women are eligible for the first 7 years following their degree, except in the case of significant interruptions to a research career.

About the award

The Else-Ragnhild Neumann award honors the scientific contribution of Professor Else-Ragnhild Neumann.

In 1981, she became ***the first female professor in Geosciences in Norway****. Neumann worked with the University of Oslo. She is still active and publish about volcanism and links to mantle processes. She studied the Oslo region, the Canary Islands and other volcanic islands, the Siberian Traps and other areas that experienced significant magmatism.*

Her most recent article is: ***E.-R. Neumann****; J.S. Marsh; C.Y. Galerne; S. Polteau;* ***H. Svensen; S. Planke*** *(2020) Co-existing low-Ti and high-Ti dolerites in two large dykes in the Gap Dyke swarm, southeastern Karoo Basin (South Africa). African Journal of Geology, 123, 19-34.*

For 2020, the award had one winner: **Ágnes (Agi) Király** from CEED, the University of Oslo (UiO). She was recognised at an digital event at Department of Geosciences, Blindern, Oslo, 18.12.2020.

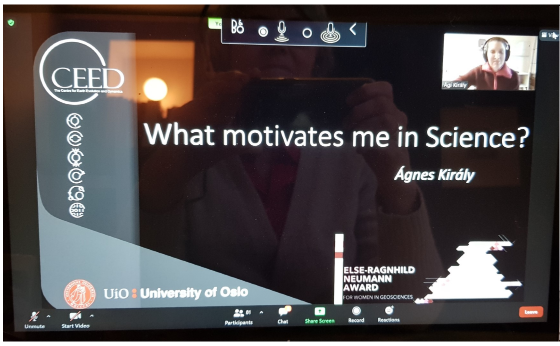
Ágnes (Agi) Király was recognized for *her outstanding results already obtained and on an important topic, with important implications in Geodynamics. She has a very good publication record and has given several invited lectures. The candidate is very promising young scientist.*

The international committee for the Else-Ragnhild Neumann Award for Women in Geosciences concluded that Ágnes Király deserves recognition due to her research within geodynamics, more specific in the research field 'Theoretical and experimental research on subducting slabs'. She has obtained outstanding results on the topic, with important implications in Geodynamics. The committee found the nomination letter very strong and convincing. All together Ágnes Király is a very promising young scientist.

The winner was nominated by Professor **Clint Conrad,** CEED.

Ágnes Király defended her Ph.D. in Earth Sciences on 28.02.2017, at Department of Sciences, Università degli Studi Roma Tre, in Italy. She came to the Centre for Earth Evolution and Dynamics (CEED) later this year as Postdoctoral Fellow. After the end of the postdoc period she is now engaged as a Research Fellow at CEED for three years.

left: Else-Ragnhild Neumann Award Logo designed by CEED`s Researcher ***Fabio Crameri***



Screen shot from Agi`s presentation during the digital event recognising her as the award winner.

About Ágnes Király

Király is known for her work to understand the dynamics of subducting slabs, which are drawn into Earth's mantle as dense tectonic plates that sink into Earth's interior. To study these features, Ágnes has developed models of sinking slabs using both computers and physical tanks of deforming syrup and putty. By modeling deformation associated with the edges of slabs, gaps within slabs, and multiple slabs subducting near each other, Ágnes has discovered new ways that the complexities of subduction can produce geological deformation. In particular, she has demonstrated that her models predict observed patterns of uplift, volcanism, and tectonic deformation made at subduction zones around the world. Her skill in model development, intuition for solid earth deformation processes, and her ability to link her models to geological observations, make her one of the most promising young scientists within the international geodynamics community.

Even in its simplest form, subduction is complex, and it is challenging to model in both numerical and analogue environments. Thus, Ágnes's effort to understand the next-level complexity of subduction represents an ambitious scientific undertaking that has been attempted by few others. She has been successful because she has developed several skills: **1. Multiple modelling approaches**: Ágnes adeptly utilizes both analogue and numerical modelling, a combination that is rare for mantle geodynamicists, **2. International collaboration**: Ágnes has co-authored with 36 different scientists on her 11 publications, and she has worked in Italy, Hungary, Norway, Australia and the US. **3. Inspiration from observations**: Ágnes has demonstrated the key role of mantle flow underpinning several geologic processes occurring at subduction zones around the world, **4. Fluid dynamic intuition**: Ágnes has developed a special insight into solid earth deformation that will lead to exciting discoveries in the coming years."

Selected, recent publications

Kiraly, Agnes; **Conrad, Clinton Phillips** & Hansen, Lars N. (2020). Evolving Viscous Anisotropy in the Upper Mantle and Its Geodynamic Implications. *Geochemistry Geophysics Geosystems*. ISSN 1525-2027. 21(10) .

Kiraly, Agnes; Portner, Daniel E.; Haynie, Kirstie L.; Chilson-Parks, Benjamin H.; Ghosh, Tithi; Jadamec, Margarete; Makushkina, Anna; Manga, Michael; Moresi, Louis & O'Farrell, Keely A. (2020). The effect of slab gaps on subduction dynamics and mantle upwelling. *Tectonophysics*. ISSN 0040-1951. 785 .

Magni, Valentina & **Kiraly, Agnes** (2019). Delamination, In: *Encyclopedia of Ecology*. Reference Module in Earth Systems and Environmental Sciences. Elsevier. ISBN 978-0-12-409548-9.

Outreach highlights

With the various personal and professional restrictions faced with the COVID-19 pandemic, CEED's outreach efforts took a digitally-focussed approach. CEED had a strong online presence, and as in previous year's it was a mix of both individual and CEED-driven outreach initiatives.

New outreach initiatives to 2020 included a monthly email summary of outreach activities, as well as the CLIPT Lab video series on YouTube. As in previous years, CEED's main avenues of outreach include the CEED website, CEED Blog, social media channels (Facebook, Instagram, Twitter, YouTube), www.EarthDynamics.org, Department of Geosciences website, GEOOnsdag at the UiO Science Library, DEEP Research School social media accounts, and UiO news outlets - Titan.uio.no, Apollon, and Uniforum. In the Norwegian media, avenues include NRK (radio, TV and online), TV2, forskning.no and geoforskning.no .


Vulkaner spiller en rolle i jordens trege karbonkretsløp, der gammel CO2 resirkuleres. Bildet er fra Java, Indonesia. (Bilde: Kanjanee Chaisin / Shutterstock / NTB)

Slik har jordens klima endret seg gjennom tidene

På jorden har det vært fuktig regnskog i Antarktis, og is som strakk seg til ekvator.

Elise Kjørstad
JOURNALIST

Lørdag 10. oktober 2020 - 04:31

Photo: Article in forskning.no highlighting several Earth Crises members

Selected highlights of outreach events from 2020 include:

Five CLIPT Lab instructional and methodology videos for the stable isotope lab produced by **W. Hagopian** and **A.H. Jahren**

GEOOnsdag presentations at the UiO Science Library and YouTube channels (**C. Gaina, V. Magni, S. Planke and M.T. Jones, H. Svensen)**

"Slik har jordens klima endret seg gjennom tidene" article in forskning.no featuring several Earth Crises members

Four books; Under Asfalten (**H. Svensen**), KOMPASS (Norwegian high school textbook, **H. Svensen)**, The Story of More (**A.H. Jahren**) and Dig to the Centre of the Earth (**D. Jerram)**

#ShareEGU20 highlights of CEED presentations during the online EGU 20 meeting

B, Heyn et al. (2020 JGR Solid Earth) research highlight in Nature Reviews Earth and Environment. "The rise and fall of mantle plumes"

Widespread associated with the colour maps paper (F. **Crameri, G. Shephard**, Heron Nature Communications), including 60.000 paper downloads in 2 weeks and over 1000 individual tweets and retweets (1028 Altimetric score)

CEED New Year wishes for 2020-2021 – compilation of greetings from members of CEED featuring different languages.

More events listed in "In the media"

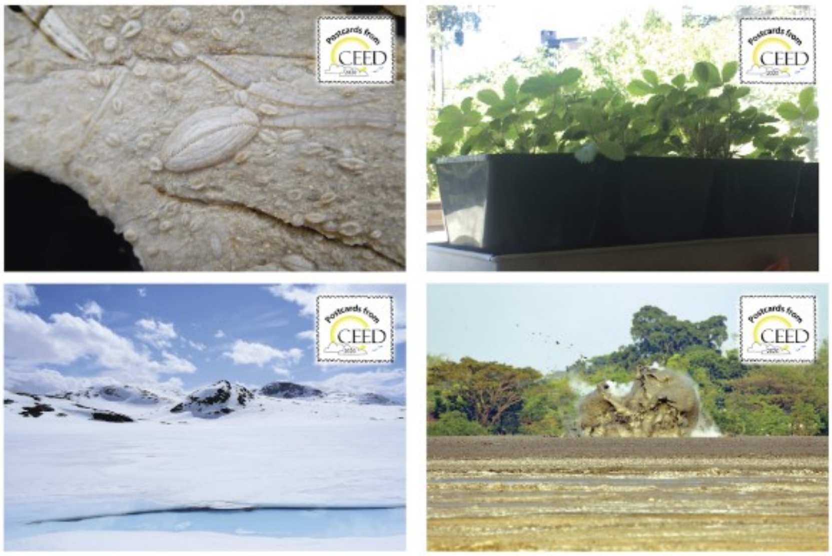


Photo: Four of the eight #PostcardsfromCEED summer 2020 edition

Some statistics from social media and outreach in 2020:

The CEED Blog – 13 blog articles published
Facebook - 639 likes/followers, 152 individual posts
Twitter - 1200 followers, 230 original tweets
Instagram – 95 followers, 28 posts
YouTube – 49 subscribers, 16 videos, 2400 views

Photo right:: Japanese twitter coverage of the ***Crameri et al.*** *The misuse of colour in science communication (2020 Nature Communications)*

Photo: above: For the COVID-19 pandemic, a "Stay Home" animation was implemented into plate reconstruction in GPlates.

CEED Outreach team members: Grace Shephard (Coordinator), **Trine-Lise Knudsen Gørbitz**, Gunn Kristin Tjoflot (GEO), **Eivind Straume, Fabio Crameri, Valentina Magni,** and **Morgan Jones.**

The Norwegian Research School for Dynamics and Evolution of Earth and Planets (DEEP) is a National Research School in Geosciences, funded by the Research Council of Norway for the period 2016-23. It is hosted by CEED and lead by Professor ***Stephanie C. Werner****, with* ***Anniken R. Birkelund*** *as the Administrative coordinator. DEEP aims to educate solid earth and planetary scientists in a holistic way, placing the Earth's structure and evolution in a comparative planetology perspective. DEEP gathers Norwegian PhD students and researchers within geophysics, mineralogy, geochemistry and comparative planetology.*

GEO-DEEP9100 Planetary Physics and Global Tectonics (26 - 30.10)

Course responsible: S**. Werner,** assisted by **M. Domeier, T. Rolf, M. Arnould, F. Crameri, V. Magni, G. Shephard** and **Kiraly.** This intensive PhD course gives an introduction to the physics and tectonic processes that govern the properties and evolution of the Earth and other planets. This was a fully digital course by Zoom.

The course was attended by 8 PhD students, 1 PostDoc, 6 master students, 1 of the participants were from CEED.

GEO-DEEP9400 400 Solid Earth – Fluid Earth Interactions (11 - 15.05)

Course responsible: **C. Gaina,** assisted **by A. Mazzini, H. Svensen, C. Conrad,** and **R.G. Trønnes.** intensive PhD course addresses topics like material recycling across the geospheres and how mantle dynamics, volcanism, plate tectonics influences long-term, global environmental and climatic changes. This was a fully digital course by Zoom.

The course was attended by 13 PhD students, 7 master students, 2 of the participants were from CEED

GEO-DEEP9504 From Small Bodies to Impact Craters (17-21.8)

An online, intensive DEEP course (5 ECTS) to learn about small bodies in the solar system. The course focused on five main themes taught by five specialists within the field; **J. Luu,** I. Mann, R. Brasser, **N. C. Prieur** and **S. We**rner. The course included lectures, student presentations, and hands on exercise for each of the five aspects.

The course was attended by PhD students, 1 master student, 1 of the participants was from CEED

DEEP generic and scientific courses

Virtual writing retreat; DEEP and Mathew Stiller-Reeve offered short introduction lectures and continued with daily warm-up sessions including smaller online discussion groups, “shut-up-and-write” sessions and progress updates. The point of this virtual writing retreat was to improve writing skills, and to motivate each other. Above all, we managed to create a constructive interactive space for everyone to enjoy whilst working from the home office.

Teaching and learning for young researchers, arranged by the Department of Geosciences & DEEP at UiO, the Centre for Teaching and Learning in Science (KURT) at UiO and the Centre for Integrated Earth Science Education (iEarth). This intensive and engaging seminar about teaching and learning for the geoscience community. The 4-days seminar was arranged on Zoom with 25 participants from all our partner institutions in Norway.

Introduction to MATLAB - a DEEP method course, arranged on Zoom with 8 participants, over 4 days and with the main lecturer Researcher **Valentina Magni.** This intense course for beginners aimed for giving a basic knowledge of programming with MATLAB. The main goal was for the participants to become comfortable enough with MATLAB so that they know its potential and are able to understand scripts, create their own, and continue learning and keep using it on their own.

Science Communication – Creating Scientific Illustrations. DEEP and Pina Kingman offered a short intensive course, 4 days with 18 participants. Place: Geophysical institute, University of Bergen. This course introduced the theory and method of how to visually represent scientific research. Being able to translate complex research into information that can be understood by a wide range of audiences is an important skill that will help throughout a career.

*Due to the Covid19 pandemic we had to cancel the scheduled General Assembly in June 2020. Instead, we offered **a virtual PhD day** 20 May 202, with the topics:*

1. Conference posters? Yeah, we can do better. This workshop gave knowledge and inspiration to design conference posters with success.

2. Communication with impact. The seminar was arranged on Zoom with 7 participants. The participants got tools to prepare and implement an effective communication situation. They learned to analyze the rhetorical situation and the recipient they wanted to influence and became aware of how nonverbal communication affects the message.

*Lectures and participats in the online version of DEEP`s scientific teaching seminar in May 2020. (Photo: **Anniken R. Birkelund**).*

Table 1. Teaching by CEED staff at UiO

DEEP courses and CEED members are given in **bold,** courses arranged by CEED outside UiO are in grey

Course code & name	**Semester**	**ECTS**	**Course responsible / assisting**
GEO1100 Jordens utvikling	Autumn 20	10	**H.H. Svensen** / T. Berntsen, K.S. Lilleøren, A. Bryn, **E.G. Ballo**
GEO2140 Solid Earth Geophysics	Spring 20	10	**A.J. Breivik / Krister S. Karlsen**
GEO2300 Physical processes in the geosciences	Autumn 20	10	J. Lacasce/**V. Maupin**, T. Vikhamar, **K.S. Karlsen**
GEO3000 Bachelor-oppgave i geologi	Spring 20	10	K.S. Lilleøren / **H.H. Svensen, E.G. Ballo**
GEO-AST3410/4410 Planetology	Autumn 20	10	**S.C. Werner,** V. Hans-teen / **E.M. Harrington, B. Steinberger, A.M. Krzesinska, B. Bultel**
GEO4120 Near-Surface Geophysics	Autumn 20	10	**A. Breivik**/ K. Muller, A. Alexander, T. Eiken
GEO4240 Seismic Interpretation	Spring 20	10	**J.I. Faleide, I**.A. Anell, M. Heeremans
GEO4360 Field methods in hydrogeo-logy	Spring 20	5	Anja Sundal, Clara Sena, Helene French (NMBU), **A. Breivik**
GEO4620 Seismic waves and seismo-logy	Autumn 20	10	**V. Maupin**
GEO4630/9630 Geodynamics	Autumn 20	10	**C. Conrad**
GEO4840/9840 Tectonics	Spring 20	10	H.J. Kjøll / **C. Gaina /M. Domeier**
GEO4860/GEO9860 Advanced Petro-logy	Spring 20	10	**R.G. Trønnes,** B. Jam-tveit
GEO-DEEP9100 Planetary Physics and Global Tectonics	Autumn 20	5	**S. Werner / M. Domei-er, T. Rolf, M. Arnould, F. Crameri, V. Magni, G. Shephard, A. Kiraly**
GEO-DEEP9400 Solid Earth – Fluid Earth Interactions	Spring 20	5	**C. Gaina / A. Mazzini, H. Svensen, C. Conrad, R.G. Trønnes**
GEO-DEEP9504 From Small Bodies to Impact Craters	Autumn 20	5	**J. Luu,** I. Mann, R. Brasser, **N. Prieur, S. Werner**

Logging and sampling of the Permian-Triassic boundary in Vardebukta, the Festningen profile at Svalbard. Photo: ***Sverre Planke***

PhD student projects (**bold**: finished in 2020 and for CEED members)

Name	Topic	Supervisors	Funding
Ballo, Eirik	Reconstructing climatic, environmental and societal dynamics in Scandinavia in the Iron- and Viking-Age (RECESS)	**H. Svensen, M. Bajard,** J. Bakke	UiO
Beloša, Lea	The Role of Fracture Zones in Geodynamic Processes.	Main supervisor **C. Gaina, A. Breivik, R. Trønnes, A. Mazzini,** and **S.**	UiO
Bostic, Joshua N.	Reconstructing the magnitude and societal effects of acute climate changes during the Viking dark ages	**A. Jahren, H. Svensen**	UiO
Broek, Joost van den	**The role of subduction in the formation and evolution of continental slivers and microcontinents**	**C. Gaina, S. Buiter, R. Gabrielsen**, **TB Andersen, V. Magni**	EU
Harrington, Elise M.	Evaporites on Mars: An in-depth study of past water-rock interaction in Paleolakes	**S. Werner, A. Krzesinska, B. Bultel**	UiO

The PhD hats created by young CEED researchers for the PhD defence celebrations. From upper left: ***Björn Heyn, Eivind O. Straume, Alexandra Zaputlyaeva*** *and* ***Joost van den Broeck*** *with their hats*

PhD student projects (cont.)

Name	Topic	Supervisors	Funding
Heyn, Björn H.	**Convective dynamics in the lowermost mantle**	**C. Conrad, R. Trønnes**	UiO
Jerkins, Annie E. (Norsar)	Improved understanding of Seismicity in the North Sea	V. Oye, **V. Maupin,** L. Ottemøller, F. Halpaap	
Karlsen, Krister S.	The effects of water on mantle convection dynamics - Linking the Earth's hydrological, thermal and tectonic histories	**C. Conrad, R. Trønnes, V. Magni**	UiO
Marcilly, Chloé F.M.	Modelling of the atmospheric CO2 and O2 levels during the Phanerozoic	**TH. Torsvik, H. Svensen, M. Jones, T. Heimdal**	UiO
Ramirez, Florence	Constraining the mantle viscosity of Greenland with geophysical observations	**C. Conrad**, **K. Selway**	SFF
Stokke, Ella W.	The effects of volcanic eruptions and degassing during the North Atlantic LIP on the PETM thorugh geochemical analyses and studies of ash layers i the Fur Fm, Denmark	**M. Jones, H. Svensen**	RCN
Straume, Eivind O.	**Paleoclimate in the Cenozoic time: Quantifying the role of North Atlantic plate tectonicsa amd mantle processes**	**C. Gaina**, J. LaCasce, **K. Nisancioglu, H. Svensen**	UiO
Uppalapati, Sruthi	Cooling of a planet – Mechanisms tested for Venus and Io	**S. Werner, T. Rolf, F. Crameri, C. Conrad**	UiO
Werdesteijn, Maaike	3D glacial isostatic adjustment modeling for Greenland using magnetotelluric constraints on upper mantle viscosity	**C. Conrad**, **K. Selway,**	RCN
Zastrozhnov, Dmitry	**Structure and Evolution of Mid-Norway Continental Margin**	**JI. Faleide, S. Planke, R. Gabrielsen**	RCN
Zaputlyaeva, Alexandra	**Fluid-rock interactions and geochemistry of the Lusi mud eruption, Java, Indonesia**	**A. Mazzini, H. Svensen**	UiO

Dr Philos project

Name	Topic
Halvorsen, Erik	Paleomagnetic and magnetic fabric studies of Early Cretaceous sills from Central Svalbard: unraveling Early Cretaceous paleopole and suggested Cenozoic remagnetization in addition to divergent magnetic fabric.

A calm day in the Atlantic ocean with the scientific crew of the Gloria Flows M126 expedition aboard RV Meteor in March 2020. The aim is to explore subsurface fluid flow and active dewatering along the oceanic plate boundary between Africa and Eurasia (the Gloria Fault). Participant from CEED was PhD student ***Lea Belosa****.*

Master student projects

Bold: finished in 2020, and for CEED supervisor(s)

Name	Topic	Supervisors
Christiansen, Vetle	Potential for analysis of microseismicity from a single-station record at the Åknes unstable rockslope	**V. Maupin**
Dahl, Helge W.	**Location of microseismic events at the Åknes rockslope**	Oye, **V. Maupin,** Langet
Labes, Alienor M.P.	The eruptive mechanisms and gas emissions of sedimentary volcanism	**A. Mazzini**
Lisica, Karlo	**Petrological and Geochronological investigation of the Lundy granite and its role in the North Atlantic Igneous Province (NAIP)**	**L.E. Augland, M. Jones**
Meza, Sergio Andres Diaz		**V. Maupin**
Opshaug, Mathilde S.	**Receiver functions at the 8 broadband seismometers of the Kongsberg array**	**V. Maupin**
Silverberg, Marcus J	**Feature and event analysis of seismic data using machine learning at Åknes.**	Langet (NORSAR), **Maupin**
Uthus, Trine N.	**Crater statistics and Geological history of Jezero Crater and Oxia Planum regions.**	**S. Werner, N. Prieur, B. Bultel**







Top row from left: ***Vetle Christiansen, Helge Dahl, Alienor Labes, Karlo Lisica***
Below: ***Sergio Meza, Mathilde Opshaug, Marcus Silverberg, Trine Nyhus***

International cooperation

Country	Activity	Person(s) involved
Australia	Joint publications and project, collaboration, visits	C. Gaina, E. Straume, G. Shephard, A. Kiraly, A. Minakov, C. Conrad
Azerbadijan	Research and education	A. Mazzini
Brazil	Collaboration, joint publication, visiting student	H. Svensen, T.H. Heimdal
Canada	Research and education	C. Gaina, J. Jakob, G. Shephard
China	Field work, supervision, visiting students	M. Domeier, T.H. Torsvik
Denmark	Field work (Fur, Greenland), joint supervision and collaboration, joint publications	M. Jones, T.B. Andersen, H.J. Kjøll, P. Doubrovine, E. Kulakov, C. Gaina, C. Conrad
France	Visitis,field work, collaboration	T.H. Torsvik, T.B. Andersen, J. Jakob, C. Gaina, A. Minakov, S. Werner, C.E. Mohn,
Germany	Visitors; Joint publication (s), collaboration	T.B. Andersen, S. Werner, A. Mazzini, C. Gaina, C. Conrad, A. Breivik, T. Rolf, V. Maupin
Iceland	Collaboration, visiting student	C. Gaina
Indonesia	Joint research project	A. Mazzini
Italy	Collaboration, visiting student	A. Mazzini, S. Callegaro, C. Gaina, A. Kiraly
Japan	Collaboration	C. Gaina, S. Werner, G. Shephard
China	Collaboration	V. Maupin,
Romania	Research	C. Gaina, A. Minakov
Russia	Field work; Research cooperation; Joint publication(s)	R. Kulakov, C. Gaina, J.I. Faleide, A. Minakov, A. Mazzini
South Africa	Field related work; Joint publication(s)	T.H. Torsvik, H. Svensen
Sweden	Collaboration, lab facilities	V. Maupin, S. Callegaro
The Netherlands	Joint publication(s), research collaboration, Exo Mars landing site.	T.H. Torsvik, C. Gaina, S. Werner
Turkey	Collaboration, visiting student	M. Domeier, T.H. Torsvik, V. Maupin
UK and Ireland	Lab work; Joint publication (s), collaboration	J. Dougal, R. Trønnes, T.H. Torsvik G. Shephard, V. Maupin, F. Crameri, C.E. Mohn, V. Magni, C. Gaina
USA	Joint publication(s), lab. fwork, visitn\ing studet ts, research cooperation	C. Conrad, A.H. Jahren, T.H. Heimdal, C. Gaina, F. Crameri

Conference organized by CEED

Date	Title and organizers (bold: organizers from CEED)
6.3.	The 7th CEED birthday symposium: Earth and Life Evolution (**C. Gaina, T-LK. Gørbitz),** with 39 participants (invited guests and participants from CEED)

Session convened by CEED members at the EGU General Assembly Online 4-8 May

PS4.2 Mars Science and Exploration. Convener: Jessica Flahaut Co-conveners: **Benjamin Bultel,** Xiao Long, Arianna Piccialli, **Agata Krzesinska**

TS7.4 Dynamics and Structures of the Tethyan realm: Collisions and back-arcs from the Mediterranean to the Himalayas Co-organized by GD7/GMPV11/SM2
Convener: **Ágnes Király**, Co-conveners: Derya Gürer, Marc Hässig, Claudia Piromallo

TS10.3 Analogue and numerical modelling of tectonic processes Co-organized by GD10/GM9
Convener: Frank Zwaan, Co-conveners: Fabio Corbi, **Ágnes Király, Valentina Magni**, Michael Rudolf

GD5.1 Subduction dynamics from surface to deep mantle Co-organized by GMPV2/SM2/TS7
Convener: Oğuz H Göğüş | Co-conveners: Taras Gerya, **Ágnes Király**, Wim Spakman

BG5.3 Extreme environments, mud volcanoes and hydrothermal systems on Earth and planetary analogues: biology, stratigraphy, structure, evolution and monitoring of active and fossil settings. Convener: **Adriano Mazzini**; Co-conveners: Monica Pondrelli, Matteo Lupi, Jessica Flahaut, Frances Westall, Barbara Cavalazzi, Helge Niemann

GD7.1 The Arctic connection - plate tectonics, mantle dynamics and paleogeography serving paleo-climate models and modern jurisdiction. Convener: **Grace E. Shephard**, Co-conveners: Frances Deegan, Karolina Kośmińska, Rebekka Steffen

Session convened by CEED members at the AGU Fall Meeting Online 1-17 December

PP042 - The Puzzles of Human Migration and the Role of Climate Change: What Can the Past Resolve? Primary Convener: Nora Richter, Conveners **Eirik Gottschalk Ballo**, Øyvind Paasche, Sunniva Rutledal

*Illustration made for the 7th CEED birthday symposium by **Grace E. Shephard** (CEED Outreach Coordinator).*

Workshops, lab work, research stay outside UiO		
1.1—15.2.	Geodynamics Laboratory, Monash University, Vic, AUS	A. Kiraly
14-16.9	Feedbacks Between Mantle Composition, Structure, and Evolution,	R. Trønnes
3.8—14.8	ASPECT Hackathon from Wyoming to online	M. Weerdesteijn
Field work outside Europe		
6.12.19-9.1.20	The SENECA expedition—the 35th Italian expedition to the Dry Valleys of Antartica.	A. Mazzini
28.1—1.4	Antarctica, King George Island	M. . Weerdesteijn
Field work in Europe		
28.2—5.4	Portugal, Scientific Expedition M162 at Gloria Fault	L. Beloša
Field work in Norway		
Summer 20	West Troms region, pre-Caledonian dykes	E. Kulakov
10-11.6	Samnanger Osterøy , Western Norway	TB. Andersen
14-18.9	Svalbard, Barentsburg, Sampling the P-T boundary and Early Triassic	LE. Augland, MT. Jones, S. Planke
Summer 20	Bygdøy, Oslo	HH. Svensen

From the SENECA expedition to the Dry Valleys of Antarcticv, December 2019 to January 2020. The two years project involves four Italian universities and research institutes, as well as participants from New Zealand and CEED. Photo: ***Adriano Mazzini***

Project funding for 2020

UiO project #	Projects, project leader	Funding in 2020*
SFF 143906	123272 Centre for Earth Evolution and Dynamics, Gaina (2013-23),	17 767
144151	246929/F20 Clim-VoTe,ISP-Geofag, Niscancioglu (2015-20)	133
144251	249040/F60 DEEP Research school, Werner (2016-23)	2 903
144312	250111 600 Myr Plate Model, Domeier (2016-20)	743
144450	263000 Ashlantic, Jones (2017-20)	1 471
190645	268094/E10 The Future is, Svensen (2017-20) CEED part	14
144657	276032 Platonics, Rolf (2018-22)	2 320
144775	288449 Magpie, Conrad (2019-23)	3 470
144995	301096 Maples, Callegaro (2020-23)	2 172
144929	309256 Geoclim, Heimdal (Support for events 2021)	60
145040	309477 Nor-R-Am II, Gaina (Intpart 2020-23)	540
651025	Subitop MSAC ITN, Gaina (-2020)	368
651021	PTAL H2020 COMPET, Werner (2016-19)	1 074
690471	3D Earth, Gaina (extension to 2020)	38
690477	Cratering Rates on Moon and Mars, ESA Prodex Werner (2017-20)	165
690591	Baia Mare, Gaina (EØS, with Romania 2020-23)	24
690604	Poles together, Augland (EØS with Poland 2020-23)	156
421307	CEED-Mod, Aker BP/Lundin/Vår energi	2 400
421269	Ørnen, Det Norske, Planke/Faleide (2018-20)	900
Basis	Tokt med Helmer Hansen, Faleide (2020)	600
UiO funding	Strategy grant (2013-22)	2 000
UiO funding	UiO contribution (Egenandel)	22 432

** in kkr unless specified*

Invited guest lectures at CEED

1. Subduction zones: Zooming in on time, space and composition. Nov. 19, 2020 1:15 PM–2:00 PM, Zoom lecture by Christoph Beier From Helsinki University, Finland Hosted by Carmen Gaina
2. Thermal and compositional evolution of the Earth's core Nov. 12, 2020 10:00 AM–11:00 AM, Zoom lecture Kei Hirose. From ELSI, Japan Hosted by Reidar Trønnes
3. Oceans and Climate Nov. 5, 2020 1:15 PM–2:00 PM, ZOOM by Cecilie Mauritzen. From Meteorological Institute, Oslo Hosted by Carmen Gaina
4. Tephra and the carbon cycle: Why should we care? Oct. 22, 2020 11:00 AM–12:00 PM, Zoom lecture by Jack Longman. From the University of Oldenburg Hosted by Morgan Jones & Ella Stokke
5. Why artificial intelligence won't replace geodynamicists any time soon. Oct. 15, 2020 1:15 PM–2:00 PM, Zoom lecture by Suzanne Atkins. From CNS Paris, France Hosted by Agnes Kiraly
6. Late Quaternary Tephrochronology of North Europe: A look back and prospects for the future Oct. 8, 2020 1:15 PM–2:00 PM, ZEB Auditorium 3 by Stefan Wastegård From Stockholm University, Sweden Hosted by Manon Bajard/Eirik Ballo
7. Factors controlling the style of back-arc extension Sep. 17, 2020 1:15 PM–2:00 PM, Zoom lecture by Zoltán Erdõs. From Eötvös Loránd University, Budapest Hosted by Ágnes Király
8. Large Igneous Provinces and Global Carbon Cycle Feedbacks Sep. 10, 2020 1:15 PM–2:00 PM, Zoom lecture By Sarah Greene. From Birmingham University, UK Hosted by Henrik Svensen
9. New Frontiers in Large Igneous Province Research May 28, 2020 2:15 PM–3:00 PM, Zoom lecture by Richard Ernst From Carleton University, USA Hosted by Trond Torsvik
10. Vertical motion along passive continental margins – observations from Greenland, Scandinavia, South America and India. Can geodynamic models explain the observations? May 14, 2020 1:15 PM–2:00 PM, Zoom lecture by Peter Japsen. From GEUS Denmark Hosted by Sergei Medvedev
11. A little goes a long way: the role of volatiles in volcanic systems Apr. 30, 2020 1:15 PM–2:00 PM, Zoom lecture by Tobias Keller. From Glasgow University, UK Hosted by Fabio Crameri
12. The Deep Water Cycle: Mantle Mixing and the Surface Ocean. Apr. 23, 2020 1:15 PM–2:00 PM, Zoom lecture by Kiran Chotalia. From UCL Earth Sciences, UK Hosted by Clint Conrad
13. Spontaneous localisation arising from multi-physics coupling - forward and inverse modelling Apr. 16, 2020 2:00 PM–3:00 PM, Zoom lecture by Ludovik Räss. From ETH, Switzerland Hosted by Alexander (Sasha) Minakov

The Wilson lecture is an annual public lecture within the fields of Geosciences, arranged by CEED. The lecture for 2020 was unfortunately cancelled due to the Covid-19 pandemic.

Scientific publications (red: high impact journals, 12 out of 111, **bold:** CEED Scientist, *: CEED Early Career Researcher as first author)

1. ***Abdelmalak, Mohamed Mansour**; Polteau, Stephane. The thermal maturity of sedimentary basins as revealed by magnetic mineralogy. Basin Research 2020 ;Volume 32.(6) s. 1510-1531

2. *__Arnould, Maëlis__; Coltice, Nicolas; Flament, Nicolas; Mallard, Claire. Plate tectonics and mantle controls on plume dynamics. Earth and Planetary Science Letters 2020 ;Volume 547.

3. Artemieva, Irina; **Thybo, Hans**. Continent size revisited: Geophysical evidence for West Antarctica as a back-arc system. Earth-Science Reviews 2020 ;Volume 202.

4. ***Bajard, M.,** Poulenard, J., Sabatier, P., Bertrand, Y., Crouzet, C., Ficetola, G.F., Blanchet, C., Messager, E., Giguet-Covex, C., Gielly, L., Rioux, D., Chen, W., Malet, E., Develle, A.-L., Arnaud, F. Pastoralism increased vulnerability of a subalpine catchment to flood hazard through changing soil properties (2020) Palaeogeography, Palaeoclimatology, Palaeoecology, 538. *All Open Access, Hybrid Gold, Green*

5. Bellwald, Benjamin; **Planke, Sverre**; Becker, Lukas; Myklebust, Reidun. Meltwater sediment transport as the dominating process in mid-latitude trough mouth fan formation. Nature Communications 2020 ;Volume 11. *All Open Access, Gold, Green*

6. Biggin, Andrew J.; Bono, Richard K.; Meduri, Domenico G.; Sprain, Courtney J.; Davies, Christopher J.; Holme, Richard; **Doubrovine, Pavel V**. Quantitative estimates of average geomagnetic axial dipole dominance in deep geological time. Nature Communications 2020 ;Volume 11. *All Open Access, Gold, Green*

7. Bocher, M., Ulvrova, M., **Arnould, M.**, Coltice, N., Mallard, C., Gerault, M., Adenis, A. Drawing everyday sexism in academia: Observations and analysis of a community-based initiative (2020) Advances in Geosciences, 53, pp. 15-31. Cited 2 times. DOI: 10.5194/adgeo-53-15-2020. *All Open Access, Gold, Green*

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9. **Breivik, Asbjørn Johan; Faleide, Jan Inge**; Mjelde, Rolf; Flueh, Ernst; Murai, Yoshio. Crustal structure and erosion of the Lofoten/Vesterålen shelf, northern Norwegian margin. Tectonophysics 2020 ;Volume 776.

10. Brož, Petr; Krýza, O; Conway, Susan; Mueller, N.T.; Hauber, Ernst; **Mazzini, Adriano**; Raack, J; Balme, M; Sylvest, M; Patel, M. Mud flow levitation on Mars: Insights from laboratory simulations. Earth and Planetary Science Letters 2020 ;Volume 545. *All Open Access, Green*

11. Brož, Petr; Krýza, O; Wilson, Lionel; Conway, Susan; Hauber, Ernst; **Mazzini, Adriano**; Raack, J; Balme, M; Sylvest, M; Patel, M. Experimental evidence for lava-like mud flows under Martian surface conditions. Nature Geoscience 2020 ;Volume 13. s. 403-407. *All Open Access, Green.*

12. Bucher, Kurt; Weisenberger, Tobias B.; Weber, Sebastian; Klemm, Oliver; **Corfu, Fernando**. The Theodul Glacier Unit, a slab of pre-Alpine rocks in the Alpine meta-ophiolite of Zermatt-Saas, Western Alps. Swiss Journal of Geosciences 2020 ;Volume 113.

13. Callegaro, Sara; Geraki, Kalotina; Marzoli, Andrea; De Min, Angelo; Maneta, Victoria; Baker, Don R. The quintet completed: The partitioning of sulfur between nominally volatile-free minerals and silicate melts. American Mineralogist 2020 ;Volume 105.(5) s. 697-707

14. Capriolo, Manfredo; Marzoli, Andrea; Aradi, László E.; **Callegaro, Sara**; Dal Corso, Jacopo; Newton, Robert J.; Mills, Benjamin J.W.; Wignall, Paul B.; Bartoli, Omar; Baker, Don R.; Youbi, Nassrrdine; Remusat, Laurent; Spiess, Richard; Szabó, Csaba. Deep CO_2 in the end-Triassic Central Atlantic Magmatic Province. Nature Communications 2020 ;Volume 11. *All Open Access, Gold, Green*

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16. Celli, Nicolas Luca; Lebedev, Sergei; Schaeffer, Andrew; Ravenna, Matteoo; **Gaina, Carmen**. The upper mantle beneath the South Atlantic Ocean, South America and Africa from waveform tomography with massive data sets. Geophysical Journal International 2020 ;Volume 221.(1) s. 178-204

17. Chotalia, Kiran; Cagney, Neil; Lithgow-Bertelloni, Carolina; **Brodholt, John Peter.** The coupled effects of mantle mixing and a water-dependent viscosity on the surface ocean. Earth and Planetary Science Letters 2020 ;Volume 530. *All Open Access, Green*

18. **Corfu, Fernando**; Hegde, V.S. U–Pb systematics of the western Dharwar Craton - Glimpses of a billion year history of crustal evolution and relations to ancient supercratons. Journal of South American Earth Sciences 2020 ;Volume 102.

19. **Corfu, Fernando**; **Larsen, Bjørn Tore**. U-Pb systematics in volcanic and plutonic rocks of the Krokskogen area: Resolving a 40 million years long evolution in the Oslo Rift. Lithos 2020 ;Volume 376-377.

20. Corseri, Romain**; Gac, Sebastien; Faleide, Jan Inge; Planke, Sverre**. The tectonized central peak of the Mjølnir Impact Crater, Barents Sea. Journal of Structural Geology 2020 ;Volume 131.

21. ***Crameri, Fabio; Magni, Valentina; Domeier, Mathew; Shephard, Grace Elizabeth**; Chotalia, Kiran; Cooper, George; Eakin, Caroline; Grima, Antoniette Greta; Gurer, Derya; **Kiraly, Agnes**; Mulyukova, Elvira; Peters, Kalijn; Robert, Boris; Thielmann, Marcel. A transdisciplinary and community-driven database to unravel subduction zone initiation. Nature Communications 2020 ;Volume 11, 3750. *All Open Access, Gold, Green*

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26. ***Das, Pratik Kumar; Mohn, Chris Erik; Brodholt, John Peter; Trønnes, Reidar G.** High pressure silica phase transitions: Implications for deep mantle dynamics and silica crystallization in the protocore. American Mineralogist 2020 ;Volume 105. s. 1014-1020

27. ***Das, Pratik Kumar**; Mondal, SK; Mandal, N. First principles prediction of exceptional mechanical and electronic behaviour of Titanite (CaTiSiO5). Materialia 2020 ;Volume 15.

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33. ***Gac, Sebastien; Minakov, Alexander; Shephard, Grace; Faleide, Jan Inge; Planke, Sverre.** Deformation analysis in the Barents Sea in relation to paleogene transpression along the Greenland-Eurasia plate boundary. Tectonics 2020 ;Volume 39.(10)

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Professor Henning Dypvik register with ***Trine-Lise K. Gørbitz*** *for his participation in the 34th the Nordic Geological Winter meeting at the University of Oslo, January 2020. Photo: Hans Arne Nakrem, NHM.*

Books and book chapters

1. **Gaina, C** and J. Whittaker, Microcontinents, 2020, in Encyclopedia of Solid Earth Geophysics revised version, ed. H. K. Gupta, Springer, Online ISBN 978-3-030-10475-7
2. **Jahren, A.H.** The Story of More: How We Got to Climate Change and Where to Go from Here. *Penguin Random House*, 2020.
3. **Jerram, D.** (2020) Dig to the Centre of the Earth: An explorer's guide to the world beneath our feet (2020) *Carlton Kids*.ISBN 978-1783125098.48 s.
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Front cover of four popular science books published in 2020 by the CEED members ***Anne H. Jahren, Henrik H. Svensen*** *and* ***Dougal Jerram****.*

Outreach activities

TV; radio; newspapers and magazines

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4. Callegaro, Sara. Interview by L. Paneghetti on PLaNCK! Italian journal for science outreach for children (Accatagliato Eds.) about the MAPLES project and the activity in the Earth Crises Group. 2020-11-09 www.planck-magazine.it/scopri_planck/la-terra-e-le-sue-crisi-quando-le-eruzioni-vulcaniche-sconvolgono-la-vita-sul-nostro-pianeta/
5. Conrad, Clinton P.. Interview in newspaper article: Korona-krisen vinge-klippet UiO-forskere. Universitas, 01-09-20
6. Conrad, Clinton P. Interview in journal article: Slowdown in plate tectonics may have led to Earth's ice sheets. Science, 22-12-20.
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11. Jerram, Dougal Alexander. Abandoned Engineering, S05E02 The Valkyrie Assassin, January 28, 2020 UKTV Yesterday.
12. Jerram, Dougal Alexander. Abandoned Engineering, S05E03 Escape from Devil's Island, February 4, 2020 UKTV Yesterday.
13. Jerram, Dougal Alexander. Abandoned Engineering, S05E04 Top Secret Nuclear Arsenal, February 11, 2020 UKTV Yesterday.
14. Jerram, Dougal Alexander. Abandoned Engineering, S06E01 The Lost Pirate City, July 9, 2020 UKTV Yesterday.
15. Jerram, Dougal Alexander. Abandoned Engineering, S06E04 North Of The Wall, July 30, 2020 UKTV Yesterday.
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*An illustrationof what the interstellar guest Oumuamua may look, based on the work: Oumuamua as a Cometary Fractal Aggregate: The "Dust Bunny" Model. By **Jane X. Luu**, Eirik G. Flekkøy, and Renaud Toussaint (2020) The Astrophysical Journal Letters, Volume 900, Number 2. Photo by Handout Reuters.*

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28. Trønnes RG, Forsnkning.no and Uniforum.uio.no, 28. oktober. Hvorfor ligger asken etter en av Norges viktigste naturforskere i en umerket grav i Oslo? Forberedende intervju med bakgrunnsinformasjon og revidering av artikkel skrevet av journalist Siw Ellen Jakobsen.

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30. Trønnes RG, NettavisenPluss, 8. november. Harry (83) ble en folkehelt for sin stahet. Så skjedde katastrofen han ble advart mot. Artikkel om 1989-utbruddet fra Mt. St. Helens. Artikkel skrevet av journalist Bjørn Vegar Digre.

31. Trønnes RG, NettavisenPluss, 28. november. I timene etter vulkanutbruddet kunne byen blitt evakuert. I stedet døde mer enn 20.000 mennesker på grufullt vis. Artikkel om 1985-utbruddet fra Nevado del Ruiz. Forberedende intervju med bakgrunnsinformasjon og revidering av artikkel skrevet av journalist Bjørn Vegar Digre.

32. Weerdesteijn, Maaike. Meteorología + TARP-02. Video interview in interview series 'Homo sapiens antarcticus' by La Prensa Austral. 6 Octobre 2020.

Other outreach activities

1. Åmli, Hanne; Fossen, Haakon; Svensen, Henrik. Meta Morhp. [Kunstnerisk og museal presentasjon] Utstilling, oljemalerier med tekst relatert til geologi. Universitetsmuséet i Bergen; De naturhistoriske samlinger, Muséplass 3. 2020-02-21 - 2020-09-01.
2. Conrad, Clint GEO-Wednesday: Earth's History of Changing Sea Level. Time and place: Feb. 26, 2020 12:15 PM–1:00 PM, Realfagsbiblioteket, Vilhelm Bjerknes hus
3. Gaina, Carmen, GEO-Wednesday: The Depths of Ignorance (Digital only) 18. nov. 2020 12:15, Realfagsbiblioteket, Vilhelm Bjerknes hus
4. Hagopian, W. and Jahren, A.H. CLIPT Lab video series, *episode 1 to 5* on YouTube: https://www.youtube.com/watch?v=oVvnHZYyQVQ
5. Heimdal, T., Jones, M. T., Svensen, H. H., & Callegaro, S. Large Igneous Provinces Commission, LIP of the Month Blog post "The Central Atlantic Magmatic Province and the end-Triassic crisis": http://www.largeigneousprovinces.org/20aug
6. Jones, Morgan Thomas; Jones, Olivia. Olivia Jones - Lundy. https://www.bricksbristol.org/2020/11/episode-2-olivia-jones [Internett] 2020-11-01
7. Kiraly, Agnes. Analog models for teaching and more, even at home, EGU Tectonics and Structural Geology blog, May 2020
8. Kjøll, Hans Jørgen. Langs dette fjellet går geologene rett ned i jordas indre. Titan.no [Internett] 2020-03-16
9. Kjørstad, Elise (journalist) *Slik har jordens klima endret seg gjennom tidene*. Article in forskning.no 10 October, and featuring several Earth Crises members
10. Luu, J. Media related to Luu et al. (2020) paper led to online attention of at least 54 outlets including https://phys.org/news/2020-09-idea-oumuamua-interstellar-bunny.html https://45secondes.fr/le-visiteur-interstellaire-oumuamua-pourrait-en-fait-etre-un-lapin-de-poussiere-cosmique/

11. Magni, Valentina, GEO-Wednesday: Sinking into the Earth's mantle. Tid og sted: 29. apr. 2020 12:15–13:00, Direktesending på YouTube

12. Mazzini, A. The article ***Experimental evidence for lava-like mud flows under Martian surface conditions*** (Petr Brož, Ondřej Krýza, Lionel Wilson, Susan J. Conway, Ernst Hauber, **Adriano Mazzini,** Jan Raack, Matthew R. Balme, Matthew E. Sylvest & Manish R. Patel (2020) *Nature Geoscience*, 13, 403–407 - attracted a very broad attention including in very high impact sites like Nature highlights, BBC, CNN, the indipendednt, sciencenet, cnrs, and many magazines all over the planet etc.

13. Planke, Sverre and Jones, Morgan T. GEO-Wednesday: Volcanism and climate change during the opening of the Atlantic 14. okt. 2020 12:15–13:00, Realfagsbiblioteket, Vilhelm Bjerknes hus.

14. Steinberger, B. Outdoor seminar talk at a meeting of young people doing a "Voluntary social year in science, technology and sustainability" about true polar wander and how it can help to break continents.

15. Steinberger, B. Outdoor talk at "Green World Tour Berlin". Title (translated to English): Why 3 degrees warming is too much -- a perspective from Earth history

16. Svensen, Henrik (interview) Svalbard avslører den største massedøden, forskning.no, 9.9.2020Svensen, Henrik H. GEO-Onsdag: Det viktigste faget. Å skrive lærebok i geografi for vgs. Tid og sted: 17. juni 2020 12:15–13:00, Direktesending på YouTube

17. Svensen, Henrik. Oppdagelsen av Jotunfjeldene – når geologi blir kunst. plnty [Internett] 2020-09-17

Statistics from CEED`s social media platforms in 2020

13• The CEED Blog – 13 blog articles published

1• Facebook - 639 likes/followers, 152 individual posts

1• Twitter - 1200 followers, 230 original tweets

28• Instagram – 95 followers, 28 posts

13• YouTube – 49 subscribers, 16 videos, 2400 views

Abstracts (talks & posters at conferences)

1. Akhmanov, G; Mazzini, Adriano; Khlystov, O.; Kudaeva, A.; Vidischeva, O. Peculiarities of mud volcanism in Lake Baikal. EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020.; 2020-05-03
2. Avseth, Per Åge; Millett, John M; Jerram, Dougal Alexander; Planke, Sverre; Healy, Dave. Rock Physics Analysis of Volcanic Lava Flows and Hyaloclastites. EAGE Conference and Exhibition 2020
3. Bagge, M., Klemann, V., Steinberger, B., Latinovic, M., and Thomas, M., Dependence of late glacial sea-level predictions on 3D Earth structure, (Geophysical Research Abstracts, Vol. 22, EGU2020-7699, 2020), General Assembly European Geosciences Union (Vienna, Austria 2020) (On line)
4. Bajard, Manon Julietto Andree; Ballo, Eirik Magnus Gottschalk; Støren, Eivind Wilhelm Nagel; Bakke, Jostein; Høeg, Helge Irgens; Loftsgarden, Kjetil; Iversen, Frode; Hufthammer, Anne Karin; Krüger, Kirstin. Record of climate and environmental changes in a dead-ice lake close to Gardermoen told by a 10 000 years old freshwater fish and a Viking King. Nordic Geological Winter Meeting 2020; 2020-
5. Baker, Don R.; Callegaro, Sara; De Min, Angelo; Whitehouse, MJ; Marzoli, Andrea. Fluorine partitioning between quadrilateral clinopyroxenes and melt. GSA 2020 Connects Online; 2010-10-26 - 2020-10-30
6. Bellwald, Benjamin; Planke, Sverre; Vadakkepuliyambatta, Sunil; Bünz, Stefan; Batchelor, Christine; Manton, Ben; Zastrozhnov, Dmitrii; Myklebust, Reidun; Kjølhamar, Bent. Extensive, Gas-charged Quaternary Sand Accumulations of the Northern North Sea and North Sea Fan . EGU General Assembly 2020; 2020-05-04 - 2020-05-08
7. Bretones, Anaïs; Nisancioglu, Kerim Hestnes; Jensen, Mari Fjalstad; Brakstad, Ailin Dale. Changes in Overturning Circulation under Arctic Sea Ice Retreat in EC-Earth. Ocean Sciences; 2020-02-16 - 2020-02-21
8. Chotalia, Kiran; Cooper, George; Crameri, Fabio; Domeier, Mathew; Eakin, Caroline; Grima, Antoniette Greta; Gurer, Derya; Kiraly, Agnes; Magni, Valentina; Mulyukova, Elvira; Peters, Kalijn; Robert, Boris; Shephard, Grace; Thielmann, Marcel. The transdisciplinary and community-driven subduction zone initiation (SZI) database. European Geosciences Union; 2020-05-04 - 2020-05-08
9. Conrad, Clinton Phillips. Sea Level and the Solid Earth, Interacting Across Timescales. Geotopics Seminar; 2020-12-14 - 2020-12-14
10. Conrad, Clinton Phillips; Domeier, Mathew; Selway, Kate; Heyn, Björn Holger. A link between seamount volcanism and thermochemical piles in the deepest mantle. Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-11
11. Conrad, Clinton Phillips; Selway, Kate; Weerdesteijn, Maaike Francine Maria; Smith-Johnsen, Silje; Nisancioglu, Kerim Hestnes; Karlsson, Nanna B. Magnetotelluric Constraints on Upper Mantle Viscosity Structure and Basal Melt Beneath the Greenland Ice Sheet. Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-11
12. Conrad, Clinton Phillips; Selway, Kate; Weerdesteijn, Maaike Francine Maria; Smith-Johnsen, Silje; Nisancioglu, Kerim Hestnes; Karlsson, Nanna B. Magnetotelluric Constraints on Upper Mantle Viscosity Structure and Basal Melt Beneath the Greenland Ice Sheet. EGU General Assembly; 2020-05-04 - 2020-05-08
13. Dalslåen, Bjørgunn Heggem; Gasser, Deta; Grenne, Tor; Andresen, Arild; Augland, Lars Eivind; Corfu, Fernando. Tectonic evolution of Ordovician-Silurian rocks in the Oppdal area, southern Trondheim Nappe Complex. 34rd Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-10
14. Egoshina, E; Delengov, M; Vidishcheva, O; Bakay, E; Fadeeva, N; Akhmanov, G; Mazzini, Adriano; Khlystov, O. Geochemistry of oil-and-gas seepage in Lake Baikal: towards understanding fluid migration system. EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020.; 2020-05-03

15. Faleide, Thea Sveva; Braathen, Alvar; Lecomte, Isabelle; Anell, Ingrid Margareta; Midtkandal, Ivar; Planke, Sverre. Seismic modelling of faults; viable geometries vs seismic resolution in the subsurface. The 34th Nordic Geological Winter Meeting; 2020 -01-08 - 2020-01-10
16. Gaina, C., Minakov, A., Panea, I., Mocanu, V., Matenco, L.C., Petrescu, L., and V. Magni. (2020), Subsurface geothermal potential of the Baia Mare region (Romania), T015-0003 AGU Fall Meeting, 1-17 Dec.
17. Harrington, Elise Michelle; Bultel, Benjamin; Krzesinska, Agata Magdalena; Werner, Stephanie C. Paleolakes and evaporite deposits across Mars. Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-10
18. Hartmann, Robert; Ebbing, Jörg; Conrad, Clinton Phillips. A Multiple 1D Earth Approach (M1DEA) to account for lateral viscosity variations in solutions of the sea level equation: An application for glacial isostatic adjustment by Antarctic deglaciation. EGU General Assembly; 2020-05-04 - 2020-05-08
19. Hernandez, Jean-Alexis Robert; Bethkenhagen, M.; Ninet, Sandra; French, M; Datchi, F.; Benuzzi-Mounaix, Alessandra; Brygoo, S.; Guarguaglini, M; Lefevre, F; Occelli, F.; Redmer, R.; Vinci, T; Ravasio, A. Equation of state and electrical conductivity of warm dense ammonia at the conditions of large icy planet interiors. American Geophysical Union Fall Meeting 2020; 2020-12-01 - 2020-12-17
20. Heyn, Björn Holger; Conrad, Clinton Phillips; Selway, Kate. Numerical constraints on heat flux variations and lithospheric thinning associated with passage of the Iceland plume beneath Greenland. AGU Fall Meeting; 2020-12-01 - 2020-12-17
21. Heyn, Björn Holger; Conrad, Clinton Phillips; Trønnes, Reidar G. How thermochemical piles initiate plumes at their edges. EGU General Assembly; 2020-05-04 - 2020-05-08
22. Jerram, Dougal Alexander; Sharp, Ian; Poulsen, Ragnar; Millett, John M; Planke, Sverre; Watton, Timothy J.; Freitag, Ulrike. 2020, Understanding the transitions from sub-aqueous to subaerial volcanic environments; inferences from exceptional exposures along the coast of Angola. NGF abstracts and proceedings. 34th Nordic Geological Winter Meeting, Oslo, Norway.
23. Jones, Morgan Thomas; Stokke, Ella Wulfsberg; Augland, Lars Eivind; Pogge von Strandmann, Philip A.E.; Liu, Emma J.; Mather, Tamsin; Rooney, Alan; Tierney, Jessica E; Whiteside, Jessica H.; Tegner, Christian; Schultz, Bo; Planke, Sverre; Svensen, Henrik. Constraining North Atlantic Igneous Province (NAIP) activity during the late Paleocene and early Eocene. EGU General Assembly; 2020-05-04 - 2020-05-08
24. Jones, Morgan Thomas; Stokke, Ella Wulfsberg; Augland, Lars Eivind; Svensen, Henrik; Pogge von Strandmann, Philip A.E.; Rooney, Alan. Constraining the activity of the North Atlantic Igneous Province across the Paleocene-Eocene boundary. Goldschmidt International Conference; 2020-06-21 - 2020-06-26
25. Karlsen, Krister Stræte; Conrad, Clinton Phillips; Magni, Valentina. Deep water cycling and sea level change since the breakup of Pangea. AGU Fall Meeting; 2020-12-01 - 2020-12-17
26. Kiraly, Agnes; Conrad, Clinton Phillips; Hansen, Lars. Evolving viscous anisotropy in the upper mantle and its geodynamic implications. AGU Fall Meeting; 2020-12-01 - 2020-12-17
27. Kiraly, Agnes; Conrad, Clinton Phillips; Hansen, Lars; Fraters, Menno RT. The formation of viscous anisotropy in the asthenosphere and its effect on plate tectonics. EGU General Assembly; 2020-05-04 - 2020-05-08
28. Kiyoshi Baba, Bernhard Steinberger, Marion Jegen, Max Moorkamp, Takehi Isse, Akiko Takeo, Antje Schloemer, and HEB research group Future geophysical observation on oceanic lithosphere and asthenosphere study: Hawaii-Emperor Bend (HEB) Project, JpGU-AGU joint meeting 2020 (On line)
29. Kjøll, Hans Jørgen; Galland, Olivier; Labrousse, Loic; Andersen, Torgeir Bjørge. Em-

placement mechanisms of a dyke swarm across the Brittle- Ductile transition. EGU2020; 2020-05-04 - 2020-05-08

30. Kjøll, Hans Jørgen; Galland, Olivier; Labrousse, Loic; Andersen, Torgeir Bjørge. Emplacement Mechanisms of a Dyke Swarm Across the Brittle-Ductile Transition. Nordic Geological WinterMeeting; 2020-01-08 - 2020-01-10

31. Labes, Alienor; Mazzini, Adriano; Akhmanov, Grigorii G.; Kürschner, Wolfram Michael. Palynology of Holocene Lake Baikal sediments. EGU General Assembly; 2020-05 -04 - 2020-05-08

32. Labrousse, Loic; Incel, Sarah; Zertani, Sascha; Baisset, Marie; Kaatz, Lisa; Schubnel, Alexandre; John, Timm; Andersen, Torgeir Bjørge; Tilmann, Frederik; Gasc, Julien; Moulas, Evangelos; Schmalholz, Stefan Markus; Vrijmoed, Johannes Christiaan; Renner, Joerg. Up-scaling eclogitization: from experimental and natural aggregates behaviours to seismological signatures. EGU 2020; 2020-05-04 - 2020-05-0

33. Manton, Ben; Millett, John M; Walker, Faye; Jerram, Dougal Alexander. 2020, Inter-Basalt Prospectivity at Elongated Ridges in the NE Atlantic . EAGE Conference and Exhibition.

34. Manton, Ben; Walker, Faye; Millett, John M; Zastrozhnov, Dmitrii; Polteau, Stephane; Jerram, Dougal Alexander; Planke, Sverre; Myklebust, R. 2020, The identification of inter-volcanic exploration targets in the NE Atlantic. NGF abstracts and proceedings. 34th Nordic Geological Winter Meeting, Oslo, Norway.

35. Marcilly, Chloe Franca Margot; Torsvik, Trond H. The impact of paleogeography on long-term CO2 models. Goldschmidt virtual conference 2020; 2020-06-21 - 2020-06-26

36. Marcilly, Chloe Franca Margot; Torsvik, Trond H.Improving long-term CO2 models for the Phanerozoic: What can be done? Nordic geological winter conference 2020; 2020-01-08 - 2020-01-10

37. Mazzini, Adriano; Akhmanov, Grigorii G.; Manga, Michael; Sciarra, Alessandra; Khasayeva, A.; Guliyev, I. Explosive mud volcano eruptions and rafting of mud breccia blocks. EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020.; 2020-03-03

38. Medvedev, Sergei; Hartz, Ebbe Hvidegård; Faleide, Jan Inge. Erosion-driven vertical motions of the circum Arctic: Comparative analysis of modern topography. Nordic Geological Winter Meeting; 2020-01-08

39. Medvedev, Sergei; Hartz, Ebbe Hvidegård; Schmid, Daniel Walter. Development of sedimentary basins: differential stretching, phase transitions, shear heating and tectonic pressure. Nordic Geological Winter Meeting; 2020-01-08

40. Medvedev, Sergei; Hartz, Ebbe Hvidegård; Schmid, Daniel Walter. Influence of glaciations on North Sea petroleum systems. Nordic Geological Winter Meeting; 2020-01-08

41. Medvedev, Sergei; Minakov, Alexander. Structural controls on stresses and deformations in a large-scale lithospheric shell. EGU General Assembly; 2020-05-04 - 2020-05-08

42. Midtkandal, Ivar; Holbrook, John; Faleide, Jan Inge; Myers, Cody; van Yperen, Anna Elisabeth; Shephard, Grace; Nystuen, Johan Petter. Testing arctic tectonic plate models with Cretaceous sediment source to sink budgets. Nordic Geological Winter Meeting 2020; 2020-01-08 - 2020-01-10

43. Millett, John M; Jerram, Dougal Alexander; Planke, Sverre. 2020, The Petrophysical Properties of Lava Flow Reservoirs . EAGE Conference and Exhibition.

44. Millett, John M; Planke, Sverre; Jerram, Dougal Alexander; Hole, M.; Famelli, N; Jolley, D.W.. 2020, Magmatism in wet sediment environ-ments: processes, deposits and implications for prospective volcanic rifted margins. NGF abstracts and proceedings. 34th Nordic Geological Winter Meeting, Oslo, Norway.

45. Nisancioglu, Kerim Hestnes; Jensen, Mari Fjalstad. Changes in Overturning Circulation under Arctic Sea Ice Retreat in EC-Earth. Ocean Sciences; 2020-02-16 - 2020-02-21

46. Planke, Sverre; Polozov, Alexander; Millett, John M; Jerram, Dougal Alexander. 2020,

The Siberian Traps magma emplacement dynamics links to environmental changes across the Permian-Triassic boundary in Svalbard. EGU General Assembly Conference Abstracts.

47. Planke, Sverre; Polozov, Alexander; Millett, John M; Jerram, Dougal Alexander; Zastrozhnov, Dmitrii; Svensen, Henrik. 2020, Emergent and invasive magmatism of the Siberian Traps in a wet forest environment. NGF abstracts and proceedings. 34th Nordic Geological Winter Meeting, Oslo, Norway.
48. Ramirez, Florence; Selway, Kate; Conrad, Clinton Phillips. Integrating magnetotelluric and seismic geophysical observations to improve upper mantle viscosity estimates beneath polar regions. AGU Fall Meeting; 2020-12-01 - 2020-12-17
49. Ramirez, Florence; Selway, Kate; Conrad, Clinton Phillips. Relationship between magnetotelluric and seismic geophysical observations and mantle viscosity. Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-11
50. Ramirez, Florence; Selway, Kate; Conrad, Clinton Phillips. Using magnetotelluric and seismic geophysical observations to infer viscosity for Glacial Isostatic Adjustment calculations. EGU General Assembly; 2020-05-04 - 2020-05-08
51. Robert, Boris; Domeier, Mathew; Jakob, Johannes. A diachronous opening of the Iapetus Ocean in the Neoproterozoic. European Geosciences Union; 2020-05-04 - 2020-05-08
52. Ruggero, Livio; Sciarra, A.; Mazzini, Adriano; Mazzoli, Claudio; Romano, V; Tartarello, M; Florindo, F.; Ascani, M; Wilson, G; Dagg, B; Hardie, R; Anderson, J; Worthington, R; Lupi, Matteo; Bigi, Sabina; Ciotoli, Giancarlo; Graziani, S; Fischanger, F; Sassi, R. SourcE and impact of greeNhousE gasses in AntarctiCA: the Seneca project. EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020; 2020-05-03
53. Ryen, Sofie Hildegard; Lundmark, Anders Mattias; Augland, Lars Eivind. Investigating Tear Faults in the Oslo Region. The 34th Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-10
54. Selway, Kate; Conrad, Clinton Phillips; Ramirez, Florence; Karlsson, Nanna B; Weerdesteijn, Maaike Francine Maria; Heyn, Björn Holger. How magnetotellurics can aid cryosphere studies: mantle rheology, GIA, surface heat flow, and basal melting. AGU Fall Meeting; 2020-12-01 - 2020-12-17
55. Selway, Kate; Conrad, Clinton Phillips; Ramirez, Florence; Weerdesteijn, Maaike Francine Maria. How can geophysical imaging help constrain mantle viscosity to improve glacial isostatic adjustment models? 9th SCAR Open Science Conference; 2020-08-03 - 2020-08-07
56. Shephard, Grace Elizabeth. Mapping the mantle from multiple seismic tomography models – visualisation and applications. Annual AlpArray/4DMB Meeting; 2020-11-11 - 2020-11-13
57. Shephard, Grace Elizabeth; Crameri, Fabio; Heron, Philip J. At the end of the rainbow – Scientific Colour Maps for science and society. AGU Fall Meeting; 2020-12-01 - 2020-12-17
58. Shephard, Grace Elizabeth; Houser, Christine; Hernlund, John; Trønnes, Reidar G; Valencia-Cardona, Juan J.; Wentzcovitch, Renata. Detection of the spin crossover in ferropericlase in the Earth’s lower mantle; an interdisciplinary approach. AGU Fall Meeting; 2020-12-01 - 2020-12-17
59. Shephard, Grace; Hernlund, John W; Houser, Christine; Trønnes, Reidar G; Crameri, Fabio. Ambient lower mantle structure and composition inferred from seismic tomography, convection models and geochemistry. European Geosci. Union, Gen. Assembly, Geophys. Res. Abstr. EGU2020-11806.. European Geosci. Union, Gen. Assembly, Geophys. Res. Abstr. 2020
60. Solovyeva, M; Akhmanov, G; Khlystov, O.; Mazzini, Adriano. The Khuray deep-water

fan: a beautifully complex lacustrine depositional system of Lake Baikal. EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020; 2020-05-03

61. Steinberger, B., and van Hinsbergen, D., An analytical model concerning the possible initiation of subduction between the India and Africa plates, caused by the Morondova plume, (Geophysical Research Abstracts, Vol. 22, EGU2020-6050, 2020), General Assembly European Geosciences Union (Vienna, Austria 2020) (On line)
62. Steinberger, B., Supercontinent breakup due to membrane stress induced by true polar wander, Harro Schmeling symposium, Frankfurt am Main, Germany (Talk)
63. Stokke, Ella Wulfsberg; Jones, Morgan Thomas; Tierney, Jessica E.; Riber, Lars; Svensen, Henrik; Whiteside, Jessica H. Volcanic cooling followed by a warm and wet Paleocene-Eocene Thermal Maximum in Denmark. Nordic Geological Winter Meeting 2020; 2020-01-08 - 2020-01-10
64. Stokke, Ella Wulfsberg; Liu, Emma J.; Jones, Morgan Thomas. Eruption mechanism and volatile budget of the early Eocene Danish ash series, and implications for the emplacement of the North Atlantic Igneous Province. Virtual Goldschmidt 2020; 2020-06-22 - 2020-06-26
65. Szwillus, W., Ebbing, J., Steinberger, B., Evidence of increased density of LLVPs from vote map constrained density inversion, (Geophysical Research Abstracts, Vol. 22, EGU2020-19405, 2020), General Assembly European Geosciences Union (Vienna, Austria 2020) (On line)
66. Torsvik, Trond Helge; Svensen, Henrik; Steinberger, Bernhard; Royer, Dana L.; Jerram, Dougal Alexander; Jones, Morgan Thomas; Domeier, Mathew. Connecting the Deep Earth and the Atmosphere. European Geosciences Union; 2020-05-04 - 2020-05-08
67. Vidischeva, O.; Solovyeva, M; Egoshina, E; Vasilevskaya, Y.; Poludetkina, E.; Akhmanov, Grigorii G.; Khlystov, O.; Mazzini, Adriano. Integrated analysis of geophysical and geochemical data from cold fluid seepage system along the Gydratny Fault (Lake Baikal). EGU General Assembly 2020, EGU2020-1315, Wien 3-8 May 2020; 2020-03-03
68. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Gassmöller, Rene; Naliboff, John; Selway, Kate. An Open-source 3D Glacial Isostatic Adjustment Modeling Code using ASPECT. AGU Fall Meeting; 2020-12-01 - 2020-12-17
69. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Naliboff, John; Selway, Kate. Developing an open-source 3D glacial isostatic adjustment modeling code using ASPECT. EGU General Assembly; 2020-05-04 - 2020-05-08
70. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Selway, Kate. Developing an open-source 3D glacial isostatic adjustment modeling code using ASPECT. CHESS Annual Meeting; 2020-09-28 - 2020-09-30
71. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Selway, Kate; Ramirez, Florence. Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution (MAGPIE). Nordic Geological Winter Meeting; 2020-01-08 - 2020-01-11
72. Werner, Stephanie. Francois Poulet, Fernando Rull, and the The PTAL Team. The Planetary Terrestrial Analogues Library (PTAL) Comic. Presented at EGU General Assembly 2020 EGU2020-18615
73. Zaputlyaeva, Alexandra; Mazzini, Adriano; Blumenberg, M; Scheeder, Georg; Kürschner, Wolfram Michael; Kus, J; jones, M; Frieling, J. Timing – an underestimated key factor for source rock evaluation, case study from NE Java, Indonesia.. Nordic Winter Meeting, January 8th-10th 2020 , Oslo, Norway; 2020-01-08 - 2020-01-10
74. Zertani, Sascha; Vrijmoed, Johannes Christiaan; Tilmann, Frederik; Andersen, Torgeir Bjørge; Labrousse, Loic. P wave anisotropy caused by partial eclogitization of descending crust demonstrated by modeling effective petrophysical properties. EGU 2020; 2020-05-04 - 2020-05-08

A PhD defence during the Covid-19 pandemic.

Alexadra Zaputlyaeva *(lower picture to the right) sccessfully defended her thesis «Fluid geochemistry and migration processes at the Lusi mud eruption, Indonesia», for the degree of Philosophiae Doctor on the 4th of December. The members of the adjudication committee were ProfessorChristian Berndt, GEOMAR, Helmholtz Centre for Ocean Research (lower left picture), Senior Petroleum Geochemist Marianne Nuzzo, Integrated Geochemical Interpretation Ltd. (middle upper picture), and Professor Reidar G. Trønnes CEED & NHM/UiO (upper left picture). Professor Carmen Gaina (upper rigth picture) chaired the defence. Photo: Trine-Lise K. Gørbitz*

Professors, Researchers and Adjunct Professors

Name & title	Funding source	Contract from	Contract to	Working months	% posi-tion	Citizenship
Andersen, Torgeir B. Prof.	UiO-IG	01.03.13	30.04.20	3	50	Norwegian
Augland, Lars Eivind Researcher	UiO-IG	01.07.19	12.10.21	12	100	Norwegian
Breivik, Asbjørn Associate Prof.	UiO-IG	01.03.13	28.02.23	6	50	Norwegian
Conrad, Clinton Professor	UiO-IG	01.08.19	28.02.23	6	100	American
Corfu, Fernando Prof. emeritus						
Dypvik, Henning Prof.	UiO-IG	01.03.13	11.09.20	2,4	20	Norwegian
Faleide, Jan Inge Prof.	UiO-IG	01.03.13	28.02.23	3,6	30	Norwegian
Kruger, Kirstin Prof.	UiO-IG	01.11.18	28.02.23	1,2	10	German
Maupin, Valerie Prof.	UiO-IG	01.03.13	28.02.23	6	50	French
Neumann, Else R. Prof. Emerita						Norwegian
Torsvik, Trond H. Prof	UiO-IG	01.03.13	28.02.21	6	50	Norwegian
Trønnes, Reidar Prof.	UiO-IG	01.03.13	28.02.23	6	50	Norwegian
Werner, Stephanie Prof	UiO-IG	01.03.13	28.02.23	6	50	German
Abdelmalak, M. Mansour, Res.	IG	01.06.19	31.12.21	12	100	Tunisian/French
Brodholt, John Adjunct Prof.	SFF	01.03.18	28.02.23	2,4	20	British
Buiter, Susanne Researcher	SFF	01.05.16	28.02.20	0,4	20	Dutch
Bultel, Benjamin Researcher	SFF	15.01.19	28.02.23	12	100	French
Callegaro, Sara	144995	22.09.20	05.03.24	9	100	Italian
Caracas, Razvan Adjunct Prof.	SFF	01.09.18	31.08,23	2,4	20	Romanian
Crameri, Fabio Researcher	SFF	01.03.19	31.12.21	12	100	Swiss
Domeier, Mathew Researcher	SFF	07.02.19	28.02.23	12	100	American
Doubrovine, Pavel Researcher	SFF	01.10.16	28.02.23	12	100	Russian
Gac, Sebastien Researcher	MOD	1.10.19	30.04.22	12	100	French
Gaina, Carmen Professor	SFF	01.03.13	30.04.21	12	100	Romanian
Jahren, Anne Hope Wilson Prof.	SFF	01.09.16	28.02.23	12	100	American
Jerram, Dougal Adjunct Prof.	SFF	01.03.13	28.02.23	2,4	20	British
Jones, Morgan Researcher	SFF	18.09.17	28.02.23	12	100	British
Kiraly, Agnes	SFF	01.08.20	28.02.23	12	100	Hunngaran
Krzesinska, Agata		15.10.20	28.02.23	2,5	100	Polish
Kulakov, Evgeniy Researcher	SFF	01.03.19	28.02.23	12	100	Russian
Luu, Jane X. Adjunct Prof.	SFF	01.09.19	28.02.23	1,2	10	American
Magni, Valentia Researcher	SFF	01.03.19	28.02.23	12	100	Italian
Mazzini, Adriano Reseacher	SFF	01.01.19	28.02.23	8	70	Italian
Mazzini, Adriano Reseacher	UiO-IG	01.03.13	28.02.23	4	30	
Medvedev, Sergei Researcher	MOD	1.7.19	30.04.23	12	100	Russian
Mohn, Chris Researcher	SFF	01.06.13	28.02.23	12	100	Norwegian

Red: new, grey: left CEED

Professors, Researchers and Adjunct Professors

Name & title	Funding source	Contract from	Contract to	Working months at CEED	% position	Citizenship
Niscancioglu Kerim H. Prof	144151	01.01.19	20.04.22	1,2	10	Norwegian
Planke, Sverre. Adjunct Prof.	190648	01.07.18	30.06.21	1,2	10	Norwegian
Planke, Sverre. Adjunct Prof.	SFF	01.07.18	30.06.21	1,2	10	
Rolf, Tobias, Researcher	144657	01.12.18	20.10.23	12	100	German
Schweizer, Johannes Adjunct Prof.	NORSAR	01.09.15		2,4	20	German
Selway, Katherine Adjunct Prof.	SFF	15.09.20	28.02.23	0,7	20	Australian
Shephard, Grace Researcher	SFF	01.05.18	28.02.23	12	100	Australian
Spakman, Wim Adjunct Prof.	SFF	01.03.13	28.02.20		20	Dutch
Steinberger, Bernhard Adj. Prof	SFF	01.05.16	28.02.23	2,4	20	German
Svensen, Henrik H. Researcher	SFF	01.05.16	28.02.23	12	100	Norwegian
Watson, Robin Researcher	SFF	01.12.18	28.02.23	1,2	10	British

PhD candidates

Name & title	Funding source	Contract from	Contract to	Working months at CEED	% position	Citizenship
Ballo, Eirik	UiO IG KD	24.09.18	23.09.23	12	100	Norwegian
Belosa, Lea	UiO IG KDF144	1.11.19	31.10.22	12	100	Croatian
Bostic, Joshua	UiO IG KDF143	04.09.17	03.09.20	8	100	American
Harrington, Elise	UiO IG F153	26.08.19	25.08.22	12	100	Canadian
Heyn, Björn H.	UiO IG KDF144	15.09.16	31.01.20	1	100	German
Karlsen, Krister S.	UiO IG KDF73	01.08.17	30.07.21	12	100	Norwegian
Marcilly, Chloe	UiO IG KDF142	05.08.19	04.08.22	12	100	French
Ramirez, Florence	SFF+Macquarie	13.08.19		12	100	Filipino
Stokke, Ella W.	144450	03.07.17	02.07.19	12	100	Norwegian
Straume, Eivind O.	UiO IG KDF214	15.08.16	14.08.20	7,5	100	Norwegian
Uppalapati, Sruthi	UiO IG KDF142	19.09.16	18.09.19	0	100	Indian
Werdesteijn, Maaike	144775	28.05.19	29.05.22	12	100	Dutch
Zaputlyaeva, Alexandra	UiO IG KDF104	19.09.16	18.09.19	12	100	Russian

Postdoc fellowships

Name	Funding source	Contract from	Contract to	Working months	% posi-tion	Citizenship
Augland, Lars Eivind	UiO-IG	01.07.16	31.06.19	6	100	Norwegian
Arnould, Maëlis	144657	01.11.19	31.10.20	12	100	French
Bajard, Manon	152200-144656	01.09.18	31.08.20	4	100	French
Bultel, Benjamin	143899 + SFF	15.01.16	28.02.23	0,5	100	French
Cordoba, Antonio	144657	16.11.20	15.11.22	1,5	100	Spanish
Heimdal, Thea H.	SFF	07.01.19	06.01.22	12	100	Norwegian
Hernandez, Jean-Alexis	SFF	02.09.19	31.03.21	4	100	French
Király, Ágnes	SFF	01.08.17	30.07.20	12	100	Hungarian
Kjøll, Hans Jørgen	SFF	01.08.19	30.07.20	5	100	Norwegian
Krzesinska, Agata M.	651021	15.10.18	14.11.20	9,5	100	Polish
Minakov, Alexander	SFF	16.11.17	30.09.20	12	100	Russian
Prieur, Nils C.	690477	01.07.19	31.12.20	3	50	Frensh
Robert, Boris	144312	29.09.17	28.09.20	3	100	Frensh

Techinical-administrative staff

Name & title	Funding source	Contract from	Contract to	Working months at CEED	% posi-tion	Citizenship
Birkelund, Anniken R.	144251	07.03.16	28.02.23	12	100	Norwegian
Gørbitz, Trine-Lise K.	SFF	01.03,13	28.02.23	12	100	Norwegian
Hagopian, William	SFF	01.01.17	28.02.23	12	100	American
Nettum, Sara	144251	01.12.20	31.03.22	0,5	50	Iranian/Norweg.
Silkoset, Petter	152200	01.01.16	28.02.23	12	100	Norwegian
Sørlie, Anita	SFF	15.06.16	28.02.23	9	75	Norwegian

Short term / hour based salary

Name & title	Funding source	Contract from	Contract to	Working months	% posi- tion
Benites, Tulio	SFF	Hour	based	0.5	
Gilje, Kristina	690477	01.08.19	31.01.20	2,5	50

Guest researchers at CEED

Name	Title	from	to
Afonso, Juan Carlos	Professor, Macquarie University Sydney, Australia	01.01	31.12
Blanchard, Ingrid	Postdoc, Germany	02.01	30.06
Bode, Anna de	Bachelor guest student from Utrecht university	17.09	14.10
Halvorsen, Erik	Dr. Philos	01.01	31,12
Scheerer, Stefan	Master student, Switzerland	02.03	06.03
Thybo, Hans	Professor, Istanbul Tecnical University, Turkey	01.01	31.12

Stipend to stay abroad (months period)

Name	Gender	Visiting University, country	from	to

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Basic research relevant to society and industry

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