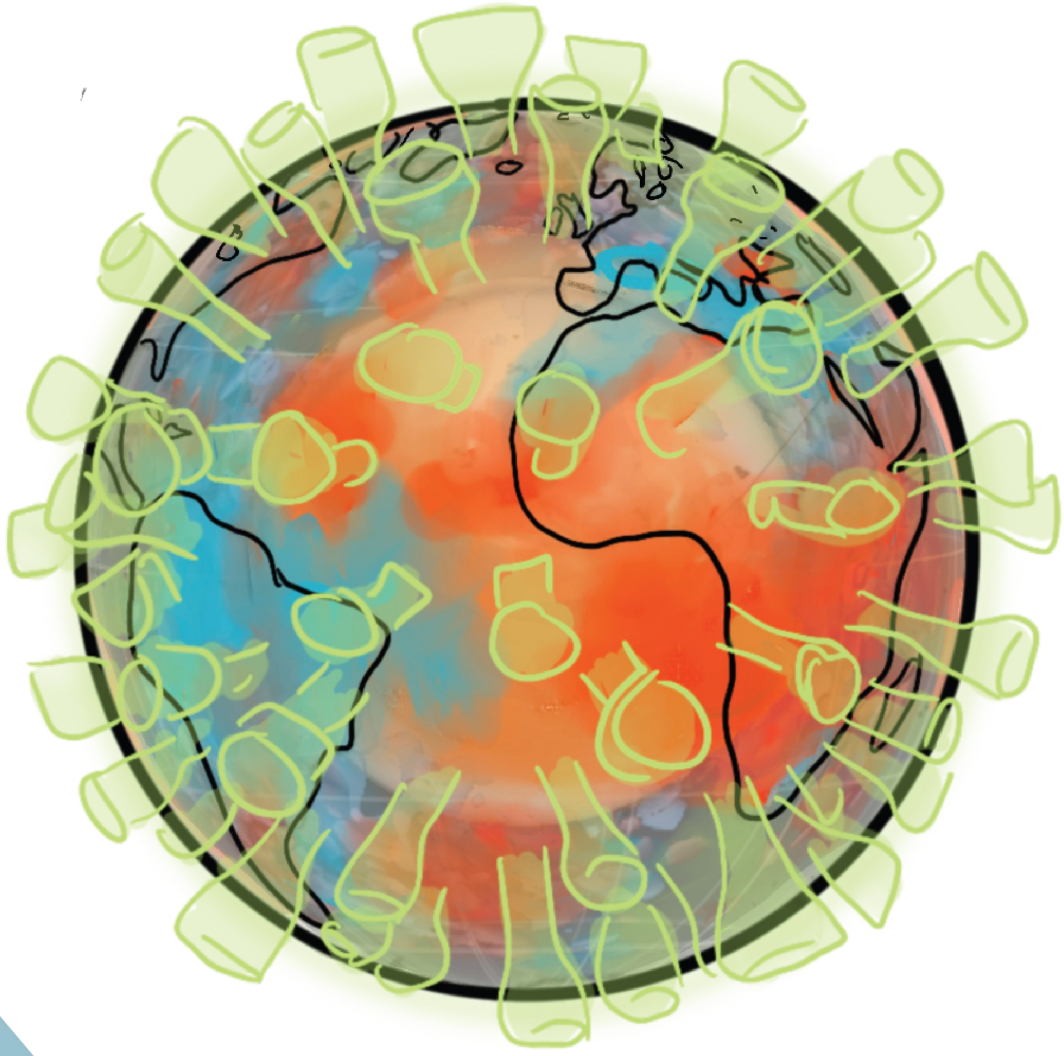
# CEED ANNUAL REPORT



2021

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



***Above:*** *CEED members and guests gathered in March 2022. Photo:* ***Gunn Kristin Tjoflot***

***Front cover:*** *View of the Earth's interior, the source of many scientific lines of enquiry at CEED, blended with a societally-defining theme of 2021, the coronavirus.*

*Figure by:* ***Grace E. Shephard.***

*Design by:* ***Trond H. Torsvik.***

***Back cover from the top:***

1. *Visitors from Romania (BAIA MARE project) and the CEED Globe. Photo by: Grace Shephard.*
2. *Grace Shephard (POLARIS YFF project winner) in front of Physics Building. Photo by: Gunn Kristin Tjoflot.*
3. *Mapping for evidence of fluids migration at the Formiche island Tyrrhenian Sea. Photo by: Adriano Mazzini.*

**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 2021

CEED published **117** publications in international journals, and **six** book chapters. This includes **12 papers in high-impact journals** with **4** as CEED personnel as the **first author**.

Two PhD candidates successfully defended their PhD projects: **Ella Wulfsberg Stokke** (29.01) and **Krister Stræte Karlsen** (16.09)

Professor **Clinton (Clint) Conrad** became an elected member of Academia Europaea. The Academy is a functioning European Academy of Humanities, Letters and Sciences, composed of individual members that are all members by invitation.

Evgeniy Kulakov received the 2020 AGU Appreciation for Excellence in Refereeing.

CEED conferred **The Else Ragnhild Neumann Award** for the third time. The 2021-award went to **Louise Mary Vick,** UiT.

**Jan Inge Faleide**, **Razvan Caracas** and **Grace Shephard** were each awarded projects from FNorwegian Research Council.



*Mapping for evidence of fluids migration at the Formiche island Tyrrhenian Sea. Photo by: Adriano Mazzini.*

# 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 **Trond H. Torsvik**

Deputy Centre leader: Professor **Stephanie Werner**

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

42 Professors, Adjunct Professors, Researchers and Research Associates

15 Postdocs

10 PhD fellows

5 Technical-administrative staff members

10 Master students

1 Professor emerita

3 Professor emeritus

**In total:**

72 paid staff members and 55 man-years representing

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)



CEED PhD student Krister Karlsen successfully defended his PhD in September 2021. Shown is Krister (center-left) and supervisors Reidar Trønnes, Clint Conrad, and Valentina Magni (left to right). Congratulations Krister!




CEED PhD student Ella Wulfsberg Stokke successfully defended her PhD on Zoom in January 2021. Congratulations Ella!

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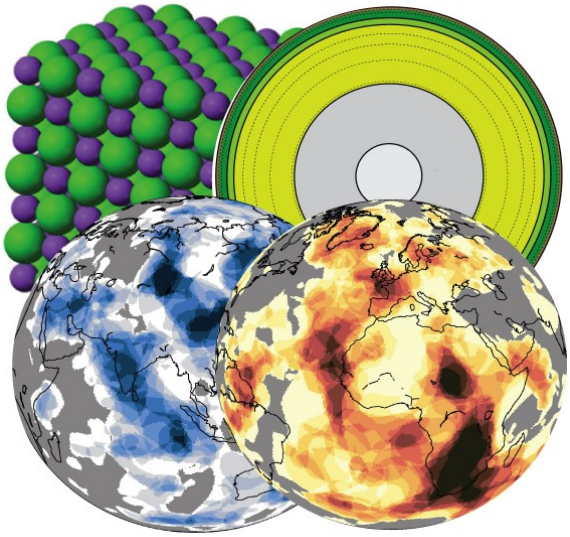
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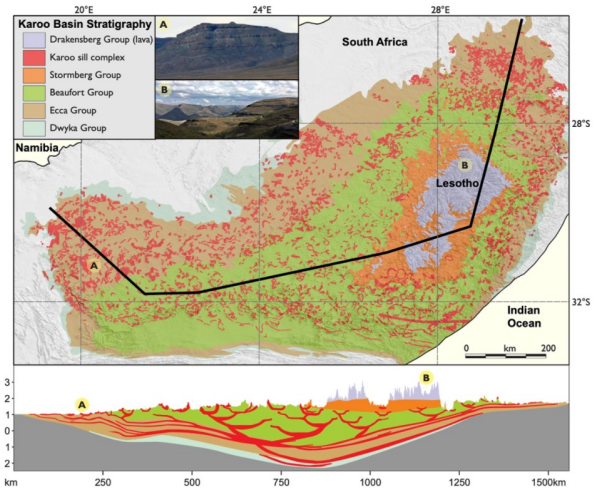
List of staff…… 136

## 1. Nature Communications

*"This study identified a seismological expression of the iron spin crossover in fast regions associated with cold ferropericlase-rich subducted oceanic lithosphere"*

**Shephard, G. E.**, Houser, C., Hernlund, J. W., Valencia-Cardona, J. J., **Trønnes, R. G.**, & Wentzcovitch, R. M. (2021). Seismological expression of the iron spin crossover in ferropericlase in the Earth's lower mantle. **Nature Communications** 12(1), 1-11.






## 2. Nature Communications

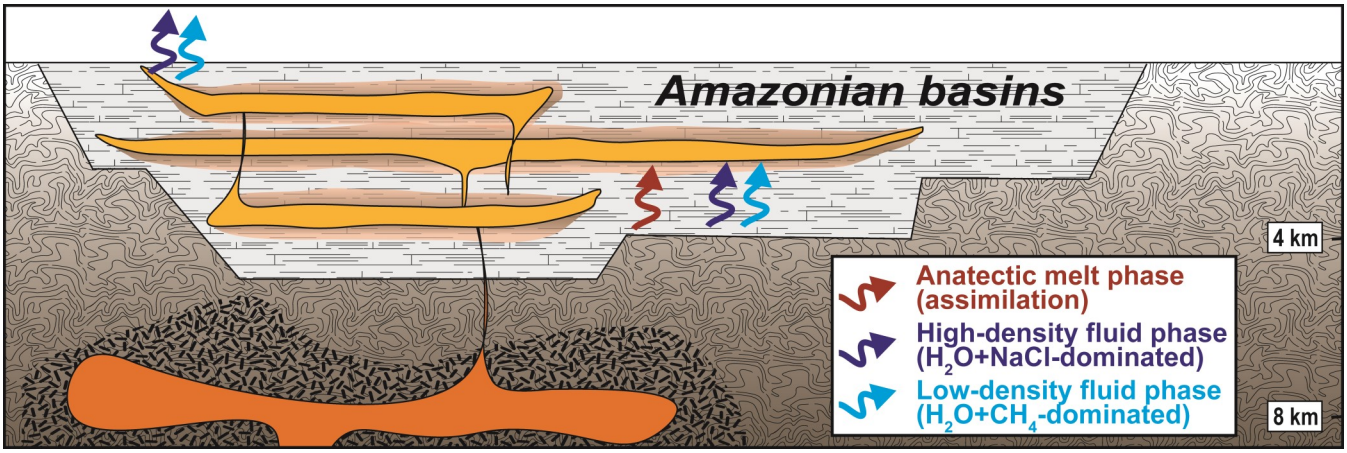
*"This paper explored the effects of pulsed carbon release from the Karoo large igneous province on atmospheric $pCO_2$ and $\delta^{13}C$ of marine sediments using the GEOCLIM carbon cycle model"*

**Heimdal, T. H.**, Goddéris, Y., **Jones, M. T.**, & **Svensen, H. H.** (2021). Assessing the importance of thermogenic degassing from the Karoo Large Igneous Province (LIP) in driving Toarcian carbon cycle perturbations. **Nature Communications** 12(1), 1-7.

## 3. Nature Communications

*"This study shows direct evidence for the presence in basaltic magmas of methane, generated or remobilized from the host sedimentary sequence during the emplacement of the Central Atlantic Magmatic Province"*

**Capriolo, M.**, Marzoli, A., Aradi, L. E., Ackerson, M. R., Bartoli, O., **Callegaro, S.**, Dal Corso, J., Ernesto, M., Vasconcellos, E.M.G., Min, A.D., Newton, R.J. & & Szabó, C. (2021). Massive methane fluxing from magma–sediment interaction in the end-Triassic Central Atlantic Magmatic Province. **Nature Communications** 12, 5534.



## 4. Nature Communications

*"This study presents direct measurements of equation of state and two-colour reflectivity of double-shocked α-quartz on a large ensemble of thermodynamic conditions, which were until now unexplored"*

Guarguaglini, M., Soubiran, F., **Hernandez, J. A.**, Benuzzi-Mounaix, A., Bolis, R., Brambrink, E., Vinci, T. & Ravasio, A. (2021). Electrical conductivity of warm dense silica from double-shock experiments. **Nature Communications** 12(1), 1-8.

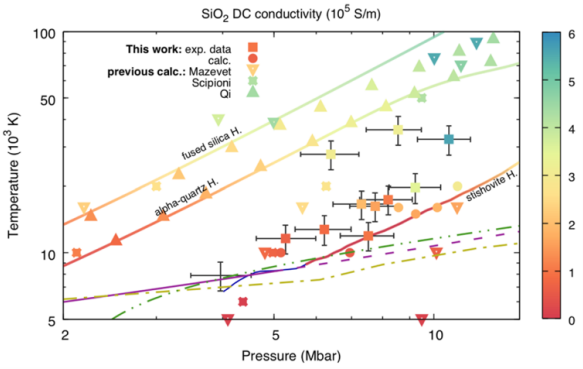
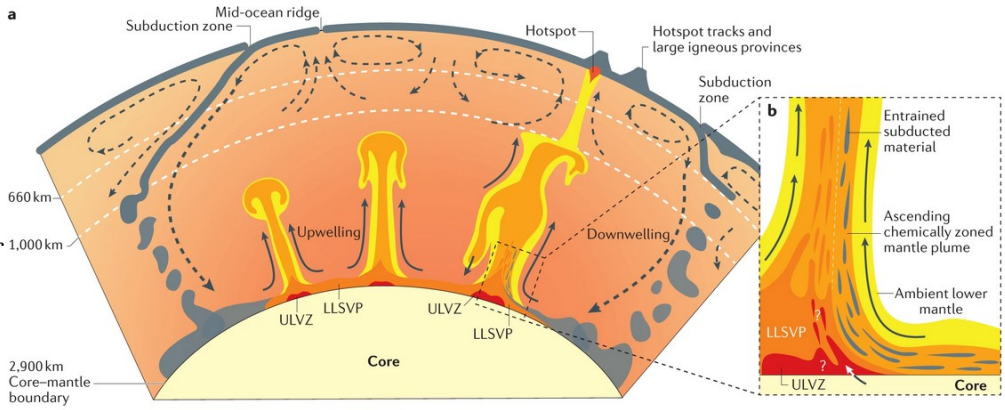


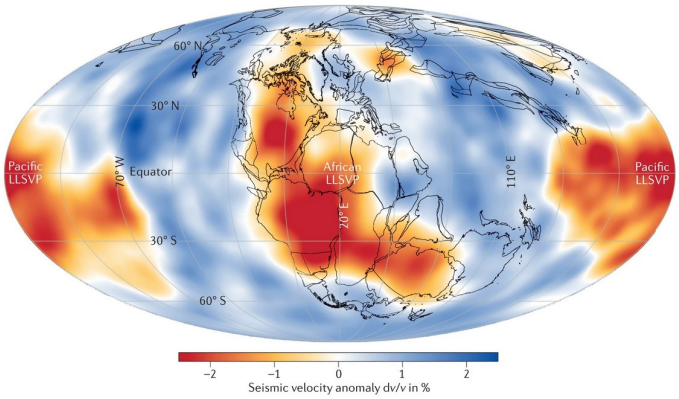

*Figure to the left: Direct current electrical conductivity of SiO2 (colour scale) as a function of temperature and pressure in the Mbar regime. Coloured squares are our experimental double shock data. The grey crosses show the error bars on our data as one standard deviation of the distribution obtained via a Monte-Carlo method. Sparse data are calculations from Mazevet et al. (2015) (reversed triangles) and Scipioni et al. (2017) (carved squares). The T–P relation along the fused silica and stishovite Hugoniot curves are from Mazevet et al. (2015) and Millot et al. (2015), respectively. Different SiO2 melting curve predictions are also presented as solid-dashed purple (Mazevet et al., 2015), dash-dotted yellow (Millot et al., 2015) and dash double-dotted green lines (González-Cataldo et al., 2016).*

## 5. Nature Reviews Earth & Environments

*"This paper discusses progress in seismic imaging, mantle flow modelling and geochemical analyses that have led to a more detailed understanding of mantle plumes"*




Koppers, A. A., Becker, T. W., Jackson, M. G., Konrad, K., Müller, R. D., Romanowicz, B., **Steinberger, B.** & Whittaker, J. M. (2021). Mantle plumes and their role in Earth processes. **Nature Reviews Earth & Environment** 2(6), 382-401.




## 6. Nature Reviews Earth & Environments

*"This study discusses how the emergence of supercontinents may provide a minimum age for the onset of the modern global plate tectonic network, whereas Archaean supercratons perhaps reflect an earlier geodynamic and nascent tectonic regime"*

Mitchell, R., Zhnag, N., Salminen, J., Liu, Y., Spencer, C. J., **Steinberger, B.**, Murphy, B. & Li, Z. X. (2021). The supercontinent cycle. **Nature Reviews Earth & Environment** 2 (5), 358-374.

## 7. Scientific Reports

*"This paper reports on significant geological methane emissions from the LUSI hydrothermal system (Indonesia), measured by ground-based and satellite techniques"*

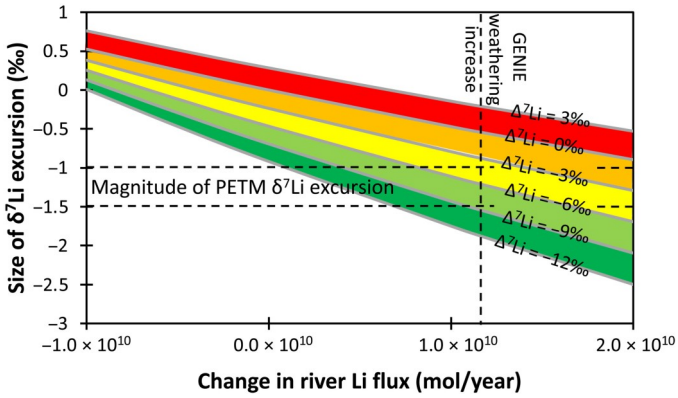
**Mazzini, A.**, Sciarra, A., Etiope, G., Sadavarte, P., Houweling, S., Pandey, S., & Husein, A. (2021). Relevant methane emission to the atmosphere from a geological gas manifestation. **Scientific reports** 11(1), 1-10.

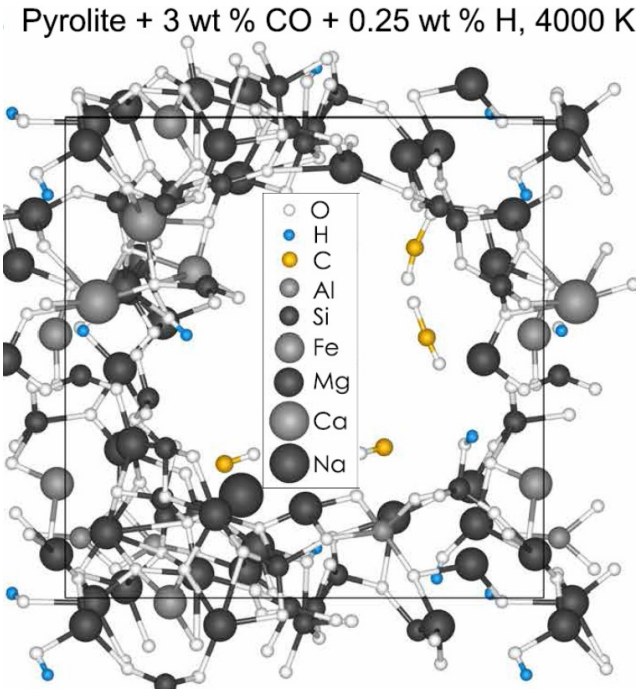


## 8. Science Advances

*"This study uses lithium isotopes to assess the global change in weathering regime, a critical carbon drawdown mechanism, across the Paleocene-Eocene Thermal Maximum (~55.9 Ma)"*

Pogge von Strandmann, P. A., **Jones, M. T.**, West, A. J., Murphy, M. J., **Stokke, E. W.**, Tarbuck, G. & Schmidt, D. N. (2021). Lithium isotope evidence for enhanced weathering and erosion during the Paleocene-Eocene Thermal Maximum. **Science Advances** 7(42), eabh4224.

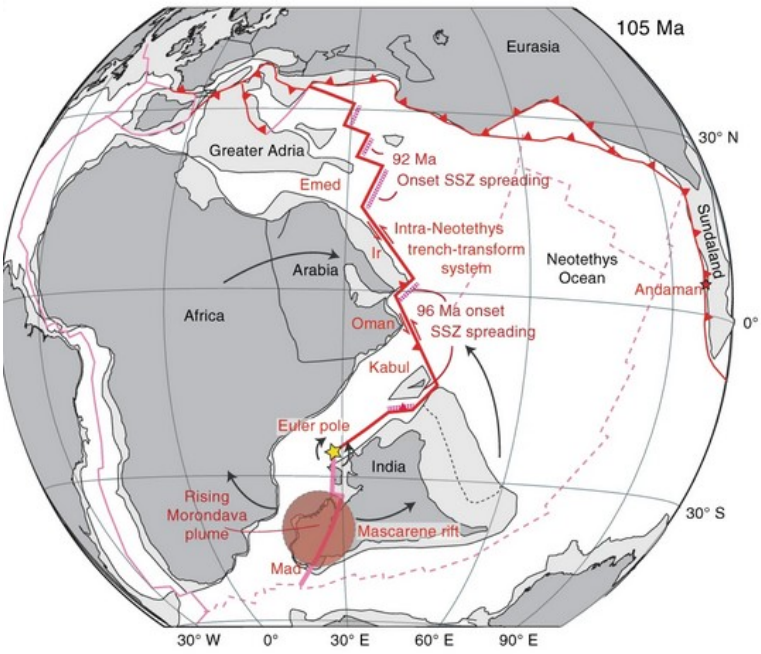



## 9. Science Advances

*"This paper investigates the vaporization of carbon and hydrogen at the boundary between the magma ocean and the thick, hot early atmosphere using first-principles molecular dynamics calculations"*

Solomatova, N. V. & **Caracas, R.** (2021). Genesis of a CO2-rich and H2O-depleted atmosphere from Earth's early global magma ocean. **Science Advances**, 7(41), eabj0406.




## 10. Nature Geoscience

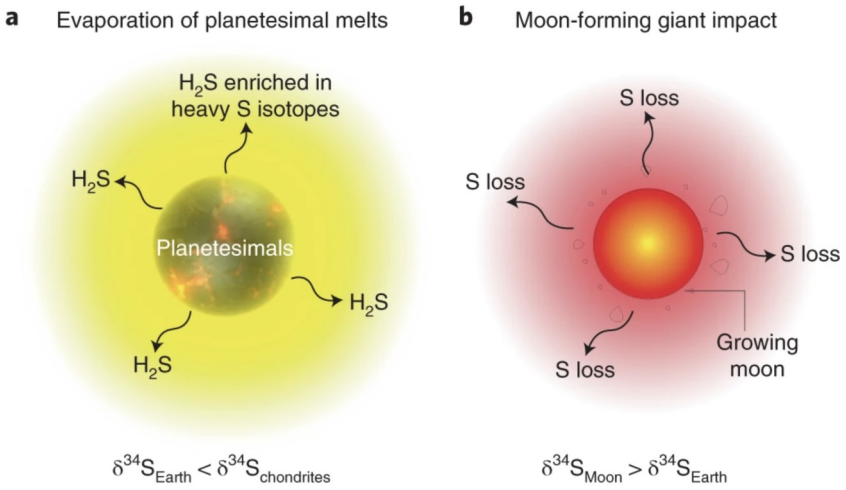
*"This study argues from geological observations that a >12,000-km-long plate boundary formed between the Indian and African plates around 105 Myr ago"*

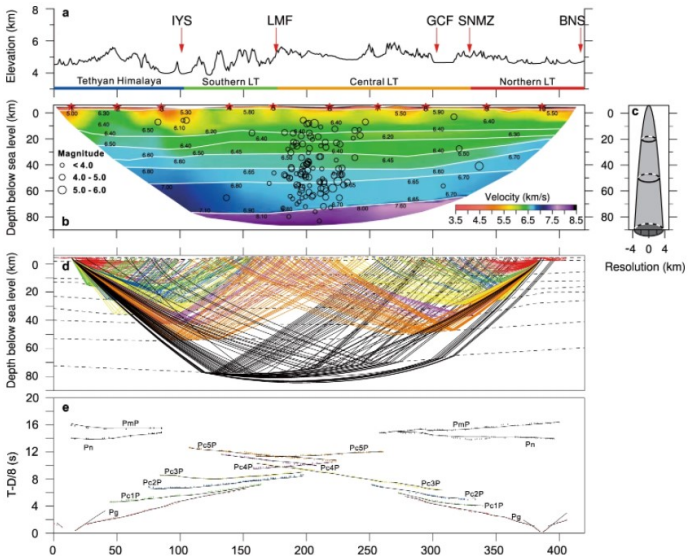
van Hinsbergen, D.J.J., **Steinberger, B.**, Guilmette, C., Maffione, M., Gurer, D., Peters, K., Plunder, A., McPhee, P.J., **Gaina, C.**, Advokaat, E.L., Vissers, R.L.M. & Spakman, W. A record of plume-induced plate rotation triggering subduction initiation. **Nature Geoscience** 14(8), 626-630.

## 11. Nature Geoscience

*"This paper uses first-principles calculations to examine sulfur isotope fractionation during core formation and planetesimal evaporation. The figure shows how the Earth's S-isotopic composition can be explained by S-evaporation from growing planetesimals."*

Wang, W., Li, C. H., **Brodholt, J. P.**, Huang, S., Walter, M. J., Li, M., Wu Z, Huang F, & Wang, S. J. (2021). Sulfur isotopic signature of Earth established by planetesimal volatile evaporation. **Nature Geoscience** 14(11), 806-811.



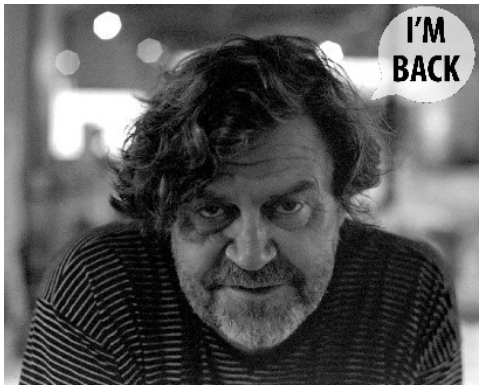




## 12. Nature Communications

*"This study demonstrates from new seismic data that some of the thickest crust on Earth in the middle Lhasa Terrane has exceptionally low velocity throughout the whole 80 km thick crust"*

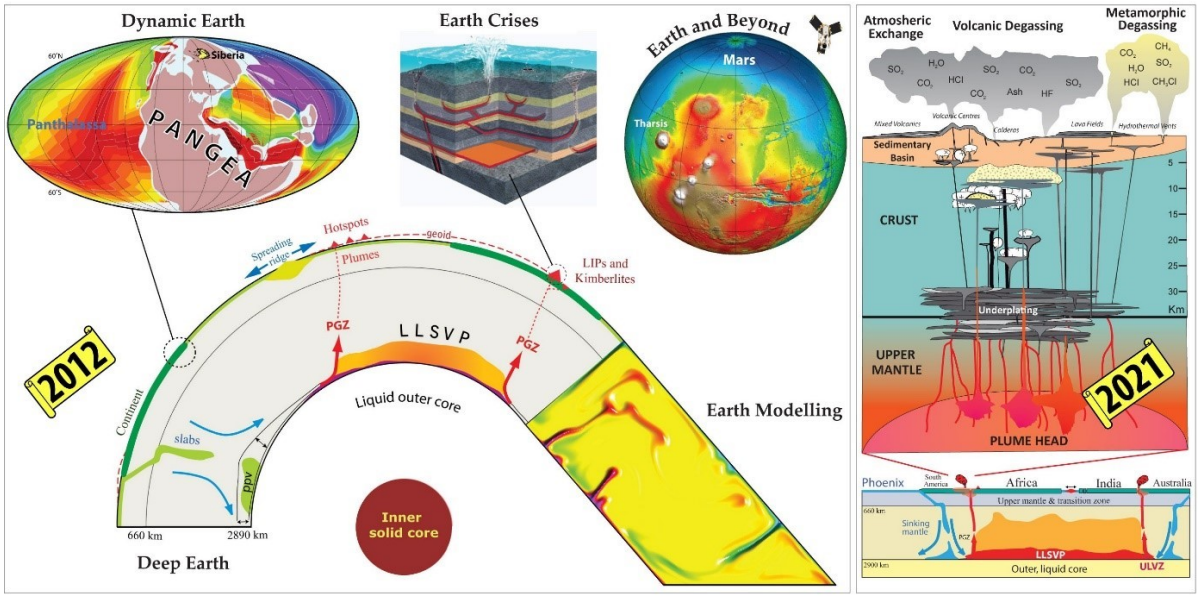
Wang, G., **Thybo, H.** & Artemieva, I. M. (2021). No mafic layer in 80 km thick Tibetan crust. **Nature Communications** 12(1), 1-9.

# From the Director




***I'll be back*** is a slogan frequently associated with Arnold Schwarzenegger in the science fiction film "The Terminator". In 2016, I handed over the CEED directorship to Carmen Gaina. Nonetheless, in 2021 I was back, but less brutal than in the famous movie where Arnold drives a car into a police station and exterminate the staff. There have been some staff changes, however: Our administrative leader over the past nine years (Trine-Lise Knudsen Gørbitz) is having a "sabbatical" year with the host Geoscience department for 2022, Nina Mino Thorud is currently our administrative leader and we have recruited a new administrative staff member (Trine Sannesmoen).

CEED has now operated for 9 years as a Norwegian Centre of Excellence, and with just one year to go, it is perhaps timely to remind us of the prime vision for CEED —*to 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.* Based on the work of CEED proponents and collaborators we hypothesised that mantle plumes are generated from the stable edges of the large low shear velocity provinces (LLSVPs; see figure below) and that deep mantle plumes explain the surface distribution of most hotspots, large igneous provinces (LIPs) and kimberlites. We further hypothesised that LIPs assisted continental break-up and have caused most of the mass extinctions and rapid climate changes of Phanerozoic times, but the environmental consequences of LIP volcanism are strongly dependent on the magma emplacement environment.




***Left-hand diagram:*** *Original cartoon used in the CEED application (2012) but Earth Modelling was originally named Virtual Earth and we also added a sixth Team (Earth Laboratory) in 2014.* ***Right-hand diagram:*** *A more recent cartoon of how six CEED scientists (from four different CEED themes) envisage the connection between the Deep Earth and the atmosphere (Torsvik et al. 2021). LLSVP, Large Low Shear-wave Velocity Province; PGZ, Plume Generation Zone; ppv, post-perovskite; ULVZ, Ultra Low Velocity Zone.*

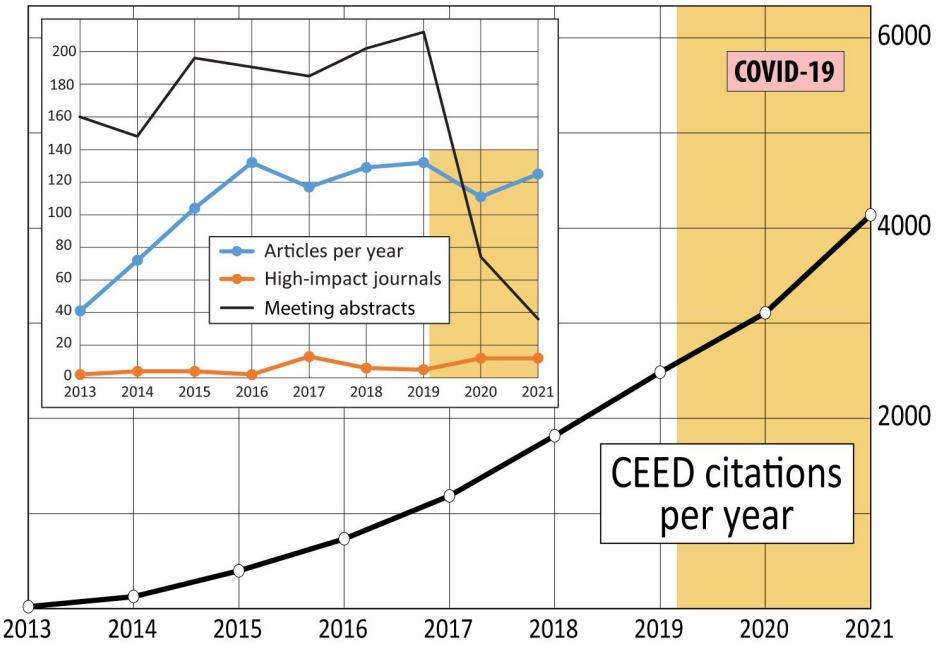
CEED activities were originally divided into a thematic research framework aiming to develop a grand scientific synergy (from top to bottom – then until now) by combining

strong numerical skills with cross-disciplinary geological and geophysical expertise. Today, CEED activities are largely still arranged within the original thematic framework, although there have been some changes, including the addition of a sixth team — *Earth Laboratory* — in 2014, and which provides critical observational data for the other teams. The *Deep Earth* holds the key to understand mantle plumes and their surface expressions through geological time, and plumes are a prime example of a phenomenon that bridges all our research themes, from the core to the atmosphere on *Earth and Beyond*. Mantle plumes take us from the *Deep Earth* to sub-lithospheric depths where partial melting occurs and to the surface where hotspot lavas are erupting today, and where episodic LIP activity through Earth history has led to *Earth Crises*. The arrival of a plume head can contribute to continental break-up and thus punctuates plate tectonics and the *Dynamic Earth* by creating and modifying plate boundaries. Conversely, plate tectonics makes an essential contribution to mantle convection through subduction. Slabs restore mass to the *Deep Earth* and could provide the triggering mechanism for plumes that rise from the margins of the stable LLSVPs. The largest volcano in our Solar System (Olympus Mons) may have been active for billions of years, and may indicate the presence of long-lived plumes on *Earth and Beyond*. Developing a robust model for plume impingement at the base of the lithosphere, the formation of LIPs as melts that make their way through the lithosphere, contributing to continental break-up, was therefore a prime numerical challenge within *Earth Modelling*, as was understanding how mantle plumes generated from the edges of the LLSVPs are triggered by subducted slabs. The *Earth and Beyond* theme was originally planned to be limited to our own Solar System but is now expanded to identify Earth-like planets (Exo-Earths) orbiting other stars. This is timely as we now embark on an unprecedented era of exploration of extra-solar planetary systems.

CEED has managed to stay focused on its original core-objectives but we have also expanded our activities to many other but related scientific avenues. We have had success in improving our understanding of how plate tectonics and the mantle interact, and how LLSVPs in the lowermost mantle control the global mantle flow, was already the topic of CEED's first *Nature* paper published in our opening year (Conrad *et al.* 2013. Nature 498, 479-482). The lowermost mantle today is dominated by two antipodal and equatorially centred LLSVPs, one beneath Africa and one beneath the Pacific, and Karlsen *et al.* (2021) have discovered that the Pacific hemisphere mantle has cooled significantly more over the past 400 million years than its African counterpart. This provides new insight into hemispheric dichotomies associated with the Wilson Cycle and supercontinent assembly and dispersal, but it also raises new questions about the history of the two hemispheres, and the extent to which they may have evolved independently of each other. This work formed an exciting final chapter to Krister Karlsen's PhD research, which he successfully defended in September 2021.

CEED aimed at publishing at least 300 refereed high quality articles and 2 books over 10 years. This was achieved already in 2016 and last year we published 125 articles, which is close to the average for the past six years (see figure below). Thus, the pandemics did not affect our paper-output for 2021, CEED articles were cited more than four thousand times and twelve articles were published in so-called high-impact journals in 2021. Three of these papers were first-authored by early-career scientists (Grace Shephard, Thea Heimdal and Manfredo Capriolo), and shed important light on our understanding of *Deep Earth* structures and LIP processes. Rapid climate-altering LIP eruptions are key issues that are addressed at CEED (*Earth Crises*), but how plate tectonics influences the *long-term* climate system was also a key issue in the original CEED application. In 2021, we addressed this for the first time with carbon cycle modelling for most of the Phanerozoic (past 541 million years), and PhD student Chloe Marcilly developed novel ways to quantify volcanic arc degassing and parameterize theoretical silicate weathering in deep time (Marcilly *et al.* 2021).

## From the Director cont.




*CEED Scopus citations per year and probably reach about 7000 in 2023. Inset diagram show articles per year (almost 1000 so far in total), the number of publications in high-impact journals (Nature-Science-PNAS related journals), and abstracts (talks/posters at conferences) per year.*

Although our article output was seemingly not much affected by the pandemics (2020 and 2021), there was a dramatic reduction in talks and posters at conferences. Physical meetings and travelling at large was strongly reduced, but in 2021, there was an increase in field-related activities. This included fieldwork in Svalbard (*Earth Crises* and *Earth Laboratory*) and successful IODP drilling on the Møre and Vøring margins. IODP Expedition 396 recovered more than 2 km of cores from 20 boreholes in August-October (2021) and Sverre Planke (co-chief) and Morgan Jones were shipboard scientists. The cored samples will provide the basis of years of further work on the interplay between the North Atlantic Igneous Province and Paleogene climate change. Samples will partly be analysed by postdoctoral worker Ella Stokke who successfully defended her PhD thesis in January 2021.

In the original application, we advocated that CEED could become a training hub for a new generation of Earth and Planetary scientists. The large number of Young Talented Researcher projects awarded to young CEED scientists clearly witness our success and postdoctoral fellow, Grace Shephard, was awarded this prestigious Norwegian Research Council Grant in 2021 for her project POLARIS. Currently CEED has four ongoing Young Talented Researcher projects, and a former winner, Matthew Domeier, was awarded an ERC 2021 Consolidator Grant for his project EPIC — Untangling **E**diacaran **P**aleomagnetism to Contextualize **I**mmense Global **C**hange. This is an extremely prestigious 5-year grant from the European Research Council and CEED congratulates.

There are no pandemic restrictions in Norway today, life is slowly becoming normal, and we look forward to fieldwork that has been postponed and attend international meetings in person and not through "Zoom". CEED will also arrange several large meetings and workshops in its final year. We have also submitted a new Centre of Excellence proposal named "Centre for Planetary Habitability" (PHAB) to the Norwegian Research Council. We are currently in the final round and the coming months will disclose if we are successful and will determine our future scientific avenue after CEED. PHAB is very different from CEED, aiming to *recognize and characterize the key conditions for planetary habitability* and addresses existentialistic research questions such as "What makes a planet hospitable? Why is Earth the only planet with life in our Solar System? And how can we recognize habitable planets around other stars?"



*Fieldwork May 2021, Kistefos. Photo by: Thea Heimdal.*

# 1. Deep Earth: Materials, structure and dynamics

*The Deep Earth team members have continued their efforts to disentangle the structure, composition, materials and dynamics of the lower mantle and outer core. In 2021, we published 22 peer-reviewed articles including two in Nature Communications and one in each of Nature Geoscience and Science Advances. One example is the contribution by Shephard et al. (2021), delineating the spatial distribution of ferropericlase (fp) in the convective parts of the lower mantle. The finding, based on the seismic signal from the pressure-induced gradual change from high to low electronic spin in the Fe-atoms of fp, indicates that the mineral is present in the high -velocity belt of cool and sinking mantle, as well as in the low-velocity rising mantle columns above the two antipodal large low S-wave velocity provinces (LLSVPs). Although this is as expected, the fp spin change signal is barely visible in 1D-averaged seismic velocity profiles through the mantle (Kennett, 2021). Because Shephard et al. did not find any spin transition signal in the average (ambient) velocity regions of the lower mantle, the implication might be that convectively stagnant regions between the cold downwelling belt and hot upwelling columns are fp-poor, bridgmanite-enriched ancient mantle structures, BEAMS (Ballmer et al., 2017).*

**Articles published in 2021**

*Material properties at extreme conditions during planetary accretion and within Super-Earths and giant planets.* The properties and phase relations involving liquid and vapour of Fe and Na, relevant to the proto-lunar accretion disk, were investigated by Li & Caracas (2021) and Li et al. (2021a). These are follow-up studies from Li et al. (2020), who determined the critical point of Fe at 9000-9300 K, 4-7 GPa and 1.9-2.4 kg/m$^3$. Although the corresponding critical point of peridotitic silicate material is about 2.5 GPa, the processes within the silicate vapour dominated disk occur at much lower pressures in the $10^2$-$10^7$ Pa range and temperatures below 4000 K (Lock et al. 2018). In laser-shock experimentation on warm, dense silica, Guarguaglini et al. (2021) found high electrical conductivity and concluded that deep magma oceans within Super-Earths are likely to produce magnetic fields. Ravasio et al. (2021) shock-compressed liquid ammonia to 350 GPa and 40 kK and recorded a gradual metallisation at about 90 GPa and 7000 K, in agreement with their own results from first principles atomistic simulations. The resulting high electrical conductivity can explain the generation of magnetic dynamos in ammonia-rich layers in ice -giant interiors. The review article by Kite et al. (2021) presents material properties, evolution stages and dynamics of different types of Earth-like exoplanets. The authors conclude that this rapidly growing research field is fundamentally important for gaining insights into Earth and planetary habitability in a wide sense.

*Earth accretion and magma ocean processes*. From first principles molecular dynamics simulations, Wang et al. (2021a) found no measurable S-isotope fractionation between silicate and metallic melts at core-forming conditions. The observed light sulfur isotope composition of the bulk silicate Earth relative to chondrites is therefore unrelated to metal-silicate fractionation. It may, however, be caused by volatile evaporation of the accreting planetesimals. Solomatova and Caracas (2021a, 2021b) investigated the effects of C- and H-volatiles (CO, $CO_2$ and $H_2O$) on magma ocean properties and degassing to the proto-atmosphere. They found that the relative magma density reduction decreases with increasing pressure in the 20-135 GPa range and inferred that the volatile-promoted buoyancy would promote convection and degassing to the atmosphere from the shallower parts of the magma ocean. Because the melt solubility of $H_2O$ is very high and increases with increasing pressure (Mookherjee et al., 2009), Solomatova and Caracas (2021b) also found that $CO_2$ would have

degassed much more extensively than $H_2O$ to the proto-atmosphere, which could therefore have thermally insulated the earliest Earth efficiently.

*Mineral chemistry, phase relations and properties of hydrous and carbonated deep Earth materials*. The role of hydrogen and water in the lower part of the mantle transition zone (TZ) is discussed by Muir et al. (2021), Thomsen et al. (2021) and Wang et al. (2021b). Whereas the two major TZ minerals, wadsleyite and ringwoodite are Al-poor, Thomson et al. found that H dissolution in ringwoodite is accomplished by the incorporation of ferric Fe in the tetrahedral Si-dominated crystal site. Muir et al. investigated the complex broadening and narrowing of the phase loop between ringwoodite and bridgmanite+periclase in the system $MgO\text{-}SiO_2\text{-}H_2O$ as a function of water content in the context of the seismic discontinuity at about 660 km depth. In order to put constraints on the TZ water content, Wang et al. (2021b) determined the elasticity and seismic velocity of hydrous ringwoodite. The results indicate that most of the seismic velocity variation may be linked to variations in water content. Li et al. (2021b) investigated the equations of state for CO and $CO_2$. The results were used to infer the phase relations of carbonates under various p-T conditions of the Earth's mantle.

The solid inner core of the Earth is characterised by shear-wave velocities well below those expected in mineralogical models for anhydrous compositions. However, based on ab initio atomistic simulations with hcp-structured $Fe_{64}H_4$, $Fe_{60}Si_4H$, $Fe_{60}Si_4H_2$, $Fe_{60}Si_4H_4$ and $Fe_{60}Si_4H_8$ (H-contents of 0.03-0.23 wt%), Wang et al. (2021c) documented strong shear softening of the solid inner core. Slightly hydrous core conditions may therefore explain the low inner core S-wave velocity.

*Geodynamics and mantle structure*. Based on paleo-age grids extending back to the mid-Paleozoic, Karlsen et al. (2021) inferred the spatio-temporal variations in surface heat loss. The heat flow from the Pacific hemisphere has exceeded that of the African hemisphere during almost the entire period, possibly related to the long-lived thermal insulation by the Rodinia supercontinent. A short-lived elevated heat-flow pulse related to Pangea break-up is also recorded in the African hemisphere. The observation of the $Fe^{2+}$ spin transition in ferropericlase based on an extensive analysis of seismic tomography models (Shephard et al. 2021), can potentially provide important insights into mantle structure and dynamics (separate section below).

*Solid-state, inorganic materials science*. Based on an investigation of the energy landscapes of a range of materials, including oxides, sulfides, nitrides, carbides and graphene, Allan et al. (2021) highlighted the importance of local structural environments, rather than limited consideration of the average structure, for disordered materials. Two ab initio atomistic simulation contributions by Mohn et al. (2021) and Stroud et al. (2021), published in the Phil. Trans. Roy. Soc. related to the Theo Murphy meeting on "Understanding fast-ion conduction in solid electrolytes", deal with fast ion conduction in $Bi_4V_2O_{11}$ and cooperative excitations in superionic $PbF_2$, respectively. Such functional materials have important applications as solid-state electrolytes in fuel cells. Das et al. (2021) documented that the monoclinic phase $CaTiSiO_5$ (mineral name: titanite) has exceptional and potentially useful mechanical, electronic and optical properties, which may be utilised in optical filters, polarisers and other

opto-electronic devices. Due to the ability of titanite to admit large and highly charged cations like REE, U and Th, titanite-based ceramics have also been suggested as suitable media for the stabilisation and storage of nuclear fuel waste.

*Biological materials*. Hassler et al. (2021) investigated the Ca-isotopic composition of a range of tissue types (blood, urine, milk, colostrum, umbilical blood and bone tissue) of adult sows and piglets to infer the Ca-isotope fractionation during mammalian lactation and gestation. The results indicate that bone mineralisation causes more limited Ca-isotopic fractionation than previously envisioned. Their model also refines the Ca-isotope applications in the monitoring of human bone balance.

*New developments of experimental and theoretical methods.* Denoeud et al. (2021) developed a setup for ultrafast x-ray powder diffraction for laser-driven dynamic compression at the LULI-2000 laser facility. This allows probing of tiny portions of compressed samples to characterise spatially and temporarily uniform thermodynamic conditions of samples with a large range of atomic numbers, thicknesses, and compression dynamics. In order to analyse melts and fluids from first principles molecular dynamics simulations, Caracas et al. (2021) developed a Python-based open-source UMD package to store and analyse atomic trajectories and relevant thermodynamic information of the simulations, saved as UMD files (for Universal Molecular Dynamics).

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**Seismic detection of electronic spin change in the lower mantle** *(G.E. Shephard, R.G. Trønnes)*

With increasing depth in the lower mantle, the $Fe^{2+}$ in the mineral ferropericlase ([Mg,Fe]O, herein fp) undergoes an electronic change from high to low spin. This gradual pressure-induced change shrinks the Fe-atoms, affecting key material properties, including density, viscosity, elasticity, thermal conductivity, and element partitioning. Sinking oceanic lithosphere slabs, as well as rising mantle columns, including focused mantle plumes, will therefore be accelerated through the spin change interval of 250-500 km vertical extent.

The spin crossover, indicated by first principles atomistic theory and experiments, is not seen in the commonly used 1D-averaged PREM-profile for seismic velocities and density, which is largely based on long-period, whole-Earth vibrations (normal modes). A detailed analysis of the 1D-averaged models ak135 and ek137, however, which are based mostly on body-waves,

yields a weak spin transition signal (Kennett, 2021). In Ocober 2021, after more than two years of reviews in various Nature journals, Nature Communications published an article on "Seismological expression of the iron spin crossover in ferropericlase in the Earth's lower mantle". Our international research team (Shephard, Houser, Hernlund, Trønnes, Valencia-Cardona and Wentzcovitch), involving experts in quantum physics, seismology, geochemistry, geodynamics and plate tectonics, was for the first time able to spatially resolve regions with the spin transition by lower mantle seismic tomography (Figure 1.1).

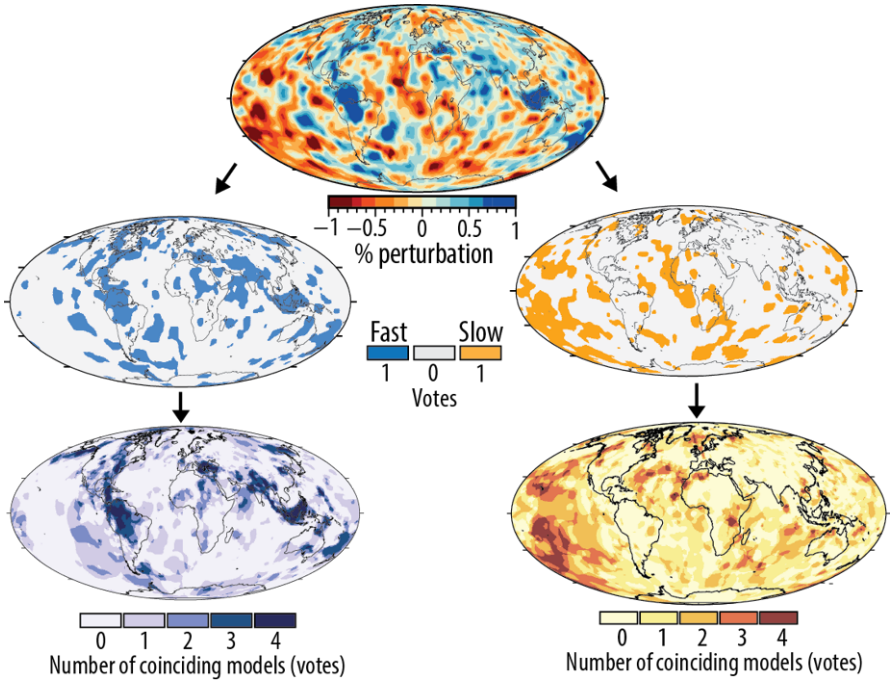



*Figure 1.1. Method description. From a given seismic tomography model representing a specific depth (top panel), the fast (blue) and slow (orange) anomalies were extracted as binary values (middle row). The criteria for high and low velocity anomalies were varied, but commonly we used deviations of >+1sigma and <-1sigma from the mean for fast and slow anomalies, respectively. After combining several tomography models, e.g. four P-wave models for fast anomalies, the individual areas were summed to give a finer picture of specific areas with either 0, 1, 2, 3 or 4 agreeing vote signals (bottom row).*

The paper is based on the premise that the compressional (P-wave) velocity decreases in the depth interval of the Fp spin crossover, while the shear (S-wave) velocity remains unaffected. The volume reduction during the spin crossover would inevitably increase the compressibility and decrease the bulk modulus of Fp. Both the onset pressure and pressure interval of the mixed spin region, where high- and low-spin states coexist, are expected to increase with increasing temperature (Figure 1.2). The team analysed several global seismic tomography models, using the "vote map" technique developed by Shephard et al. (2017), and confirmed that elevated P-wave anomalies largely disappear within the expected spin crossover intervals, below about 1400 and 1800 km depth in the high-velocity (cool) and low-velocity (warm) regions, respectively. The results suggest that Fp is present in the convective lower mantle, including the regions of cold, sinking lithospheric slabs in a wide longitudinal belt beneath the Arctic, Asia, Australia, Antarctica and the Americas, as well as within the hot, rising mantle columns above the large low S-wave velocity provinces (LLSVPs) under the

Pacific and Africa. Because there are no indications of a Fp spin crossover signal in the intermediate regions of the lower mantle, characterised by average (or ambient) P- and S-wave velocities, a possible implication is that these regions are Fp-poor. The extremely weak Fp spin crossover signal in the global 1D-averaged ak135 and ek137 models supports this inference. Such Fp-poor domains might be isolated Hadean refractory reservoirs, referred to as bridgmanite-enriched ancient mantle structures or BEAMS (Ballmer et al., 2017).

The paper and study was led by CEED researcher Grace Shephard (also Team Dynamic Earth) in collaboration with Reidar Trønnes, and researchers from ELSI at ELSI, Tokyo Institute of Tech (Japan), Columbia University (USA) and Univ. of Minnesota Uni (USA). Since publication, it has featured in several science news outlets, including Science (in the section: "In Other Journals – A mantle spin transition"), and it was selected to feature on the cover of Nature Communication from mid-Jan 2022 (for at least a month).

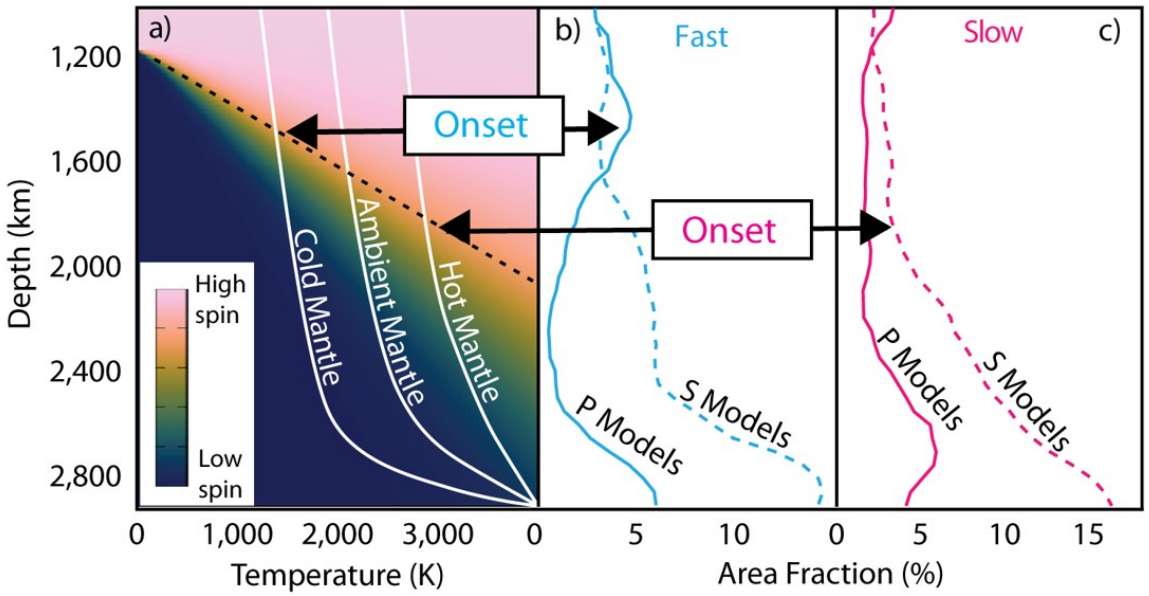



*Figure 1.2. Slightly modified from Fig. 1 of Shephard et al. (2021). a) Depth-temperature distribution of the Fe spin state in ferropericlase and three schematic mantle geotherms. The onset of the mixed-spin region occurs at shallower depths at relatively low temperatures and at greater depths and over a broader range at higher temperatures. Area fractions of fast (b) and slow (c) velocity anomalies (based on unanimous consensus, i.e. agreement of all 4 models) as a function of depth in the lower mantle. The onset of the mixed spin regions is seen where the P-wave velocity decreases relative to the S-wave velocity, resulting in concomitant loss of some of the strong fast anomalies and therefore a reduction of the area fraction of four unanimous fast anomaly votes. In the lowermost 300 km above the core-mantle boundary, which is the depth range of the LLSVPs and a strong bimodal velocity dispersion, the area fractions of the fast and slow S-wave velocity anomalies increase considerably.*

**Counterintuitive diffusion rates of He and Ne in periclase** *(C.E. Mohn)*

The relationship between diffusion rate and atomic properties, such as charge, size and mass, is a useful guide for understanding many dynamical processes within the Earth's interior, particularly under extreme conditions where samples are not accessible or experiments might be challenging or impractical. The conventional textbook model to solid state diffusion states that *smaller atoms move faster than larger ones* (e.g. Glicksman, 1999; Baxter, 2010). This is intuitive, and rationalised qualitatively by lattice-strain considerations. Larger atoms are expected to encounter a higher activation energy barriers as they jump from one site to another, decreasing the diffusion rate and mobility. In the case of noble gases, for example, we expect that diffusion increases with increasing atomic number so that $D_{He} > D_{Ne} > D_{Ar}$, where D is the diffusion coefficient. This is indeed the trend observed experimentally and computationally in a number of anhydrous minerals, such as ilmenite, olivine and quartz (Glicksman, 1999; Futagami et al, 1993), as well as in hydrous minerals like serpentine and amphibole (Wang et al., 2020).

This commonly accepted strain model of lattice diffusion is challenged by our *ab initio* molecular dynamics (MD) calculations of absolute diffusion rates of noble gases in pure MgO periclase at pressures up to 100 GPa and temperatures up to 5000 K (Mohn and Allan, submitted). The lack of previous measurements of noble gas diffusion in periclase (or ferropericlase) is unfortunate, because ferropericlase constitutes roughly 20 % of the lower mantle volume. As tracers, the diffusivity of noble gases in periclase are therefore important for understanding the thermal and chemical evolution of the Earth.

Fig. 1.3 shows that the larger Ne diffuses faster than the smaller He below about 1325, 3570 and 6173 K at 0, 50 and 100 GPa, respectively. To understand this, we have compared the activation energy for a jump from one interstitial site to another. Fig. 1.4 shows that Ne has substantially lower activation energy than He, which can in part be explained the highly strained *equilibrium* configuration for Ne in MgO, and in part by the "softer" Ne which can more easily "squeeze itself" through the transition state compared to He. This counter-intuitive finding is intimately linked to the cubic close-packing of anions, with the cations filling all of the octahedral sites in periclase. We suspect that there might be other minerals with similar diffusional relations.

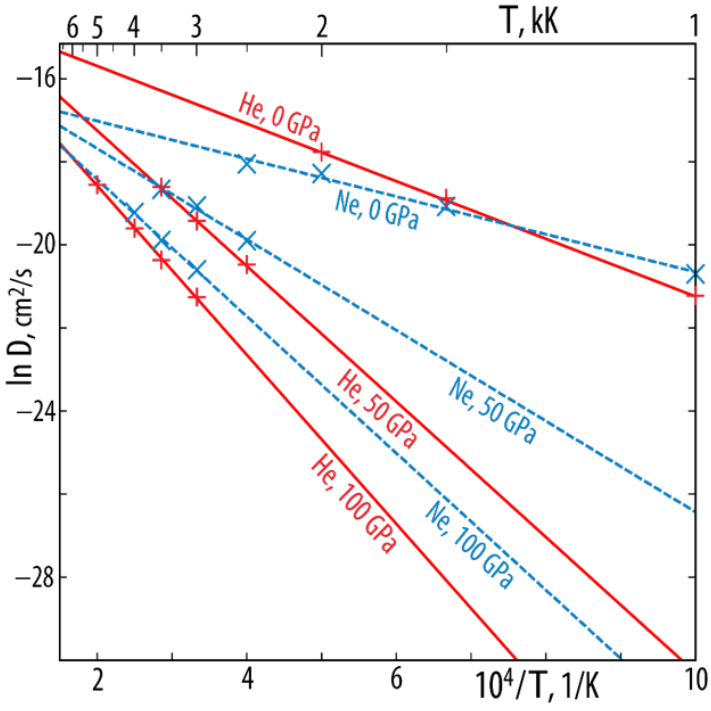



*Figure 1.3. Arrhenius plots with ln D versus inverse temperature for He and Ne self diffusion in pure MgO periclase, calculated from ab initio molecular dynamics. D: diffusion co-efficient.*

Although the temperature of the crossover-point where He and Ne have identical diffusion coefficients is higher than the mantle geotherm, we expect Ne to have only slightly higher diffusion coefficient (by a factor 1.5) in the lower mantle. He and Ne are unlikely to be diffusionally fractionated in mantle peridotite if He and Ne diffusion rates are also similar in bridgmanite. Diffusion of He in ferropericlase may also be important to unveil hidden mantle reservoirs with high $^{3}He/^{4}He$ ratios, if ferropericlase form an interconnected network and noble gas diffusion is faster in ferropericlase compared to surrounding mantle. Such interconnected networks may act as "channels" for noble gas diffusion which, in turn, can help to constrain the size of possible "primordial" reservoirs over the age of the Earth.

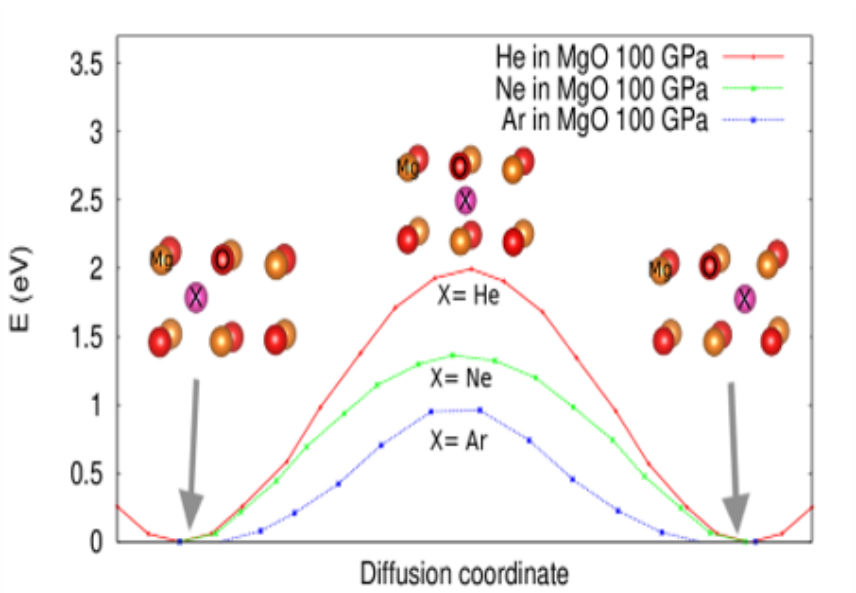



*Figure 1.4. The activation energy barrier of diffusing noble gas elements between interstitial positions in periclase, calculated using ab initio molecular dynamics.*

**Composition, evolution and structure of the lower mantle** *(R.G. Trønnes)*

Several recent developments, some of them in 2021, have led to an updated view of the phase relations, composition and structure of the lower mantle. The completion of first principles atomistic computations on the bridgmanite (bm) to post-bridgmanite (pbm) phase transition for $MgSiO_3$ and the two-phase loops in the systems $MgSiO_3$-$FeSiO_3$ and $MgSiO_3$-$FeAlO_3$, with exploratory work in the system $MgSiO_3$-$Al_2O_3$ (Mohn, in prep.; Trønnes and Mohn, in prep. CEED Annual Report for 2017) has been central to these developments. Our evolving insights have also been influenced by experimental studies indicating (1) that the bm-pbm phase transition in a natural peridotite composition has a Clapeyron slope of less than 8 MPa/K (Kuwayama at al., 2021), (2) that the peridotite solidus at core-mantle boundary (CMB) conditions might be as low as 3800 K (Nomura et al. 2014; Kim et al. 2020; Kuwayama et al. 2021) and (3) that a low Fe-melting curve (Sinmyo et al. 2019) might be consistent with an inner core boundary temperature in the 5000-5500 K range and a CMB temperature well below 4000 K. We therefore suggest a downward revision of the CMB temperature to 3600 K and find that pbm is stable in the entire depth range from the bottom to about 300 km above the CMB, even within the hot LLSVP regions, and regardless of whether the the LLSVP base layers comprise Fe-rich magma ocean cumulates, concentrated recycled oceanic crust (ROC) or, most likely, a combination of both (e.g Torsvik et al. 2016; Trønnes et al. 2019). The new

realisation is also supported and influenced by the seismological evidence presented by Koelemeijer et al. (2018).

***Initiation of deep subduction and the model age of MORB- and OIB-sources.*** Another fundamentally important realisation concerns the overall structure of the lower mantle and the composition of the convective mantle, which has been continuously replenished by the sinking of subucted oceanic lithosphere. The onset of plate tectonics is unconstrained, with recent estimates ranging between 3 and 4 Ga (e.g., Shirey and Richardson, 2011; Greber et al., 2017; Bauer et al., 2020). The transition from stagnant to mobile lid tectonics was probably gradual and quasi-episodic in the beginning (Korenaga, 2013).

The earliest crustal reworking might have been quite shallow and in the form of Venus-type plume-related subduction (e.g., Gerya et al., 2015; Davaille et al., 2017; Sobolev and Brown, 2019), density-driven drip tectonics (Smithies et al., 2021) or Iceland-type crustal subsidence (Reimink et al., 2014). More familiar plate tectonics with deep subduction and recycling might have started at about 3 Ga (e.g., Shirey and Richardson, 2011). The input of subducted oceanic lithosphere into the convecting mantle during the 3-0 Ga period can potentially be estimated, based on the relation between rate of plate generation, oceanic lithosphere thickness, mantle potential temperature and secular cooling (e.g., Herzberg et al., 2010; Ganne and Feng 2017; Korenaga, 2013). The thickness of the oceanic crust and total lithosphere, the plate velocities and the subduction flux, however, become increasingly uncertain with increasing age. It the absence of accurate estimates of accumulated subduction volume during the last 3 Ga, it is interesting to note that the model ages based on the uranogenic Pb-isotopes, $^{207}$Pb (from short-lived $^{235}$U) and $^{206}$Pb (from long-lived $^{238}$U) of the mantle sources of mid-ocean ridge basalts (MORB) and ocean island basalts (OIBs) are about 2.0 Ga (Hart, 1984; Jackson et al. 2020) and within the 1.5-2.5 Ga range (Andersen et al. 2015), respectively.

***Subduction flux, mantle secular cooling and composition of ROC and depleted mantle***. The global volume flux variation of subducted oceanic lithosphere from 400 Ma to the present has been estimated by K.S. Karlsen (pers. comm., previous Earth modelling member), based on seafloor age grids from plate tectonic reconstructions (Karlsen et al., 2020), plate velocities (Matthews et al., 2016) and oceanic lithosphere thickness (Parsons and Sclater, 1977). Although the variations are relatively large within 20-50 My periods, the long-term trend involves decreasing volume flux from about 445 km$^3$/y at 400 Ma to about 300 km$^3$/y at the present. A very rough and possibly conservative estimate of the cumulative volume from applying a constant median flux of 372.5 km$^3$/y for the 0-3 Ga period, is $1.12*10^{12}$ km$^3$. Such a cumulative subducted lithosphere volume, which is 1.23 times the volume of the entire mantle and approximately 1.56 times the convective mantle volume (Figure 1.5), suggests that the convecting mantle might have been fully replenished in the last 3 Ga. The model ages of the MORB and OIB sources, exceeding 1.5 Ga, might indicate that the tentative assumption of a roughly constant volume flux, corresponding to the 0-0.4 Ga period average, during the 0 -3 Ga period, is too conservative. The major plume-derived oceanic islands are characterised by relatively old and distinct model ages ranging from 1.7-1.8 Ga for Hawaii and Iceland, 1.9 for LaPalma and parts of the Azores to 2.1-2.4 Ga for French Polynesia, Samoa, Reunion and other parts of the Azores (Andersen et al., 2015). Olivine hosted sulphide inclusions in Cook island basalts have also S-isotopic compositions indicative of Archean recycling (Cabral et al., 2013). These age indications combined with other distinct geochemical features and the

observations that about 25% of the current major plumes rooted near the LLSVP margins have bilateral zonation with the enriched zone facing towards the LLSVP interior, indicate storage of ROC material of specific ages in specific regions of the LLSVP base layers (Torsvik et al., 2016).

***Compositions of ROC and depleted peridotite in the convective mantle.*** An important consequence of relatively old recycled oceanic crust (ROC) in the convecting mantle is that the bulk compositions must be picritic, rather than basaltic. The primary picritic melts formed by decompression melting of ambient upwelling mantle in the 0.5 to 3.0 Ga period would have MgO contents of 14-21 wt%. Our best estimates for the current potential temperature (Tp) of passively upwelling ambient mantle is about 1400 C (Putirka, 2008; Dalton et al., 2014; Bao et al. 2022). We have adopted the Bao et al. (2022) Tp estimate of 1388 C for average MORB upwelling, resulting in a primary basaltic melt with 12.0 wt% MgO (Herzberg and O'Hara, 2002). This is much higher than the evolved MORB compositions with 8-9 wt% MgO, which are commonly used as starting materials for experiments and input into petrological models. From the Herzberg et al. (2010) compilation of primary melt compositions as a function of Tp for passively upwelling mantle at spreading axes, and reasonable mantle secular cooling models, we estimate that the picritic ROC compositions at 3.0, 2.5, 2.0. 1.5, 1.0 and 0.5 Ga might have had 21.1, 20.6, 19.7, 18.2, 16.4 and 14.3 wt% MgO, respectively. Although the lower mantle mineralogy in such picritic compositions would be similar to that of evolved basalt compositions, the proportions of bridgmanite would be higher and those of the other minerals, and especially the silica minerals, would be lower. In an evolved basalt composition, the proportions of bridgmanite, Ca-perovskite, Al-rich Ca-ferrite-phase and silica minerals are about 36, 26, 20 and 18 mol%, respectively, whereas a picritic lithology with 18 wt% MgO would have 61, 21, 11 and 6 mol% bm, Ca-pv, cf-phase and silica, respectively.

The common use of pyrolitic model compositions to represent mantle peridotite in mineral physics modelling is also an unfortunate practice. The convective mantle, which is unlikely to contain pyrolitic material, is mainly a mix of ROC and variably depleted mantle. Korenaga (2013) presented a simple model for the thickness of the ROC and depleted part of the mantle lithosphere, indicating that the ratio of ROC to depleted lithosphere increases from about 0.1 today to 0.25 at 3 Ga. With aging and cooling away from the spreading ridges, the lithosphere thickens by incorporating ambient convective mantle, which is less melt-depleted than the upper part. The progressive melting and melt extraction from the upwelling asthenosphere result in increasing depletion upwards. Based on this, the proportions of ROC and variably depleted mantle lithosphere in the aging and evolving convective mantle is likely to remain at about 10 and 90%, respectively. The likely accumulation of some ROC-material in piles on top of the LLSVP base layers will tend to limit the ROC-proportion in the convective mantle. Olivine fractionation of the primary melt in magma chambers near the spreading ridges might also produce some olivine-rich lower cumulate layers, which might effectively become part of the mantle, rather than the ROC.

During decompression melting of passively upwelling mantle at higher ambient Tp, e.g. at 1.5 Ga, the degree of melt depletion was higher than at the present Tp. The peridotite component (about 90%) of the evolving convective mantle is therefore likely to be more depleted today than during the mid-Proterozoic, and we have selected an average abyssal peridotite composition in our model for the convective mantle.

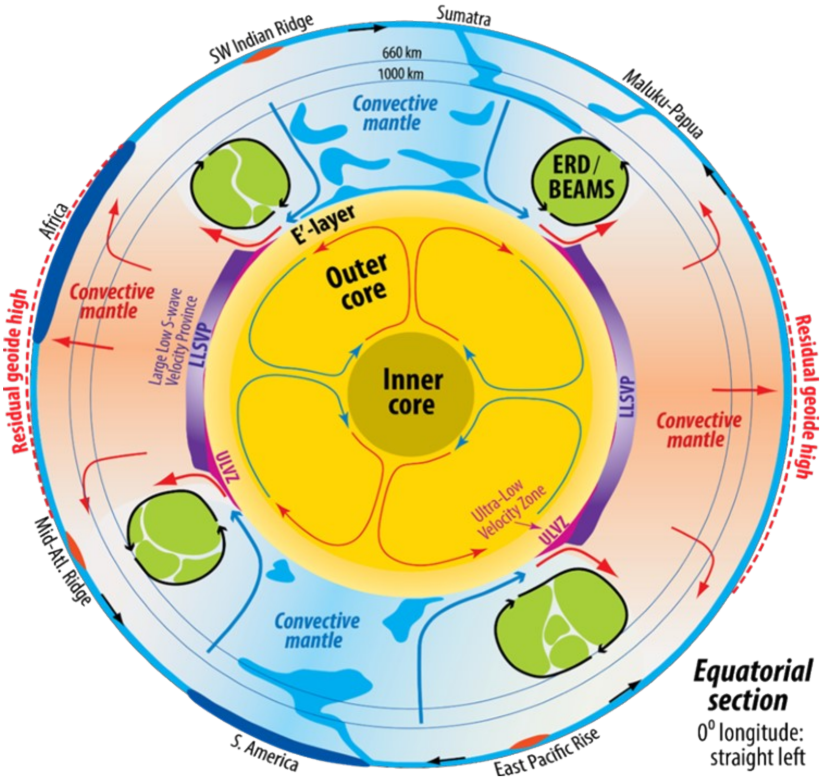



*Figure 1.5. Approximate equatorial section, showing Earth's main structural features and domains. ERD: Early refractory domains; BEAMS: bridgmanite-enriched ancient mantle structures. The section is constructed in accordance with the observations of subducted slab remnants of van der Meer et al. (2010, 2018) and the SMEAN tomography model of Becker and Boschi, (2002) at 2800 km depth, defining the large low S-wave velocity provinces (LLSVPs), surrounded by a nearly longitudinal high-velocity belt (60-90 W, 90-120 E). The BEAMS are limited in extent to account for the van der Meer et al. observations of slab remnants. Our rough volume calculations are based on this section and the SMEAN horizontal projection to 2800 km depth, assuming an average thickness of 300 km for the LLSVP base layers, an average thickness of 100 km for the subcontinental lithospheric mantle (SCLM) and a continental surface fraction of 40%. The volumes proportions of LLSVPs, BEAMS, SCLM and the remaining convective mantle are 1.1, 13.0, 2.3 and 83.6 %, respectively, of the total mantle volume.*

***The bridgmanite to post-brigmanite transition and the seismic D" discontinuity.*** There has been considerable confusion about the observed seismic D" discontinuities and their relations to the bm-pbm transition over the last eighteen years. Thomas et al. (2004) recorded sets of two discontinuities in several areas: an upper discontinuity 206-316 km above the CMB, characterised by an S-wave increase, and a lower reverse discontinuity with a velocity decrease, 55-85 km above the CMB. This, and the observation that the bm-pbm transition has a rather large Clapeyron slope of 7-14 MPa/K (e.g. Oganov and Ono, 2004; Tsuchiya et al., 2004; Tateno et al. 2009), led Hernlund et al. (2005) to suggest a double-crossing of the phase boundary with an ambient or cool geotherm and a CMB temperature of at least 4000 K. A possible double-crossing would be caused by re-stabilisation of high-entropy bm in the hottest mantle region close to the CMB. Recent refinements of the bm-pbm phase transition in $MgSiO_3$ and complex peridotite compositions (e.g. Mohn, in prep.; Kuwayama et al. 2021) have shown that the dp/dT slope is less that some of the early determinations, especially that

of Tateno et al. (2009), and the CMB temperature is considerably less than 4000 K (see first paragraph). The double-crossing scenario is therefore untenable, and our new results (Mohn, in prep.; Trønnes and Mohn, in prep.) indicate that pbm persists from an elevation of 200-300 km above the CMB, even in the LLSVP base layers. The seismic evidence presented by Koelemeijer et al. (2018) and Kuwayama et al. (2021) supports this conclusion. The observation of a lower reverse, and generally weaker and more ambiguous, discontinuity in certain areas (Thomas et al. 2004) might conceivably be related to partial melt zones (tenuous low velocity zones, much weaker than the ULVZs, ultra-low velocity zones) or e.g. to some form of flow-banding with strain-localised shear zones (Dobson et al. 2019).

Another major controversy linked to the D" discontinuities, centres on the nature of the bm-pbm phase loops in the systems $MgSiO_3$-$FeSiO_3$, $MgSiO_3$-$FeAlO_3$ and $MgSiO_3$-$Al_2O_3$, as well as in complex natural compositions. Several of nineteen experimental studies have resulted in very wide phase loops, partly covering the core rather than the mantle pressure ranges in some of the studies.

More than half of these experiments recorded partitioning of the Fe-components in the wrong direction, towards bm rather than pbm. The wide phase loops would contradict the bm-pbm transition as the cause of the main D" discontinuity at about 300 km above the CMB, even if Amman et al. (2010) found than the strongly anisotropic nature of pbm might facilitate deformational flow and efficient conversion to pbm, causing a seismic interface when a critical pbm fraction of 40-50% is reached. The extensive first principles atomistic computations by Mohn (in prep.) have clarified the $MgSiO_3$-$FeSiO_3$ and $MgSiO_3$-$FeAlO_3$ phase relations, characterised by narrow and relative pressure-insensitive phase loops, especially for the $MgSiO_3$-$FeAlO_3$ system. With our depleted mantle composition (abyssal peridotite average), relatively sharp D" transitions would occur at about 400, 300 and 200 km above the CMB for a cool subduction adiabat (Nishi et al., 2014), an ambient adiabat (Stixrude et al., 2009) and a LLSVP geotherm extended from an adiabat 500 K above the ambient adiabat, respectively. In accumulations of picritic ROC-material within the LLSVP base layers under the hot LLSVP-geotherm, the transition would occur at 230-250 km above the CMB. Under the same LLSVP-geotherm, late-stage bridgmanitic cumulates from the basal magma ocean containing a combined total of about 16 mol% of the $FeSiO_3$ and $FeAlO_3$ components (Trønnes et al. 2019) would experience the transition at elevations between 250 km (for 16 mol% $FeSiO_3$, only) and 330 km (for 16 mol% $FeAlO_3$, only). The results, which are broadly consistent with the seismic observations of Koelemeijer et al. (2019), appear to settle the controversies related to the D" discontinuities.

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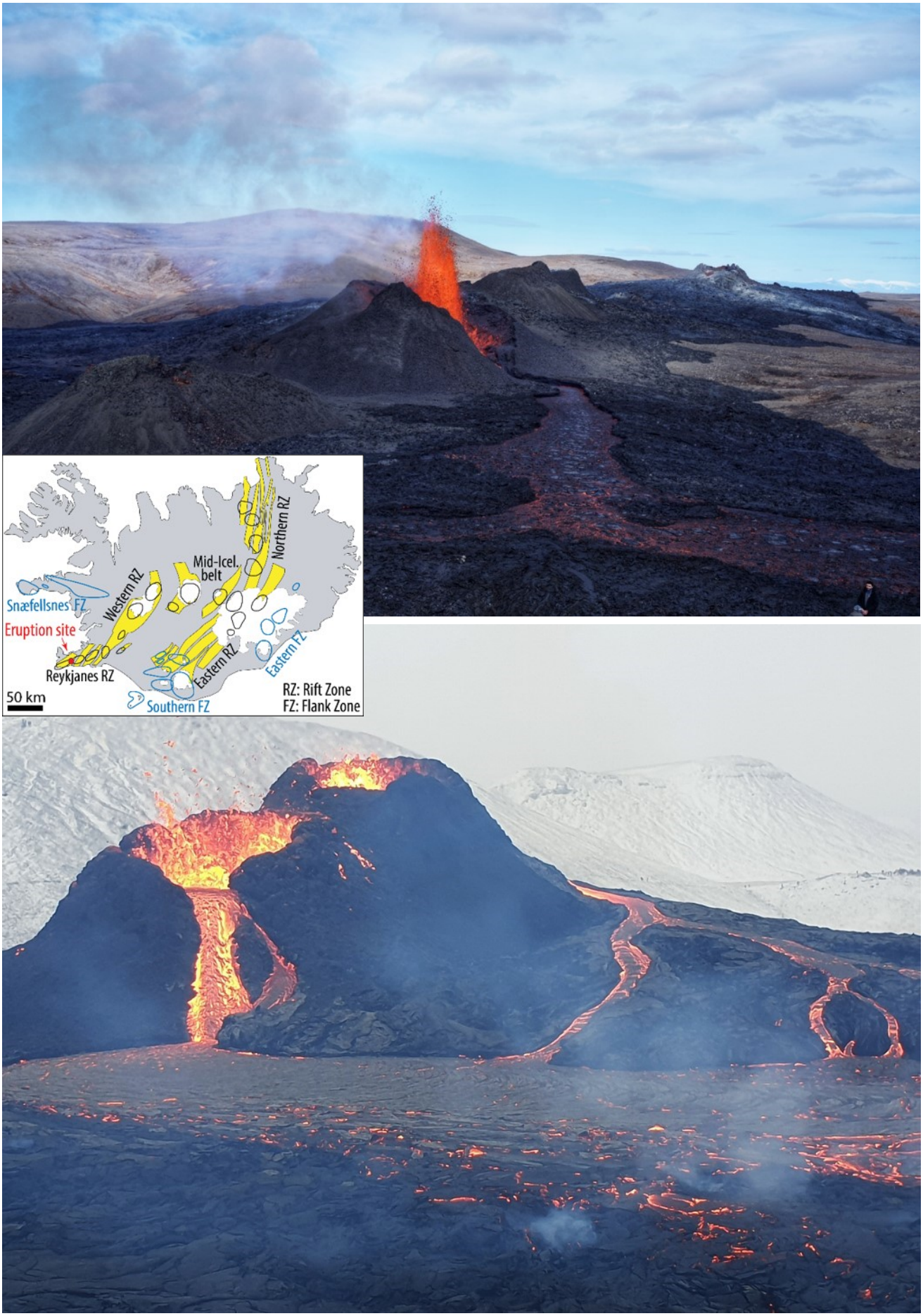
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*Geldingadalur eruption (March 19 to Sept. 2, 2021) in the Fagradalsfjall volcanic system, Reykjanes, SW Iceland. Image credits: Top: M Geng, Háskoli Islands & CEED, Bottom: Creative Commons, BY-SA 4.0. Map: RG Trønnes, CEED.*



# 2. Earth Modelling: Numerical Models of Earth Dynamics

*The Earth Modelling Team uses 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 2021 the group was active in a wide variety of projects including: plumes interacting with and eroding the continental lithosphere, tectonic plates controlling patterns of mantle heat loss, viscosity anisotropy influencing geodynamic processes, subduction zones interacting with each other, seismological imaging of Scandinavia, seismic event detection in the North Sea, using geophysical methods to estimate mantle viscosity, and numerical modelling of glacial isostatic adjustment. We have also contributed to broader efforts in education, methodological advances in geodynamic modeling and seismic data interpretation, and scientific visualization.*

The Earth Modelling Team had an exciting year, despite the ongoing pandemic restrictions. Although difficulties with international travel complicated our meeting attendance and postponed another Greenland fieldwork season, we were still able to make excellent progress toward the overall goals of CEED. We also enjoyed some exciting events:

- **Krister Karlsen** defended his PhD in September.

- **Ágnes Király** was awarded NFR *young talent* funding and started the ANIMA project.

- **Clint Conrad** was elected as a member of Academia Europaea.

The Earth Modelling Team has continued to further the overall goals of CEED. For example, **Krister Karlsen** discovered that the Pacific hemisphere mantle has cooled significantly more than its African counterpart, perhaps providing new insight into hemispheric dichotomies associated with the Wilson Cycle the of supercontinental aggregation and dispersal. The idea that one half of the Earth is cooling faster than the other half attracted significant media attention. In addition, **Ági Kiraly** developed models of subduction zone interactions, **Bernhard Steinberger** looked at the effects of mantle plumes on subduction and tectonics in the Indian Ocean, and **Valerie Maupin** used ScanArray data to improve our understanding of Scandinavian tectonic structures. Although the pandemic forced **Kate Selway** to postpone magnetotellurics fieldwork in Greenland until 2022, the MAGPIE project had other successes: **Florence Ramirez** improved our ability to use geophysical observations to constrain upper mantle viscosity structures, **Björn Heyn** developed a new analysis that explains plume interaction with the continental lithosphere, and **Maaike Weerdesteijn** adapted a finite element code normally used for mantle convection into one that is useful for modelling glacial isostatic adjustment in regions with large viscosity variations. **Ági Kiraly**'s new NFR-funded ANIMA project started up within CEED in 2021, with a goal to understand the role of anisotropic viscosity within geodynamic processes. **Yijun Wang** was hired within ANIMA to examine the impact of anisotropic viscosity on subduction. Finally, **Annie Jenkins** developed new techniques for detecting seismic events in the North Sea, and **Fabio Crameri** developed a new online resource for sharing geoscience images among researchers and educators.

Here is a synopsis of the Earth Modelling Team's most important activities during 2021.

**Plumes of the Indian Ocean: Influence on Subduction Initiation and the Geoid**

Mantle plumes are often invoked to explain regions of strong volcanism, especially in intraplate locations, however, they may also cause other effects. In two papers, CEED associate professor **Bernhard Steinberger** and collaborators discussed the possible effects of a plume on the geoid, and how a plume may cause or influence subduction initiation.

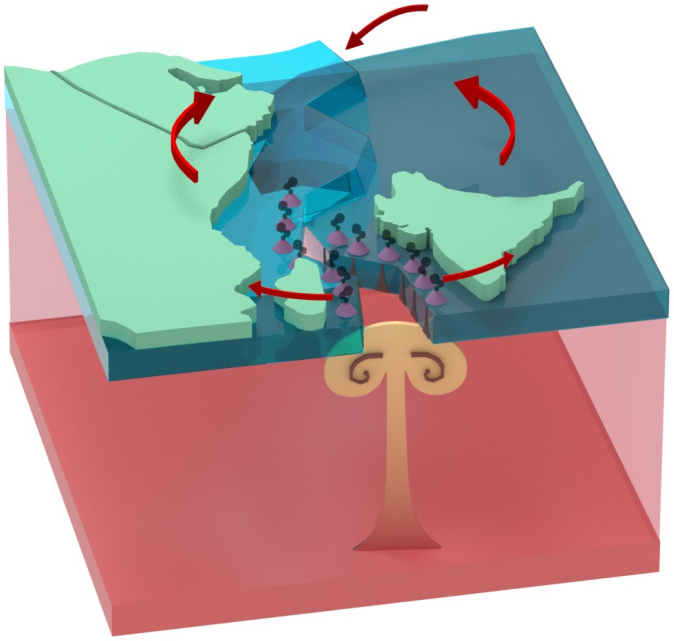


*Figure 2.1. Illustration showing how a plume that pushes two plates apart in one place may cause convergence, and subduction initiation, elsewhere. Figure made by Alisha Steinberger.*

The Indian Ocean Geoid low is one of the geoid's most prominent features. Previously, Ghosh et al. (2017) had shown how low-density material in the upper mantle, as inferred from seismic tomography, can give rise to a regional geoid low that is superimposed on a larger geoid trough between the two geoid highs above the African and Pacific Large Low Shear Velocity Provinces. We now asked ourselves: What may be the origin of these low-density materials? In Steinberger et al. (2021) we concluded that they likely have flown eastward from a plume in East Africa, perhaps the Kenya Plume, and that the roughly circular geoid low is in fact a superposition of two troughs, one above the outflow of plume material eastward from Africa and the above-mentioned, roughly North-South oriented one. We also show that our conclusion is supported by seismic tomography, in particular "votemaps", and global mantle flow models.

Another question that we addressed was: What caused subduction initiation between the Indian and African plates around 105 Myr ago? The mantle plume causing the Morondava LIP in Madagascar could have pushed the Indian and African plates apart (Figure 2.1). But given that this push occurred at the southern end of the India-Africa plate boundary, convergence could have also been induced at its northern end. This can be visualized using cardboard "continental plates" (see https://www.youtube.com/watch?v=1VzCzg2KRgg). Van Hinsbergen et al. (2021) show that the force provided by this process may be sufficient for inducing convergence, if the plate boundary is already pre-weakened. Also, the amount of convergence induced may be sufficient to generate initial slabs that can induce self-sustaining subduction.

In the future, we plan to apply this approach to other plumes, such as the ones in East Africa discussed above, to determine if these plumes may influence plate motions.

## Asymmetrical Cooling of the Earth

Earth's interior is cooling because its rate of heat loss exceeds its rate of internal heat production. Heat loss happens at the Earth's surface and is highly variable, with thick continents providing strong insulation to Earth's interior and thin seafloor allowing more rapid heat transfer. To investigate spatial variations in Earth's heat loss, CEED PhD student **Krister Karlsen**, with CEED collaborators **Clint Conrad, Mat Domeier** and **Reidar Trønnes**, reconstructed the history of cooling at Earth's surface for the past 400 million years. They found that the Pacific hemisphere has lost heat at a much faster rate than the African hemisphere, and indeed the mantle below the Pacific has cooled ~50 °C more than its African counterpart (Figure 2.2). In their paper in *Geophysical Research Letters*, Karlsen et al. [2021] show that a hotter Pacific may have resulted from insulation by Rodinia, a long-lived supercontinent that covered the Pacific mantle about one billion years ago. This extra heat has made for faster cooling on the Pacific side ever since, by decreasing mantle viscosity and supporting faster plate motions. The idea of a hemispheric dichotomy in planetary cooling captured significant media attention following this publication, with several articles about the research appearing in popular media outlets. It also formed an exciting final chapter to Krister Karlsen's PhD research, which he successfully defended in September.

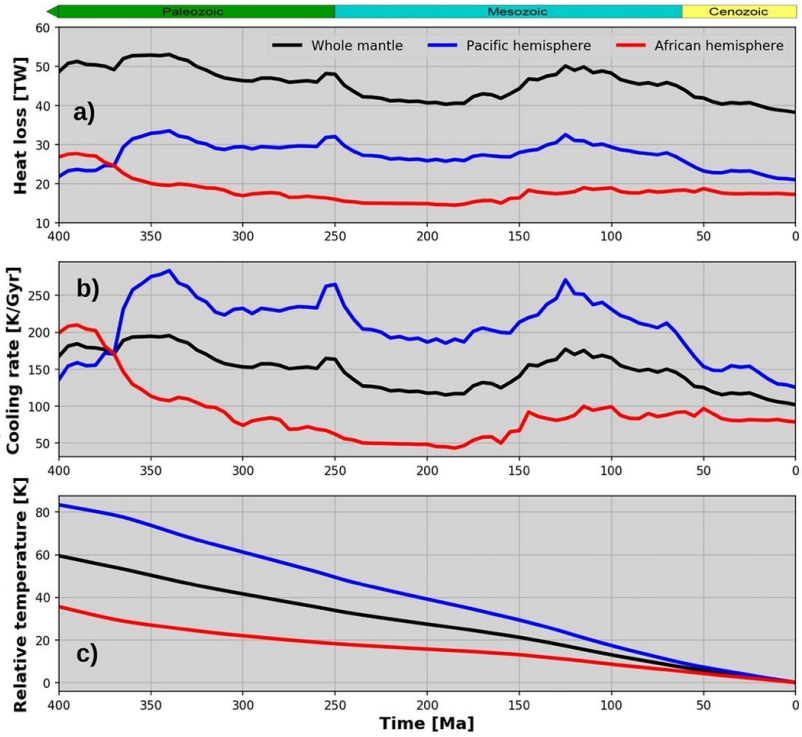



*Figure 2.2. Estimated mantle cooling rates suggest significantly more cooling of the Pacific hemisphere's mantle during the past 400 Myr, compared to the mantle beneath the African hemisphere. (a) Total mantle heat loss (oceanic + continental + hotspots) and its distribution between the two hemispheres. (b) Mantle cooling rates computed based on the balance between heat loss (a) and estimated heat sources. (c) Curves showing mantle temperatures relative to the present-day temperature, obtained by integrating the cooling rates (b) backwards in time.*

**The MAGPIE Project**

Researchers with the Earth Modelling Team continued to work on the NFR-funded **MAGPIE project** (Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution, 2019-2023). We had planned to return to the magnetotellurics fieldwork in Greenland, which we had to postpone from 2020 due to COVID-related shutdowns. However, the COVID restrictions on international travel continued to pose problems for polar research, and MAGPIE had to postpone the fieldwork again. CEED associate professor **Kate Selway** is planning a return to the ice for MAGPIE in the summer of 2022, with operations out of SUMMIT and RAVEN stations (Figure 2.3). If we can collect magnetotellurics data within snowmobile driving distance of these stations, we can greatly expand our coverage of central Greenland by supplementing the data we collected in 2019 out of EastGRIP station. This data will provide valuable constraints on the upper mantle structures beneath central Greenland, including those influenced by the passage of the Iceland plume.

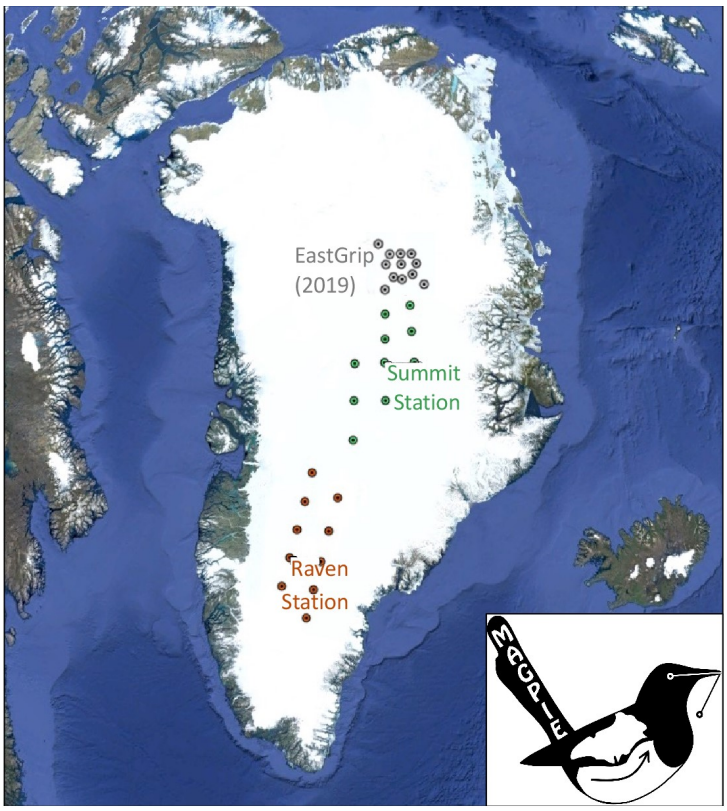



*Figure 2.3. Plans for the 2022 MAGPIE field season. Locations of stations where magnetotellurics data was collected in 2019 (out of the Danish EastGRIP Station) are shown by grey dots. Our plan for 2022 is to collect MT data out of Summit Station (green dots show planned locations) and RAVEN station (red dots).*

Work nevertheless continued with MAGPIE during 2021. CEED PhD student **Florence Ramirez** has developed a method to estimate mantle viscosity, and its uncertainty, using a combination of geophysical constraints on seismic wave speed (e.g., from a seismic survey) and electrical conductivity (e.g., from a magnetotellurics survey). CEED Postdoc **Björn Heyn** is developing numerical models of the interaction of the Iceland plume with the lithosphere, and has proposed a new analytical model for the evolution of heat flow following the passage of a plume. Finally, CEED PhD student **Maaike Weerdesteijn** has adapted the mantle convection code ASPECT for use in GIA problems. All of these research components of MAGPIE are described in more detail later in the Earth Modelling report.

**Estimating Mantle Viscosity from Geophysical Observations**

Many geological processes depend on the viscosity of the upper mantle, which describes how easily the rocks can 'flow'. The larger the viscosity of the upper mantle, the slower and/or harder it is for rocks to deform over geological timescales. Thus, constraining upper mantle viscosity would certainly help us to understand and even simulate many geodynamic processes, such as Earth's surface response to past ice melting. Although mantle viscosity cannot be measured directly, rock deformation experiments tell us how viscosity depends on rock properties, many of which can be estimated regionally using geophysical observations. As part of the NFR-funded MAGPIE project, CEED PhD student **Florence Ramirez** developed a method that calculates mantle viscosity from estimates of temperature and water content inferred from seismic and magnetotelluric (MT) observations, respectively. In a paper submitted to *Journal of Geophysical Research*, Ramirez et al. (2021) show that the combination of these two observations improves viscosity estimates compared to either observation alone (Fig. 2.4a-b).

In addition, she showed that when estimating viscosity from seismic and MT data, rock composition has to be considered. This is because rock composition directly affects the interpretation of geophysical observations, so better knowledge of rock composition can greatly reduce uncertainty in viscosity estimates (Fig. 2.4c and 2.4e). MT data can be used to distinguish whether upper mantle minerals are hydrated, which is also important for reduction of viscosity uncertainty (Fig. 2.4d and 2.4e). Overall, additional MT surveying (one of the goals of the MAGPIE project) offers new opportunities to better constrain viscosity in regions where robust geodynamic modelling is needed.

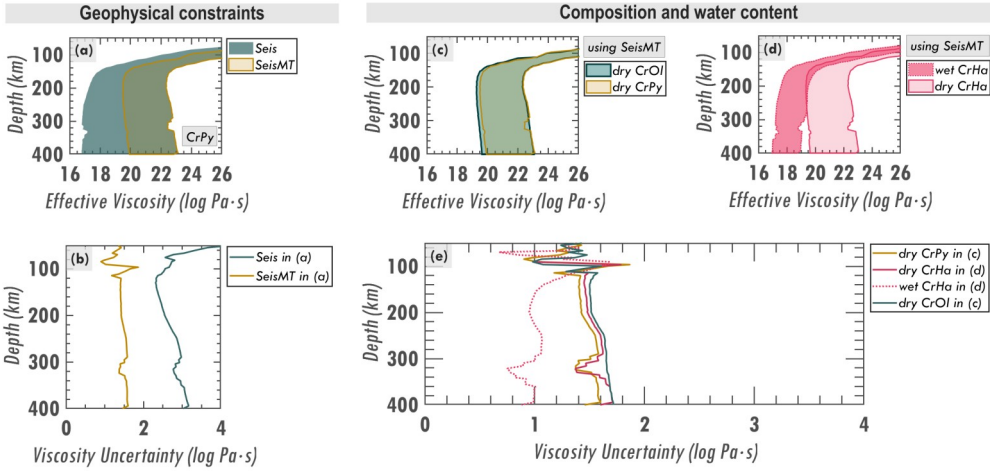



*Figure 2.4. Viscosity estimates and their uncertainties. (a-b) Geophysical constraints. Using only constraints on seismic velocity (with an associated uncertainty range) to estimate mantle viscosity yields large uncertainty (green band in (a) and line in (b)). If MT constraints on electrical conductivity (with uncertainty) are added to the seismic observations, the viscosity estimate is significantly improved (yellow band in (a)), thus reducing viscosity uncertainties (yellow line in (b)) because seismics constrain temperature and MT constrains water content. (c-e) Composition and water content. Variations in rock composition (green, pink and yellow bands in (c) and (d)) produce associated variations in viscosity uncertainties (e). Thus, knowledge of rock composition reduces the viscosity uncertainty. Variations in bulk water content (light and dark pink bands in (d)) similarly result in variations in viscosity uncertainty (pink solid and dotted lines in (e), but can be constrained using MT observations. Abbreviations: CrHa – cratonic harzburgite, CrPy – cratonic pyrolite, CrOl – cratonic olivine, Seis – using seismic constraints only, SeisMT – using both seismic and MT constraints.*

**Hidden Plume Tracks: Heat Flux and Plume Interaction with Continental Lithosphere**

Mantle upwellings, also known as mantle plumes, are major sources of extrusive volcanism, as observed at hotspots such as Hawaii and Iceland. These plumes are long-lived and remain at approximately the same location, while tectonic plates move above them. For oceanic plates, plume-generated melt can be easily erupted to form volcanoes along the plate, and the continuous plume-lithosphere interaction therefore results in tracks of volcanic islands as seen in Hawaii. In contrast, thick continental and cratonic plates can inhibit the eruption of melt in most places, which makes it more difficult to identify hotspot tracks in continental regions.

As part of the NFR-funded MAGPIE project, and with additional funding from the European Space Agency's 3D Earth - Greenland Project, CEED Postdoc **Björn Heyn** has performed numerical simulations of mantle convection to model the interaction between plumes and continental lithosphere. In particular, he used these models to understand how seismically observed variations in lithospheric thickness can be linked to heat flux anomalies above the plume. Although the work aims to understand the general relationship between plume-related lithospheric thinning and heat flux anomalies, it has special importance for Greenland and its interaction with the Iceland Plume.

Model results indicate that plume-related surface heat flux anomalies are associated basal erosion of the lithosphere caused by the plume. Thus, increased lithospheric thinning results in a larger heat flux anomaly, and both are primarily controlled by the viscosity structure of the lower lithosphere and asthenosphere. In a new paper submitted to *Geophysical Research Letters*, Heyn and Conrad (2022) show that the relationship between heat flux anomaly and the amount of lithospheric thinning is independent of the model geometry, and can be approximated by an analytical expression derived from the thermal equilibration of a stationary system (see Figure 2.5). In all cases, the maximum heat flux anomaly follows the position of the maximum lithospheric thinning, although the heat flux maximum occurs about 40-140 Myr after the passage of the plume. As a consequence, young continental or cratonic plume tracks can be identified via

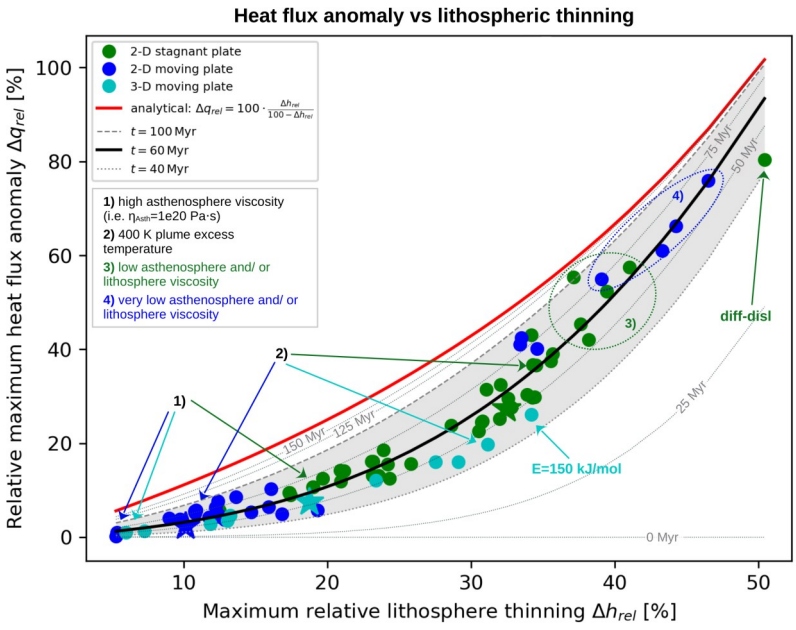



*Figure 2.5. Overview of the relationship between relative surface heat flux anomaly (in % on the y-axis) and the relative lithosphere thinning (in % on the x-axis) for all the numerical models performed (dots, colors indicate the geometry of model, and different models are for different choices of viscosity structure and plume characteristics some of which denoted by the numbered text). Red, black and gray lines indicate the analytical predictions of a stationary system for given equilibration times (red line: maximum heat flux anomaly after infinite time).*

thinned lithosphere, while older tracks will be more obvious in heat flux measurements. Finally, a plume-induced heat flux anomaly and lithospheric thinning might (temporarily) appear misaligned if the lithosphere has pre-existing topography on the lithosphere-asthenosphere boundary (as might be the case for Greenland).

**A New Finite Element Code for Modelling Glacial Isostatic Adjustment: Modelling Earth Deformation Due to Contemporary Ice Melting**

Models of glacial isostatic adjustment (GIA) are useful as they help us understand topography change in formerly and currently glaciated regions. To obtain better models of GIA, CEED PhD student **Maaike Weerdesteijn** has developed a new viscoelastic earth deformation model by adapting the finite element (FE) code ASPECT, which was originally developed for mantle convection problems. We use ASPECT because it is open-source, built for parallel processing, and has adaptive mesh refinement capabilities. Maaike benchmarked her new code using a 3D box geometry against (1) the commercial FE code ABAQUS using a non-self-gravitating box geometry, and (2) the open-source spectral code TABOO using a self-gravitating spherical geometry.

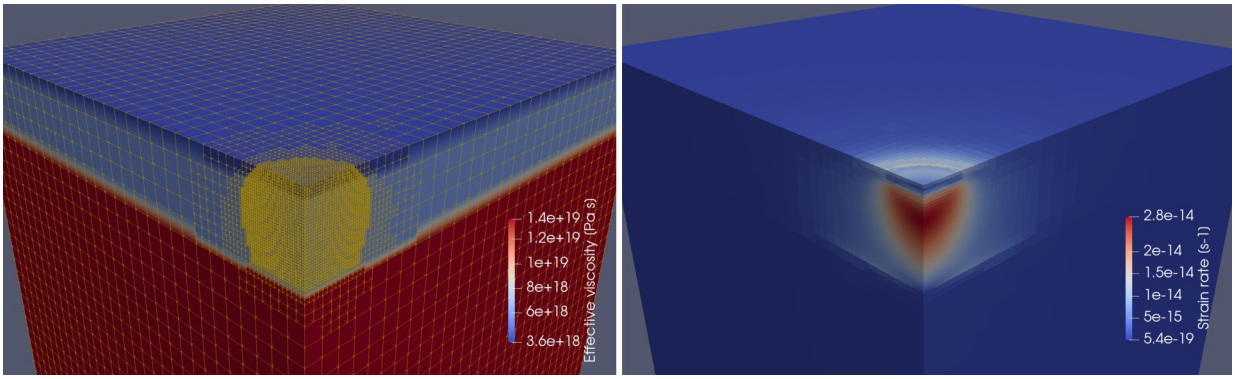



*Figure 2.6. Visualization of the adaptive mesh in ASPECT in yellow with the effective viscosity colored in the background (left), where the finer mesh coincides with the larger strain rates from the boundary traction (right).*

For the simulation in ASPECT, we make us of adaptive mesh refinement, and a free surface. The mesh refinement criterion is based on the strain rate norm at the center of each cell (Figure 2.6). The model has an elastic lithosphere (modelled with a very high viscosity), a low -viscosity asthenosphere, and a viscoelastic mantle. Our model is axisymmetric, and we apply a quarter cylindrical ice load with a height linearly increasing with 1 m/yr over 100 yr.

The vertical surface deformation (Fig. 2.7, left) and rate (Fig. 2.7, right) as function of time at different distances from the load center show a good agreement between ASPECT, ABAQUS, and TABOO. Although the deformation solutions do not perfectly agree, the differences can be explained by (1) differences in mesh resolution, (2) fully spherical (TABOO) vs. box model

(ASPECT and ABAQUS) geometries, (3) slightly different lateral boundary conditions for ABAQUS, and (4) self-gravitation in TABOO. The good agreement despite these model differences gives us confidence that our new viscoelastic earth deformation model using ASPECT will provide a new tool for modeling GIA processes, especially those that incorporate large viscosity variations.

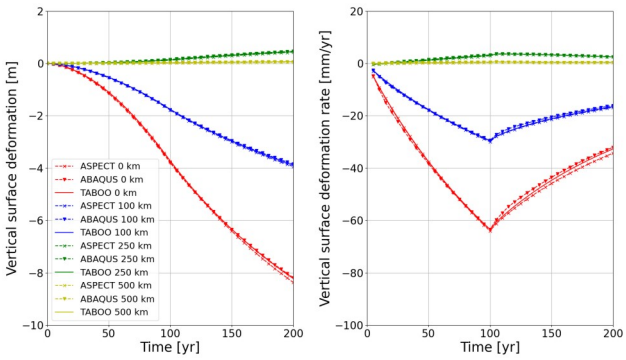



*Figure 2.7. Vertical surface deformation (left) and vertical surface deformation rate (right) as function of time for ASPECT (dashed line with crosses), ABAQUS (dashed line with triangles) and TABOO (solid line) at 0 (red), 100 (blue), 250 (green), and 500 km (yellow) horizontal distance from the load center.*

We have begun to use this new tool to investigate the effect of a low-viscosity region in the upper mantle on solid earth uplift due to contemporary ice melt. We have already demonstrated that in the presence of a low-viscosity region, GIA uplift from contemporary ice melt occurs on decadal or centennial timescales. This rapid uplift may be fast enough to impact ice sheet dynamics, for example in southeast Greenland and West Antarctica. We expect that some observations of vertical ground motion are already significantly impacted by this GIA response to contemporary ice melting. Our new GIA modelling tool is already allowing us to investigate how uplift rates depend on the location, dimensions, and viscosity of the low-viscosity region. Constraining the impact of these parameters is essential for distinguishing between the uplift coming from historic and contemporary ice melt, and for studies of the future of our ice sheets.

## The ANIMA Project

ANIMA: ANIsotropic Viscosity in MAntle Dynamics, is a new Young Research Talent Project funded by the Norwegian Research Council, and it started in May 2021 at CEED. The PI is CEED Researcher **Ágnes Király**, and Professor **Clint Conrad** is a partner on the project. The aim of ANIMA is to evaluate the role of anisotropic mantle viscosity (AV) on geodynamic processes (Figure 2.8).

Rock textures are a primary focus of ANIMA, because they can affect the viscosity of the mantle, and thus deformation patterns. The viscosity of a material depends on many factors, including temperature, composition, and the forces applied to it, but recent laboratory experiments showed that the viscosity also depends on the direction of these forces relative to the texture of the rock. We call this behaviour anisotropic viscosity (AV) because it causes deformation rates to be direction-dependent. Because the viscosity of the mantle affects many dynamic processes, from the movement of tectonic plates mountain building, fault formation, and volcanism, it follows that anisotropic viscosity can greatly impact the dynamics of our planet.

To assess the role of AV for geodynamics, we must first understand its origin. Laboratory experiments on mantle minerals (olivine) showed that anisotropy originates from the structure

and the alignment of these minerals. Such alignment usually results from deformation in the mantle due to tectonic forces. Hence, we have to study anisotropic viscosity in combination with texture formation (alignment of olivine crystals) in the mantle. In our 2020 paper (Király et al., 2020), we found that the two are interlinked. To understand this complex relationship between the olivine texture and anisotropic viscosity, we will develop 4D numerical models of geodynamic processes, and we will track olivine textures.

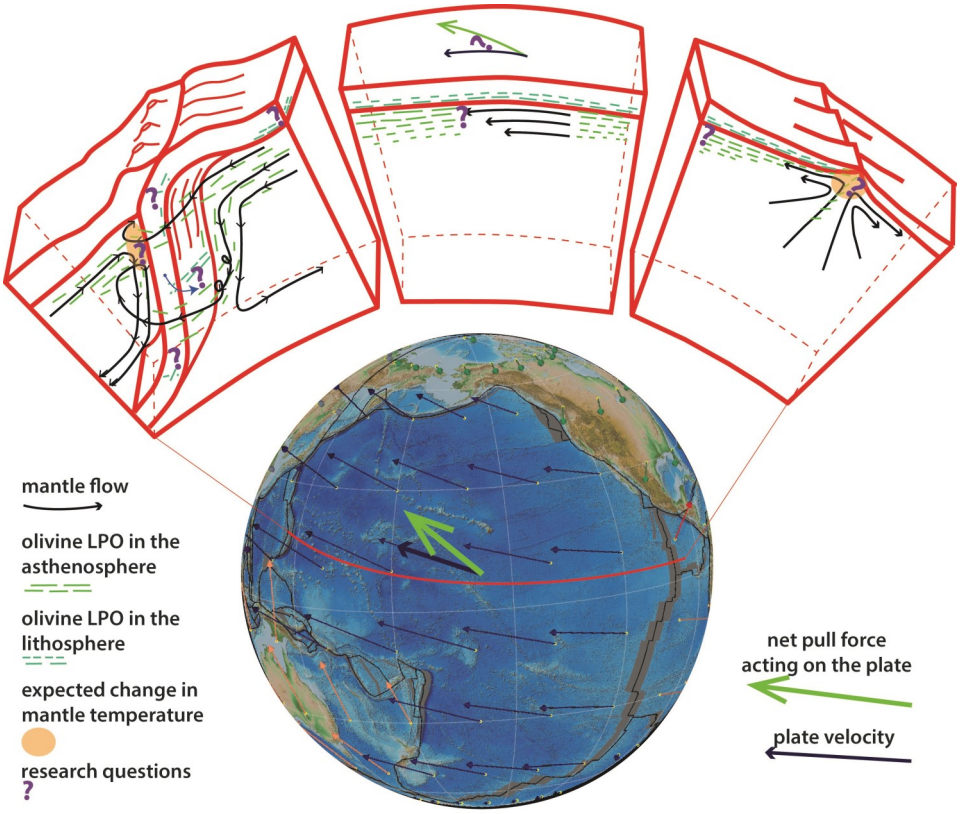



*Figure 2.8. Formation and de-formation of olivine texture (LPO, green hashes) and associated anisotropic viscosity (AV) generated by mantle flow (black lines) and plate motion (below) during ocean plate tectonics. Here we highlight the main research questions for ANIMA (see text). Figure after Crameri et al. (2019) and using the 1 Ma plate reconstruction of Müller et al. (2008).*

In this first year we had two main objectives: 1) to find a strong PhD candidate, and 2) to implement 3D anisotropic viscosity into the ASPECT finite element code. The PhD position has been filled at the beginning of September, by the employment of new PhD student **Yijun Wang**. Her task in ANIMA will be to study anisotropic fabric formation and related viscous anisotropy around subduction zones. The implementation of AV calculation into ASPECT (our 2nd objective) is in progress. A basic model, where we calculate stresses and the viscosity tensor in a shear-box with prescribed velocity has been implemented by PI, Ágnes Király. In the remainder of ANIMA's first year, we will work to develop a more versatile material model, where fabric development and AV can be tracked together in various setups.

**Subduction Zone Interactions – A Synthesis**

In a paper in collaboration with Italian and Australian researchers (Király et al., 2021), CEED Researcher **Ágnes Király** has reviewed the geological and geophysical observations of subduction zone interactions, and compared them with geodynamic modeling studies. Four gen-

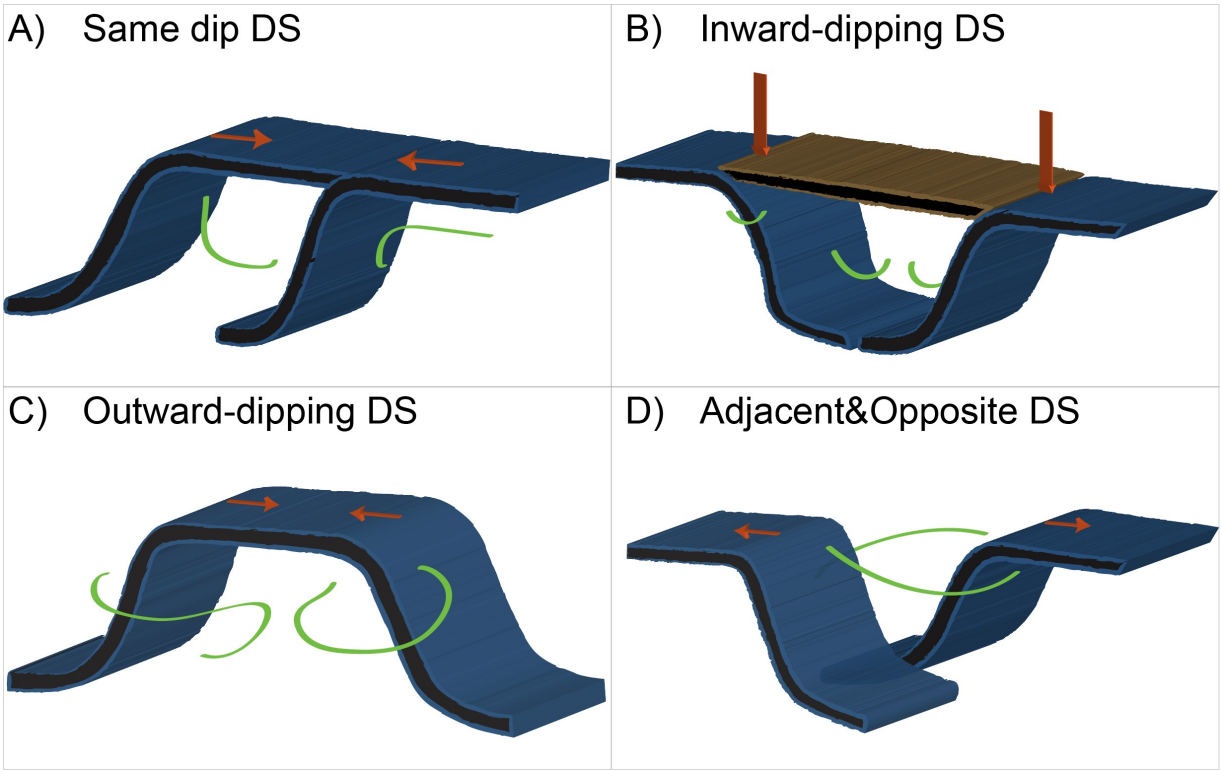



*Figure 2.9. Illustration of the possible modes of slab-slab interaction, and their connections through mantle flow (green lines) and trench kinematics (red arrows).*

eralized geometries are discussed (Figure 2.9): same-dip double subduction, inward-dipping double subduction, outward-dipping double subduction, and adjacent & opposite double subduction.

The paper synthesized that slabs can interact and affect each other by stress transfer through the mantle and the lithosphere, regardless of the imposed geometry. The characteristic distance of interaction depends on the stress-transferring media. Having weaker rheology, the asthenosphere is marked with a shorter (couple of hundreds of km) characteristic distance. Slab-slab interaction through the mantle can be observed as an increase of stress and dynamic pressure around the subduction zone, or by a change in mantle flow. The increase in dynamic pressure on either side of the slabs affects their dip angle and, in turn, the motion of the trenches at the surface. The characteristic distance for slab-slab interaction through the lithosphere is likely much larger (estimated to be a few thousands of km), causing the movement and deformation of plate segments in between the interacting subduction zones. In some ways, all subduction zones are coupled as the movement of tectonic plates on the Earth's surface are interdependent on each other.

**Improved Detection of Seismic Events in the North Sea**

CEED PhD student **Annie Jerkins**, working also at NORSAR, is conducting work for the NNSN (Norwegian National Seismic Network) project. The aim of her PhD project is to get an improved understanding of seismicity in the North Sea, which is important for oil/gas exploration and CO2 storage projects. The major issue when locating earthquakes in the North Sea is that all stations are deployed on mainland Norway (Figure 2.10), resulting in one-sided azimuthal coverage and uncertain epicenter locations. Annie has tested and developed new

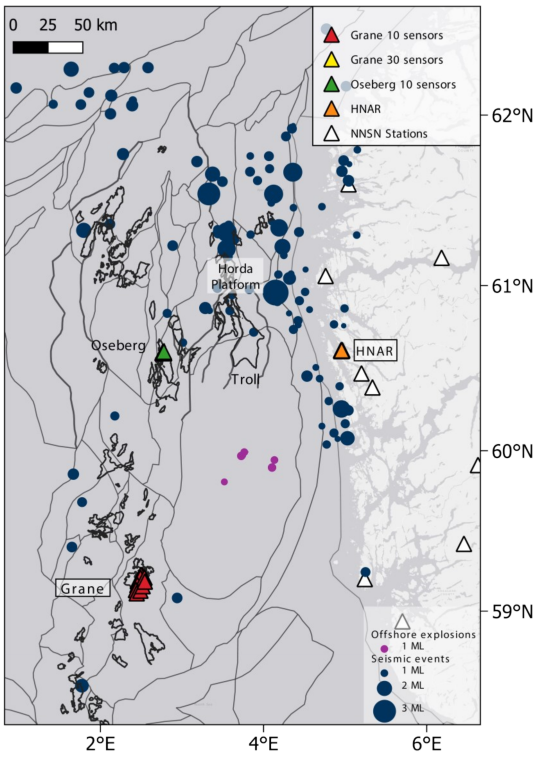



*Figure 2.10. Seismic events (occurring between 23.05.2020 and 19.03.2021) in the Norwegian part of the North Sea (blue circles, event magnitude is proportional to the symbol size), offshore explosions conducted by the Norwegian army (purple symbols) and seismic stations (triangles). The boundaries of oil and gas fields in the region are plotted with black lines, and the major structural elements with grey lines. The Green, red, orange, and white triangles correspond to the Oseberg, Grane, HNAR and*

methods for the use of offshore sensors (deployed for permanent monitoring at oil/gas reservoirs) for passive seismic monitoring of earthquakes in the North Sea. These stations improve event locations and reduce the azimuthal station gap significantly. By applying array processing methods to offshore sensors, for instance at Grane (Figure 2.10), it is possible to determine back azimuth and slowness, which decreases the detection threshold for seismic events in the region.

**ScanArray: Seismic Structure of the Crust and Upper Mantle in the Baltic Shield**

CEED professor **Valerie Maupin** and colleagues have pursued the exploitation of the seismological data collected during the ScanArray experiment (2012-2017; Thybo et al. 2021) using surface waves and body-wave tomography in order to provide seismic models of the crust and upper mantle in Fennoscandia.

The surface wave analysis is done in cooperation with GFZ Potsdam, in particular Alexandra Mauerberger who defended her thesis this year, and Univ. of Uppsala. It has resulted this year in a new tomographic model of the S-wave velocity in the crust and upper mantle and in a new Moho depth map based on analysis of the phase velocities of ambient-noise-derived and teleseismic Rayleigh waves (Mauerberger et al., submitted). The Moho map has a lateral sampling denser and more uniform than previous maps. The crustal and upper mantle structure appears to be very different beneath the topographic highs of southern Norway 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. The tomographic images suggest, in particular in the southern Scandes, the presence of edge-driven convection cells in the upper mantle which can sustain part of the topography. The joint analysis of Love wave and Rayleigh wave phase velocities shows that radial anisotropy is present across the whole of Fennoscandia, from northern Norway to southern Sweden. This anisotropy is present in the upper mantle from Moho to at least 200km depth, and results from crystalline preferred orientation of olivine.

Another tomographic study using the ScanArray data, but based on finite-frequency P-wave traveltime residuals, has been pursued this year in cooperation with Nevra Bulut, a PhD student at Istanbul Technical University and her main supervisor Hans Thybo (Bulut et al., submitted). Zones with relatively large lateral velocity gradients have been found in the lithosphere, which might coincide with the trace of ancient suture zones previously imaged with active seismics. Regions with very low velocities have also been imaged in the Lofoten region.

**Seismological Methods**

CEED researchers, including professor **Valerie Maupin**, also contributed to research related to seismological method development in 2021. Questions related to the validity of merging datasets from different seismological experiments into a tomography model has resulted in a methodological study (Maupin, 2021). In this work, Maupin showed how a simple trick in the formulation of the tomographic inversion allows us to combine data recorded asynchronously without biasing the resulting models. Finally, two PhD students affiliated with CGG Norway (Jing Sun and Volodya Hlebnikov), co-supervised by Maupin, developed approaches to use machine learning for seismic processing.




*Figure 2.11. The s-Ink.org logo.*

**Data Visualization, Accessible Graphics, and Modelling**

As part of collaborative effort to promote graphics sharing among geoscientists, CEED researchers **Fabio Crameri** and **Grace Shephard**, along with former CEED PhD student **Eivind Straume**, developed the s-Ink.org graphics collection (Figure 2.11). The collection is freely-available online at s-ink.org, and provides a wide variety of eye-catching, quality-checked, and accessible graphical images for number of different geoscience disciplines. The collection is searchable and will provide a useful resource for any geoscientist needing a high-quality image, e.g., for a presentation or for teaching. The caretakers of this resource have described their collection in a new publication (Crameri et al., 2022).

CEED researchers were involved in an extensive review of geodynamics modeling (van Zelst et al., 2022). CEED researcher **Fabio Crameri** helped with this effort, which describes the methods, theory, usefulness, implementation, and application of geodynamic modelling. **Fabio Crameri** also contributed to an online article *in The Conversation* that describes the misleading nature of rainbow colormaps (Heron et al., 2021) and wrote a *News & Views* article in *Nature Geoscience* article about subduction initiation (Crameri, 2022).

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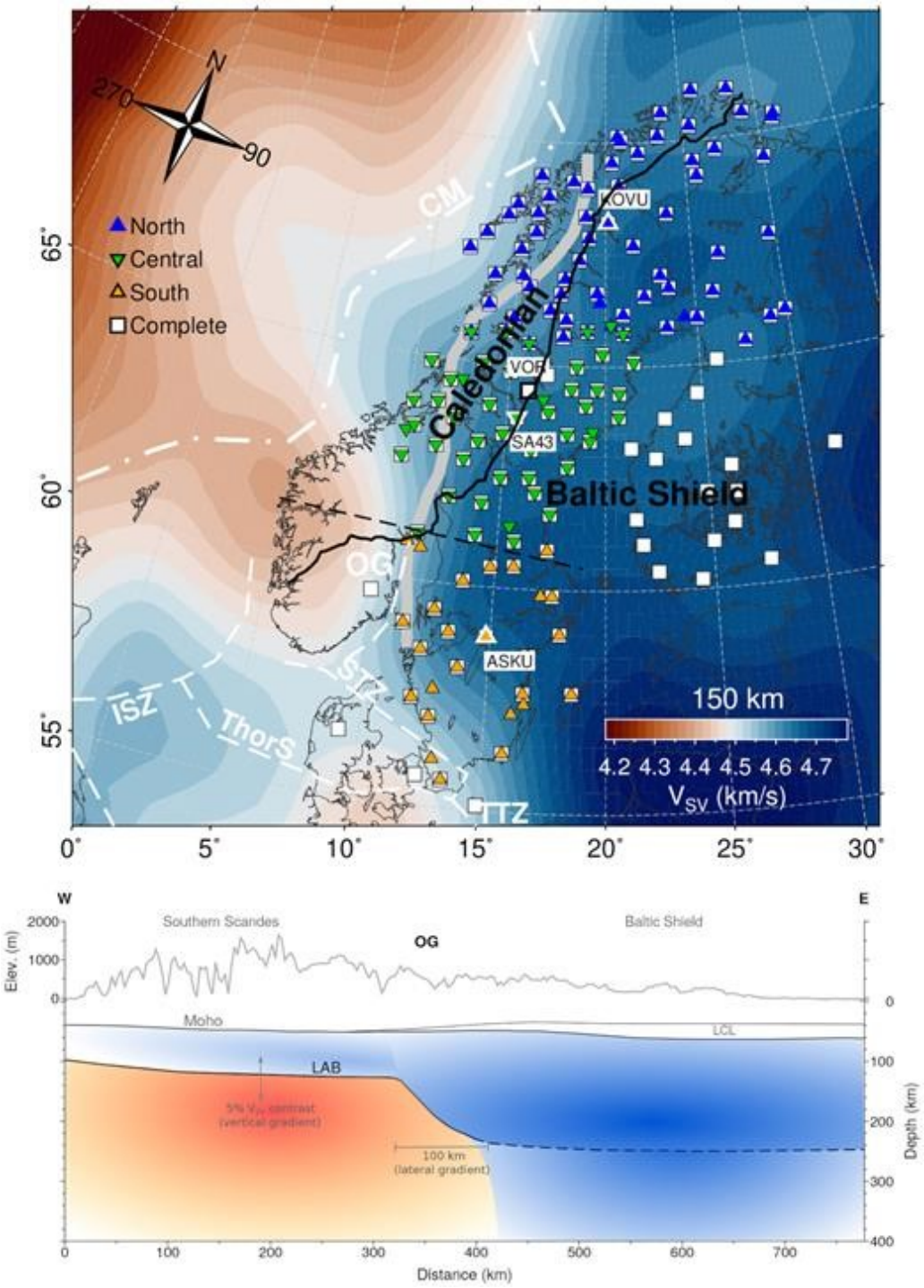
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*Top: Definition of the subarrays in the context of the global surface waveform tomography shear velocity model by Schaeffer & Lebedev (2013) (version SL2013sv, updated April 2018). Note that the model uncertainty is high for central and northern Norway and Sweden due to the lack of data coverage for their model. The reference station of each array is highlighted with its name. The black line marks the Caledonian front and separates the thrust sheets of the Scandes. OG = Oslo Rift Graben. ISZ is the potential Iapetus-Suture-Zone; ThorS = Thor suture; CM = Continental Margin. The Sorgenfrei-Tornquist Zone (STZ) is the northern extension of the Tornquist-Teisseyre-Zone (TTZ). The gray shaded zone outlines the sharp transition in LAB thickness derived from Kolstrup et al. (2015); Hejrani et al. (2017). Bottom: Schematic west–east cross-section through southern Norway and Sweden, marked by the dashed black line on the map. LCL is a high-density lower crustal layer after Ebbing et al. (2012). The transition in LAB thickness is constrained to be <□100 km wide by the body wave tomography of Kolstrup et al. (2015).*

# 3. Dynamic Earth: Plate motions and Earth history

*The Dynamic Earth Team comprises 18 members, including adjunct and Emeritus positions. The mission of our team is to explore, in the framework of Plate Tectonics and the Wilson Cycle, the link between the lithosphere and the convecting mantle and quantify how paleogeography and true polar wander have influenced the climate system. In 2021, Dynamic Earth members and their collaborators published about 50 articles on a variety of topics, including: the architecture of rifted margins, spreading ridges at back-arc basins, Arctic tectonic reconstructions, mantle properties and seismology, mantle plumes, and carbon cycle and climate over geological timescales. 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 postdocs joined our team in 2021:* ***Elizabeth Dowding****, a paleontologist who works on marine biogeography and* ***Maik Neukirch****, a geophysicist who works on magnetotellurics.*

Exciting news this year came from the Norwegian Research Council; two new projects led by Dynamic Earth team members started at the end of 2021. **Grace Shephard** was awarded the Young Researcher Talent grant with her project "POLARIS - evolution of the Arctic in deep time" and **Jan Inge Faleide** was awarded the Researcher Project grant with his project "DYPOLE - Dynamics of polar confined basins - The Eurasia Basin from breakup in greenhouse to present in icehouse conditions".

Two papers were published in higher impact journals - van Hinsbergen et al. (2021) featuring **Carmen Gaina** in Nature Geoscience, and **Shephard** et al. (2021) in Nature Communications (which was also the cover image for the journal for Feb-March 2022).

In 2021, the Dynamic Earth team continued to work on different aspects of the Wilson cycle from both a global and a regional perspective. Below, we report a few highlights of our research starting from global models, passing through the Arctic/North Atlantic region and its tectonic history, and ending with studies on subduction environments.

**Understanding climate forcings over geological timescales**

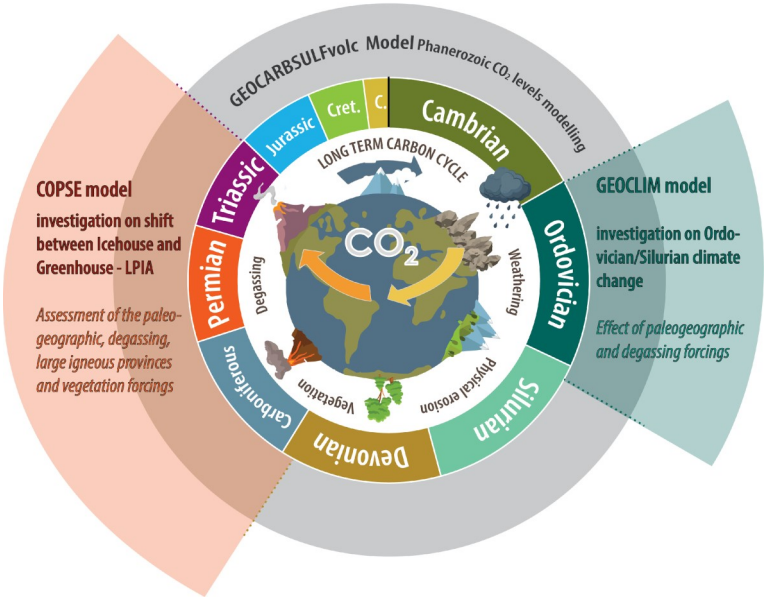



*Figure 3.1. Overview of the project with the three different investigations carried out, aims and model used for them*

Ph.D. candidate **Chloé M. Marcilly** started her doctorate on Carbon modeling and climate forcings over geological timescales in 2019 (Fig. 3.1). The project is divided into three parts using each a different long-term carbon models as described in the figure below. The main aim is to assess the effect of changing paleogeography and solid Earth degassing on $CO_2$ levels over the Phanerozoic. Paleogeography dictates how much chemical weathering will take place over time by defining the land availability under the right temperature and runoff. This land availability is lacking constraints in the present long-term carbon models. In this project, reviewed plate models, climatically sensitive fossils and lithological indicators were used over the last 520 Myrs eve-

ry 10 Myrs to create more constrained exposed land maps. Additionally, two new proxies for solid Earth degassing were produced. While Subduction fluxes derived from a full-plate model were used as proxy mostly for the recent geological periods, the age zircon distribution was argued to provide more accurate estimates for degassing in deeper time. The model GEOCARBSULFvolc was first used to produce a new $CO_2$ levels evolution over the Phanerozoic. The more complex models GEOCLIM and COPSE were then used with the developed revisions to investigate challenging periods where triggers for climate changes are debated. GEOCLIM was used to simulate the dramatic climate cooling of the Ordovician while COPSE was used to understand the shift from icehouse to Greenhouse of the late Paleozoic.

**Validating Devonian Marine Biogeography**

The Devonian record presents an opportunity to test and validate an existing marine bioregionalization. The work **Elizabeth M. Dowding** completed at CEED is the first to use comparative biogeography and phylogenetic data to test Devonian bioregionalization. Proposed in the 1960s, the Old World, Eastern Americas and Malvinokaffric realms have been the functional standard for marine Devonian biogeography but are an hypothesis of are relationships that has not been tested. Data from 32 published phylogenies of Devonian marine taxa, and a database of c. 800 occurrences were analysed using phylogenetic software to test for area monophyly. The taxic occurrences in our database were then tested against total fauna Devonian occurrences in the Paleobiology Database (https:// paleobiodb.org) to identify differences in sampling. Our results indicate that the current Devonian bioregionalization is not representative of natural areas and requires revision (Dowding et al., 2021). The results highlight areas that are most robust from which the E. Dowding made recommendations to improve the process and diagnosis of Devonian biogeographical areas (Fig. 3.2). We found that legacy issues, for example colonialism, within palaeontology are evident within the results and their interpretation. The validation of bioregionalization and process is critical to the advancement of biogeography and palaeontology. The sensitivity of bioregionalization shows biotic and geographical relationships, how life and earth evolved together, and how geographical bias is evident in scientific process.

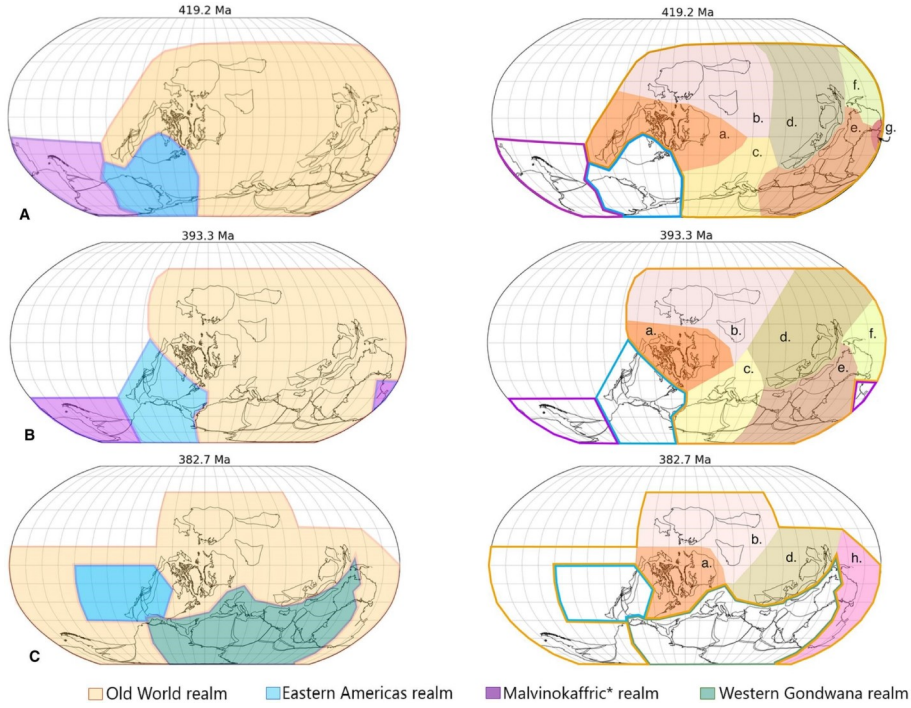



*Figure 3.2. A summary of realms, regions, and provinces of the: A, Early (419.2 Ma); B, Middle (393.3 Ma); C, Late (392.7 Ma) Devonian. Regions of the Old World realm: a, Cordilleran; b, Ural; c, Rhenish–Bohemian; d, South China; e, Mardoowarra; f, Tasman; g, New Zealand; h, Eastern Australasia.*The name 'Malvinoxhosan' was recently proposed as an alternative to 'Malvinokaffric'.*

## Introducing the POLARIS Young Researcher Talent project

CEED researcher **Grace Shephard** was awarded a 2021 "Young Researcher Talent" project from the Norwegian Research Council. The project is titled *POLARIS – evolution of the Arctic in deep time*. The main aim is to build an integrated geodynamic model of the circum-Arctic back to the Devonian (ca. 419 Ma) with a focus on the interplay of plate tectonics and whole mantle convection (Fig. 3.3). In turn, the models aim to explain large-scale magmatic events and significant paleogeographic changes. One key hypothesis that will be addressed is whether there is a distinct deep-mantle connection between major episodes of Arctic volcanism (including the Siberian Traps at 250 Ma, the High Arctic LIP at 120-85 Ma, the North Atlantic Igneous Province from 60/53 Ma and the Iceland Plume). This will require analysis of seismic tomography, models of mantle convection using the code ASPECT, and plate reconstructions. The project has a budget of 8 million NOK, and includes funds for an additional three-year postdoctoral or researcher position. The project will run for a period of 4 years - from December 2021 until December 2025, and will involve collaborations with several other CEED team members and international collaborators.

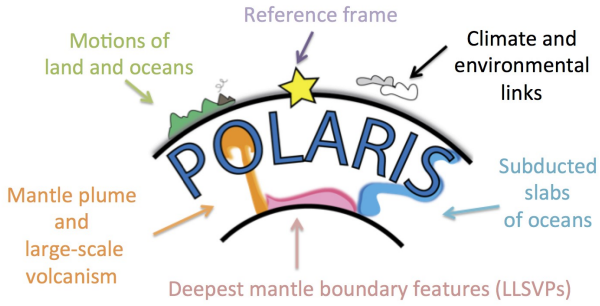



*Figure 3.3. POLARIS – Evolution of the Arctic in deep time project logo labeled with key features/ processes of the surface and deep Earth connection.*

## The enigmatic Vesteris Seamount

Vesteris seamount is an alkaline seamount placed in the central part of the Greenland Basin, located ca. 480 km west from slow-spreading Mohn's ridge and ca. 250 km north from the Jan Mayen Fracture Zone (Fig. 3.4). This is a solitary volcanic center far away from an active ridge regime and has an eruptive age ranging from 650 – 10 ka (Mertz & Renne, 1995). Previous hypotheses based on geochemical data suggested a source similar to the Jan Mayen volcanic island and different from volcanism produced by the Iceland plume. CEED scientists (Adriano Mazzini and Sverre Planke) collected several samples from the summit of this seamount that was dredged during the East Greenland Sampling campaign EGS-2012. To probe the origin of the Vesteris seamount and its geodynamic evolution, CEED PhD candidate **Lea Beloša** is studying the geochemical signature of the dredged rocks. This is a collaborative project between the Dynamic Earth (**Lea Beloša** and **Carmen Gaina**) and Earth Crises (Sara Callegaro, Adriano Mazzini and Sverre Planke) teams and their international collaboraters. The results from the geochemical analysis will be interpreted in a regional framework, where links between magmatism and the structure of the Northeast Atlantic lithosphere will be queried. Preliminary results of this study were communicated at the international Goldschmidt conference (2021) (Beloša et al., 2021).

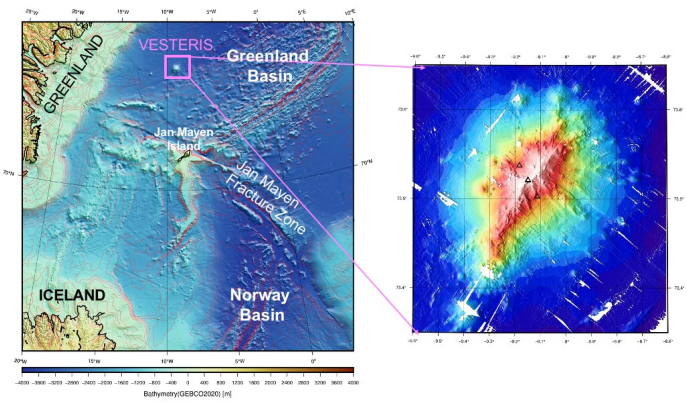



*Figure 3.4. Bathymetry of NE Atlantic (GEBCO2020) and the location of Vesteris Seamount in the Greenland Basin left image). High-resolution bathymetry shows the elongated shape of the seamount and several volcanic cones. Black triangles indicate the position of dredged samples analyzed in this project.*

**Restoration of the NE Atlantic margin architecture during Late Permian-early Cenozoic multi-rift events**

CEED researchers **Mansour M. Abdelmalak, Sebastien Gac,** and **Jan Inge Faleide** worked on the restoration of the architecture of the NE Atlantic conjugate margins. The aim of this study is to restore with detail the pre-breakup architecture and kinematic of the NE Atlantic passive margins from the mid-Permian to breakup time at early Eocene, using a forward basin modelling approach calibrated by direct geological observations. This study benefits from the existence of a wealth of geological and geophysical data in-house covering the study area. Numerical models of extensional basin formation are used to extract the amount of stretching experienced by the NE Atlantic margins during its long pre-breakup multirift history, from the stratigraphy recorded along a series of 2D conjugate transects. The basin models are required to reproduce key geological and geophysical observations such as: (1) the observed stratigraphy, (2) the observed beta factors along the transect calculated from observed crustal thickness, (3) the breakup volcanism and magmatic additions into the lower crust, (4) vertical motions and paleobathymetric observations. Results from this study will allow the establishment of full-fit palinspastic plate kinematic models for the NE Atlantic since the late Permian time and will provide new data and concepts that aid in reducing exploration risk and refine resource potential estimates of the active exploration regions in the Norwegian Continental Shelf (Fig. 3.5).

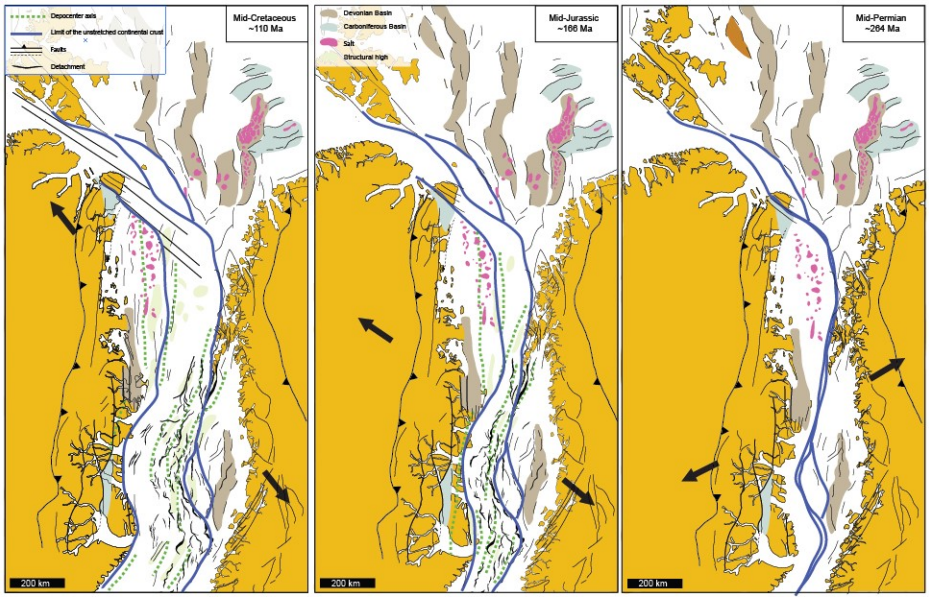



*Figure 3.5. Full-fit palinspastic plate kinematic reconstruction for the NE Atlantic since the late Permian time.*

**Basin modelling of a complex rift system: The Northern Vøring Volcanic Margin case example.**

Extensional processes can lead to complex crustal configuration depending on the mechanisms of lithospheric thinning and the impact of magmatic additions during rifting and breakup. In this context, **Sebastien Gac, Jan Inge Faleide,** and collaborators studied the Vøring volcanic passive margin offshore Norway (Gac et al., 2021). The evolution of the inner Vøring Margin is well explained by standard models of lithosphere extension. However, these models fail to reproduce key observations at the outer (volcanic) province such as regional uplift at the time of breakup and excess magmatism. Therefore, additional processes are required to explain these observations. Excess magmatism and uplift have been related to mantle processes such as the arrival of the hot Icelandic mantle 'plume' or small-scale convection processes. Melt retention in the asthenosphere has also been proposed to explain uplift. At last, mantle phase transitions during extension may contribute to uplift. We present tectonic

and thermal models of basin evolution along a seismic profile crossing the Northern Vøring Margin. The thermal and isostatic history of basins is constrained through time-forward basin modelling based on an automated inverse basin reconstruction approach. Two scenarios are evaluated: The first one includes pronounced mantle stretching during the last late Cretaceous-Paleocene rifting event, and the second one includes late Paleocene-early Eocene mantle thinning, at the breakup time around 56–54 Ma. Models incorporating late Paleocene-early Eocene mantle thinning and taking into account magmatic processes (melt retention and magmatic underplate) and mantle phase transitions satisfactorily reproduce the specific observations of the outer (volcanic) margin. This result supports the contribution of the hot Iceland plume on the evolution of the Vøring Margin. Our results also indicate that thin-crust models can produce a partially serpentinized mantle beneath the highly extended parts of the Vøring Basin. However, this model fails to reproduce observations. This suggests that serpentinization can occur locally but could not explain the entire lower crustal body nature.

### Cenozoic reshaping of the Barents-Kara Shelf

The morphological evolution of the Barents-Kara Shelf is an excellent example of how erosion and glaciation reshape the face of the Earth. The Cenozoic history is a subject of longstanding debate in the Barents realm because of scale of erosion, which makes traditional erosion analysis inapplicable. There are only few studies of the entire Barents region and the precision of these studies is limited due to uneven distribution of measurements and uncertainties in paleo-conditions. A project by **Sergei Medvedev, Jan Inge Faleide**, and the **CEED-Mod team** aims to provide improved estimation of masses eroded from the entire shelf and compare them with erosional products accumulated off-shelf (Fig. 3.6). Two time-slices are considered. (1) The mass balance between erosion and sedimentation demonstrates that the major part of Quaternary erosion is expressed within modern troughs and fjords. In contrast with previous studies, this analysis shows that the bathymetry of the shelf at the beginning of the Quaternary was mainly submarine. (2) A newly developed map of the Cenozoic erosion of the Barents-Kara shelf utilizes recently acquired borehole data and published thermo-chronological and morphological studies. However, even smaller than previously published, the estimated masses of erosion volume are almost twice larger than masses of off-shelf sediments. This enigmatic misbalance may be due misleading load of thick ice caps during ice ages. The study illustrates that the real erosion may be much smaller than traditionally assumed.

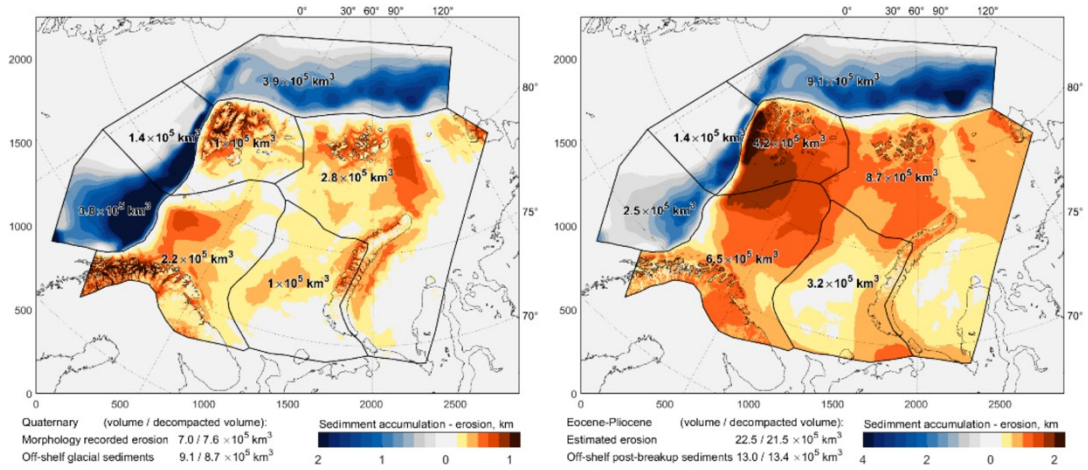



*Figure 3.6. Left - Morphologically recorded erosion (fjords and troughs) accounts for more than 85% of glacial sediments off-shelf. The Quaternary shelf was never dominantly subaerial. Right - The Eocene-Pliocene erosion map, derived within this study, presents extreme mismatch with off-shelf sediments.*

**Searching for Hot Water in the Romanian Carpathians: The Geysir-BaiaMare EEA project**

Geothermal energy is known as a renewable natural resource with minimal negative effect on the environment, and its use could be especially valuable in polluted areas. CEED researchers have teamed up with a group of scientists from the University of Bucharest (Romania) to assess the geothermal potential of the most polluted long-lasting mining region in NW Romania. The Baia Mare region is a Neogene depression in the larger Pannonian Basin, developed in the vicinity of a large strike-slip fault and the Middle Miocene Tibles-Gutai volcanic mountains. The region is known for surface hot springs, and salt and metal mining, all of which can be indications for the presence of a hydrothermal system that potentially can be exploited for geothermal energy. Hydrothermal systems are typically characterized by alteration mineralogy and the presence of melt, both of which control subsurface conductivity that can be imaged with magnetotellurics (MT).

Consequently, the CEED team (**Maik Neukirch, Alexander Minakov** and **Carmen Gaina**) and their collaborators from Romania and Sweden (Lulea University) set up an MT experiment to measure the subsurface conductivity in the Baia Mare region with the aim to identify hydrothermal systems potentially linked to the east-west oriented Dragos Voda strike-slip fault zone. The team spent three weeks in Romania (Fig. 3.7) and the data collected is now being processed and analysed, with preliminary results to be presented at the EGU 2022 conference (Neukirch et al., 2022). An initial 3D regional lithospheric model built on existing data will be used for identifying subsurface structures with high potential for geothermal exploration (Minakov et al., 2022) and will be updated with the novel interpretation resulting from the recent MT experiment.



*Figure 3.7. Left - CEED team and collaborators in Baia Mare, Romania. Right – Maik Neukirch (CEED) and Romanian students collecting new MT data.*

## Ridge Jumps and Mantle Exhumation in Back-Arc Basins

Back-arc basins are common features of subduction zones that often present a complex structure caused by changes in the dynamics of subduction. CEED researcher **Valentina Magni** uses numerical models to study the evolution of this type of basins.

In a recent study, Magni et al. (2021) performed 2D numerical models of continental extension to study the formation of a back-arc basin in a continental upper plate. These models include asymmetric and time-dependent velocity boundary conditions that simulate changes in extensional velocity due to episodic trench retreat. They find that, in all models, multiphase extension leads to rift and/or ridge jumps. Importantly, they show that the duration of the first extensional phase controls the final architecture of the basin. Indeed, with the shortest duration of the first extensional phase, they observe a strong asymmetry in the margins of the basin, with the margin further from trench being characterised by outcropping lithospheric mantle and a long section of thinned continental crust (Fig. 3.8a). In other cases, ridge jump creates two consecutive oceanic basins, leaving a continental fragment and exhumed mantle in between the two basins (Fig. 3.8b). Finally, when the first extensional phase is long enough to form a well-developed oceanic basin, they observe a very short intra-oceanic ridge jump (Fig. 3.8c). These models are able to reproduce many of the structures observed in back-arc basins today, showing that the transient nature of trench retreat that leads to episodes of fast and slow extension is the cause of ridge jumps, mantle exhumation, and continental fragments formation.

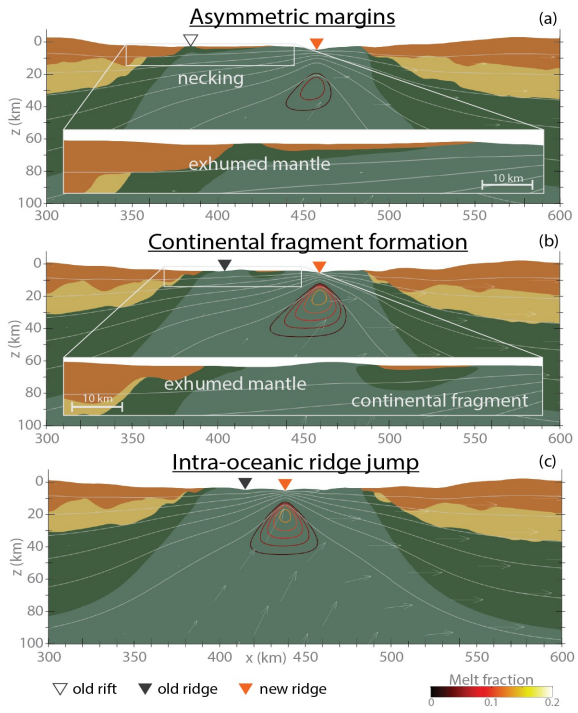



*Figure 3.8. Different structures of back-arc basins depending on the time of the first extensional phase; (a) the continental margin on the left of the basin is much more stretched than its conjugate margin on the right, (b) formation of a continental fragment bounded between two oceanic basins and exhumed mantle, and (c) intra-oceanic ridge jump.*

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# 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, focusing 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 2021, focusing on the following highlights: 1) IODP Expedition 396 drilling offshore Norway targeting Paleogene breakup magmatism and paleoclimate implications, 2) the PETM in Denmark and the environmental response to sustained warming, 3) carbon cycle modelling of Large igneous province-related environmental changes in the Early Jurassic, 4) the first large-scale analysis of the geochemistry of sills in the Siberian Traps and the correlations to lava geochemistry, 5) active Earth degassing systems, 6) fieldwork of the erupting volcano on La Palma, 7) a detailed analysis of the pre-Viking society and their adaptation to environmental changes, and 8) update and projects from the CLIPT stable isotope lab. In addition, we have contributed to papers on topics related to the use of mercury as a volcanic proxy (Percival et al., 2021), and PETM tephra diagenesis (Longman et al., 2002). The papers from the Earth Crises group were published in journals like Earth and Planetary Science Letters, Nature Communications, Scientific Reports, Nature Reviews Earth and Environment, and Geophysical Research Letters, to name a few.

**1) Successful IODP drilling on the Møre and Vøring margins**

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. The North Atlantic Igneous Province (NAIP) is an ideal case study as it was one of the largest LIPs in the Cenozoic, and numerous exposures around the Northeast Atlantic preserve igneous and sedimentary sequences across the Paleocene Eocene Thermal Maximum (PETM). Collecting high resolution core across this interval will be able to constrain NAIP activity in both a geochronological and paleoclimate timeframe.

The EC team have led two international drilling applications to collect high quality cores of volcanic rocks and sediments across the PETM interval. The highly successful International Ocean Discovery Program (IODP) Expedition 396 recovered more than 2 km of cores from 20 boreholes in the Norwegian Sea in August-October 2021. Sverre Planke (co-chief) and Morgan Jones (geochemist) were shipboard scientists, while Henrik Svensen, Ella Stokke, Madeleine Vickers, and Dougal Jerram provided shore-based support (Planke et al., 2021; 2022). The samples collected will form integral parts of the postdoctoral works of Ella and Madeleine in 2022 and 2023, and will provide the basis of years of further work on the interplay between the NAIP emplacement and Paleogene climate change.

The International Continental Scientific Drilling Program (ICDP) 'PVOLC' project was approved for $725,000 of ICDP funding to cover drilling costs, and is planned for September-October 2022. These boreholes will target Oligocene to Paleocene strata in northwest Denmark, where previous work by the EC team has shown a complete and expanded PETM section exposed around Limfjorden. Morgan Jones and Sverre Planke are PIs for the project, leading a consortium of 12 different universities.

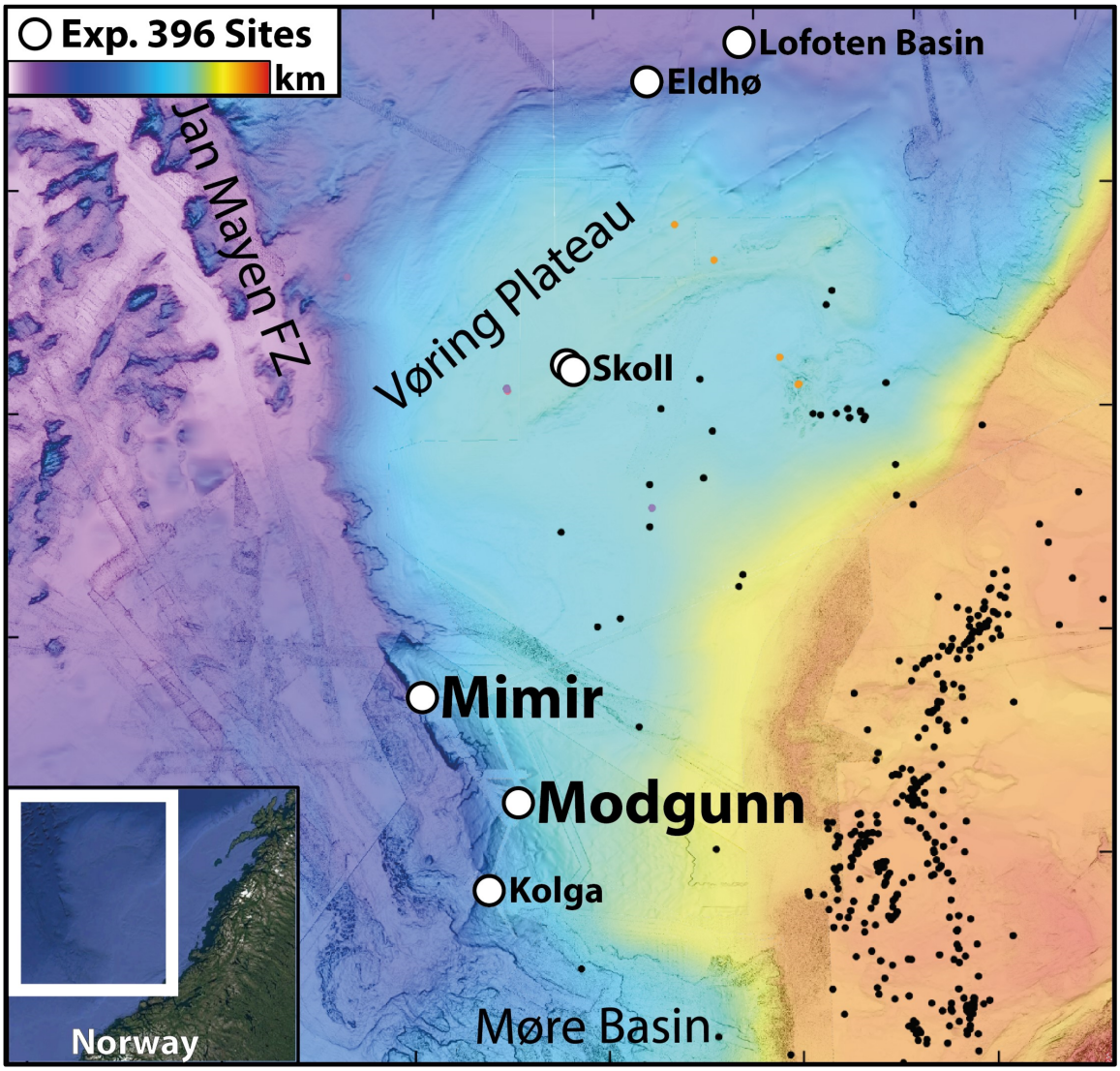



*Figure 4.1. A bathymetric map of the Norwegian continental margin, showing the localities drilled as part of IODP Expedition 396. The Modgunn and Mimir localities are the two key sites for Paleocene to Eocene strata (Planke et al., 2022).*

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

Ella Stokke defended her PhD thesis in January 2021. Her project was about the PETM in the former North Sea, now located on land in Denmark. One of her papers was published in 2021. Only a very limited number of PETM studies exist from the North Sea, despite its ideal position for tracking the impact of both changing climate and NAIP activity. Stokke et al. present sedimentological, mineralogical, and geochemical proxy data from Fur in Denmark, exploring the environmental response to the PETM. An increase in the chemical index of alteration and a kaolinite content up to 50 % of the clay fraction indicate an influx of terrestrial input shortly after the PETM onset and during the recovery, likely due to an intensified hydrological cycle. The volcanically derived zeolite and smectite minerals comprise up to 36 % and 90 % of the bulk and clay mineralogy respectively, highlighting the NAIP's importance as a sediment source for the North Sea and in increasing the rate of silicate weathering during the PETM.

X-Ray fluorescence element core scans also reveal possible hitherto unknown NAIP ash deposition both prior to and during the PETM. Geochemical proxies show that an anoxic to sulfidic environment persisted during the PETM, particularly in the upper half of the PETM body with high concentrations of molybdenum, uranium, and pyrite (~ 7 % of bulk). At the same time, export productivity and organic-matter burial reached its maximum intensity. These new records reveal that negative feedback mechanisms including silicate weathering and organic carbon sequestration rapidly began to counteract the carbon cycle perturbations and temperature increase and remained active throughout the PETM. This study highlights the importance of shelf sections in tracking the environmental response to the PETM climatic changes and as carbon sinks driving the PETM recovery.

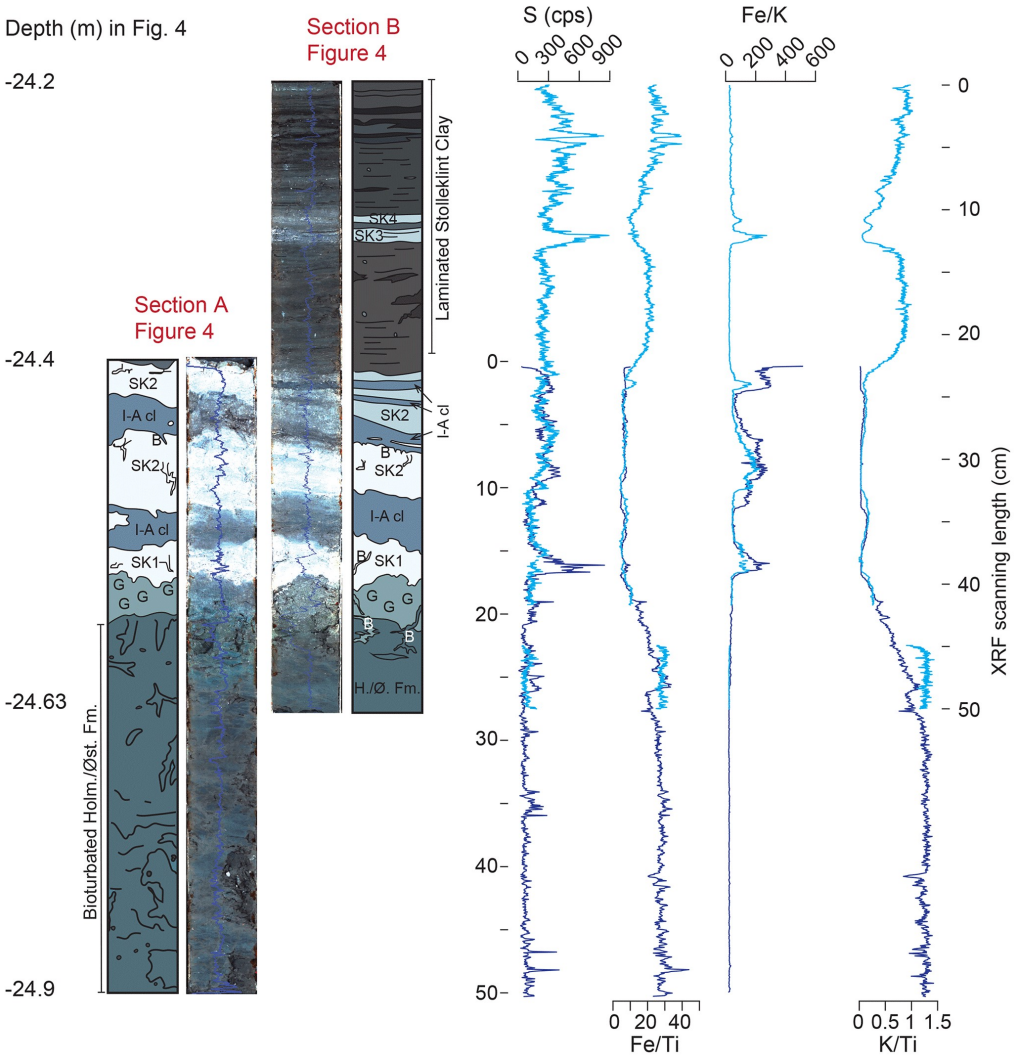



*Figure 4.2. XRF element core scans and radiographic images of two box cores crossing the PETM onset at the Stolleklint beach. Note that the sample preservation is overall good and XRF core scanning were conducted on a smoothed surface along the centre avoiding any substantial irregularities. Interpretive logs next to the images indicate the lithological changes. G: glauconite; B: burrow; I-A cl: inter-ash clay. XRF data are given as counts per second (cps) or as dimensionless ratios.*

### 3) Volcanic and thermogenic triggering of the end-Triassic crisis

The emplacement of the Karoo Large Igneous Province (LIP) occurred synchronously with the Toarcian crisis (ca. 183 Ma), which is characterized by major carbon cycle perturbations. A marked increase in the atmospheric concentration of $CO_2$ ($pCO_2$) attests to significant input of carbon, while negative carbon isotope excursions (CIEs) in marine and terrestrial records suggest the involvement of a $^{12}C$-enriched source. Thea H. Heimdal and CEED researchers have worked on understanding the effects of pulsed carbon release from the Karoo LIP on atmospheric $pCO_2$ and $\delta^{13}C$ of marine sediments, using the GEOCLIM carbon cycle model (Heimdal et al., 2021). They showed that a total of 20,500 Gt C replicates the Toarcian $pCO_2$ and $\delta^{13}C$ proxy data, and that thermogenic carbon ($\delta^{13}C$ of −36 ‰) represents a plausible source for the observed negative CIEs. Importantly, an extremely isotopically depleted carbon source, such as methane clathrates, is not required in order to replicate the negative CIEs. Although exact values of individual degassing pulses represent estimates, they consider the emission scenario realistic as it incorporates the available geological knowledge of the Karoo LIP and a representative framework for Earth system processes during the Toarcian.

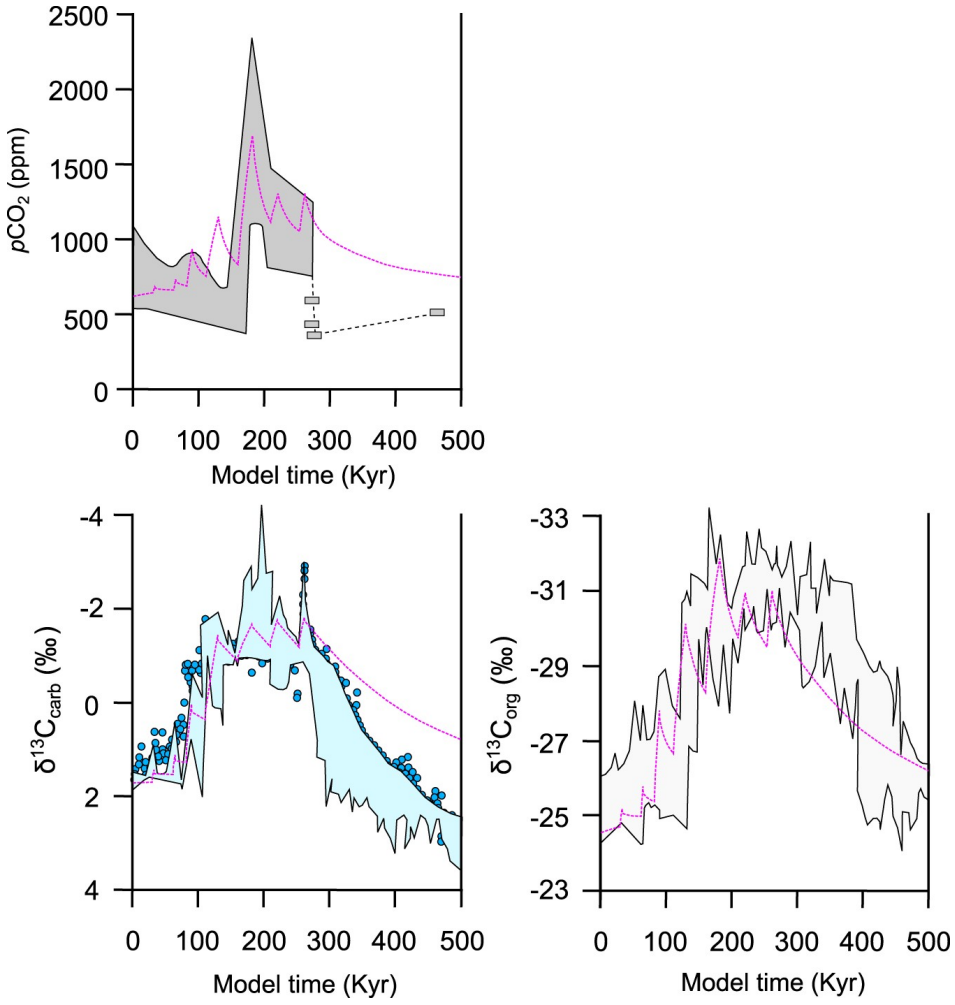



*Figure 4.3. Curves obtained by carbon cycle modeling (pink dashed lines) of the atmospheric concentration of $CO_2$ and carbon isotope composition of marine carbonate and organic matter in response to carbon emissions from the Karoo Large Igneous Province. The model curves are compared to observed values shown by the gray and blue outlines.*

### 4) Geochemistry of the subvolcanic rocks in the Siberian Traps

A vast portion of the plumbing system of the Siberian Traps Large Igneous Province (STLIP) is emplaced in the Tunguska Basin, where borehole data reveal ubiquitous and abundant sills with great lateral extension. These intrusions intersect Cambrian–Ordovician evaporite, carbonate and siliciclastic series, and locally coal-bearing Permian host rocks, with a high potential for thermogenic gas generation. Sara Callegaro and colleagues have presented new geochemical data from 71 magmatic and 4 sedimentary rock samples from the Tunguska Basin center and periphery, recovered from 15 deep sills intercepted by boreholes (Callegaro et al., 2021). The studied samples are all low-Ti basalt and basaltic andesites, confirming absence of high-Ti and alkaline STLIP magmas in the Tunguska Basin. The sills derive from picritic parental melts produced by extensive melting of a mantle source with recycled crustal components below a thinned lithosphere (50–60 km), within the spinel stability field. The mantle source was dominantly peridotitic, with enriched pyroxenitic domains formed by recycled lower crust, in agreement with previous models for the main tholeiitic STLIP phase. Limited amounts (up to 5%) of highly radiogenic granitoids or moderately radiogenic metapelites were assimilated in upper crustal magma reservoirs by some of the melts originating the sills. After emplacement, sills intruded in Cambrian evaporites assimilated marlstones and interacted with the evaporitic host rocks, probably via fluids and brines. This is the first time that such process is described in subvolcanic rocks from all across the volcanic basin. The sills are correlated

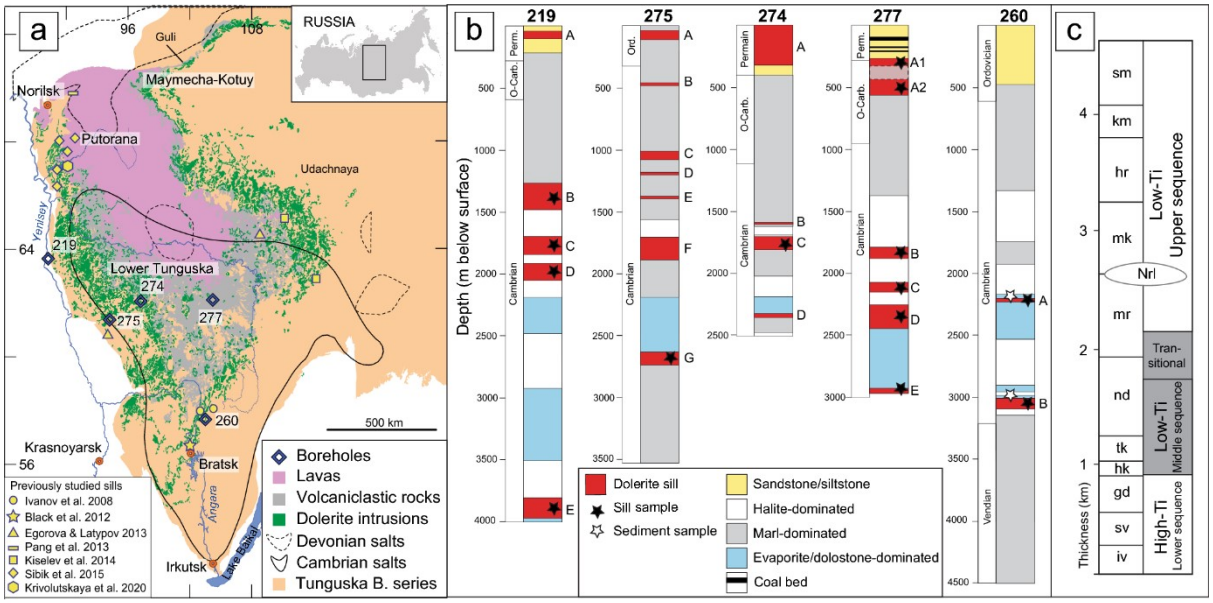



*Figure 4.4. a) Overview of the Tunguska basin in the context of the Siberian Traps Large Igneous Province, with the location of the analyzed boreholes; b) schematic log description of the investigated boreholes; c) Overview of the volcanostratigraphy in the Norilsk region. Modified after Callegaro et al. (2021).*

geochemically with the established chemostratigraphy for the on-craton STLIP lava piles and intrusions (Norilsk region). Sills correlated with the Morongovsky–Mokulaevsky lava formations and the Norilsk-type intrusions are the most voluminous, present all across the central Tunguska Basin, and bear the strongest evidence of interaction with evaporites. Recent palaeomagnetic data support the concept that the Morongovsky–Mokulaevsky lava formations and

the Norilsk-type intrusions are coheval and might represent a single, voluminous magma-batch. These geochemical correlations demonstrate that also a significant portion of the Tunguska sills belong to this batch. Massive discharge of thermogenic volatiles generated by sill-host rocks interaction is supported by explosive pipes and hydrothermal vent structures throughout the Tunguska Basin. We propose that this voluminous pulse of magmatism is a good candidate for the hitherto unidentified early intrusive phase of the STLIP, and may link the deep Tunguska basin sills to the end-Permian environmental crisis. This link is also highlighted in the recent review published by Dal Corso et al. (2022) in Nature Reviews Earth and Environment, including Sara Callegaro as coauthor.

Moreover, a study by Sibik et al. (2021), involving CEED researchers, documented the role of the evaporites in the basin in contaminating the magma, by studying whole-rock halogen concentrations and ratios. Sara Callegaro and Thea Hatlen Heimdal are now taking these observations a step further by investigating halogen concentrations at the mineral scale.

**5) Active Earth degassing systems**

Our studies in the framework of the ERC-LUSI LAB project (with PI Adriano Mazzini) continue. The Lusi eruption in Indonesia (Figure 4.5) represents a modern analogue for the palaeo-vent systems that released to the atmosphere large amounts of volatiles. We successfully quantified the amount of $CO_2$ and methane emissions from Lusi revealing that this is one of the largest natural gas systems on Earth. The results deepen the scientific debate on the global emission of geological methane sources, and suggests that recent pre-industrial estimates are significantly underestimated (Mazzini et al., 2021a). Further, we completed the first 3D deep electrical resistivity tomography survey (15km$^2$) ever attempted on an active clastic system (i.e. Lusi). The obtained data expose the subsurface morphology (Figure 4.5) of this new-born eruption and disclose the link between a well-developed fault system (Mazzini et al., 2021b). These results have been complemented with gravimetry and 3D modelling data (Osorio Riffo et al., 2001; Sohrabi et al., 2021). CEED student Sergio Andrés Díaz Meza successfully defended his MSc thesis exploiting the seismic data collected by the LUSI LAB network arrays and investigating various phases of the volcanic tremors.

Also the field activities of the HOTMUD project (PI Adriano Mazzini) continue. We investigated active degassing sites in Lake Baikal where tectonic discontinuities facilitate the exten-

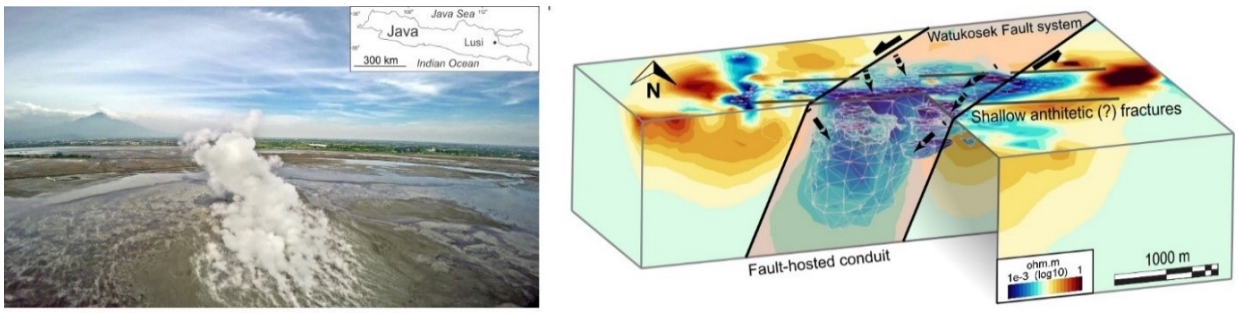



*Figure 4.5. Left: Drone view of the Lusi eruption and the Arjuno-Welirang volcanic complex in the background. Right: 3D projection of the acquired deep electrical resistivity tomography data showing the Lusi conduit at depth.*

sive migration of fluids at the lake floor (Vidishcheva et al., 2021). During the activities of the Azerbaijan Summer School we unraveled the explosive mechanisms of the most active mud volcano on Earth (i.e. Mazzini et al., 2021c). Finally, during the Training Through Research 20 expedition we surveyed the northeastern Barents Sea to investigate glaciomarine landforms and depositional systems and to identify areas of focused fluid discharge.

**6) The La Palma 2021 eruption: Understanding lava deltas**

The 2021 volcanic eruption on La Palma (Fig. 4.6A) provides rare and valuable information on emplacement processes when subaerial lava flows enter an aqueous environment. Such lava deltas are commonly identified in Large igneous provinces and can have important implications for volcanic explosivity, interaction of the volcanism with the environment, and the nature of the volcanic deposits (Bischoff et al., 2021; Walker et al., 2021). Dougal Jerram and Sverre Planke are involved in field studies of the lava deltas that formed during the 2021 volcanic eruption at La Palma in the Canary islands. Dougal first visited in October during the early stages of the eruption and also undertook a number of outreach TV interviews about the volcanic event. Three drone surveys and sampling of the new lava deltas (Fig. 4.6B) took place in November and December 2021 and in January 2022, including drone-mounted thermal cameras. The ongoing research will use this 'time lapse' information to understand how lava deltas develop, and to use them as analogues for understanding lava delta deposits that are cored and imaged on 3D seismic data in the Norwegian Sea.

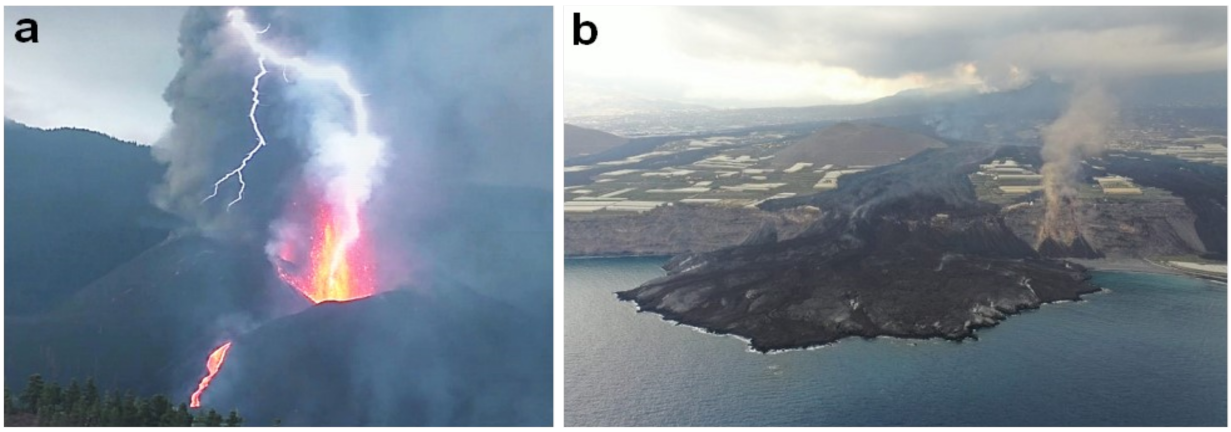



*Figure 4.6. A Lighting strike photographed during the eruptive phase of the La Palma eruption during the October 2021 visit of Dougal Jerram. B: Drone image from 3D drone survey of the new lava deltas developing as the lava flows enter the Atlantic Ocean in November 2021.*

**7) Pre-Viking societies and environmental changes**

Understanding how the Viking societies were impacted by past climate variability and how they adapted to it has hardly been investigated. CEED researcher are part of the externally funded Vikings-project and have studied lake sediments spanning the Viking age. Bajard et al. (2022) carried out a new multi-proxy investigation of lake sediments, including geochemical and palynological analyses, to reconstruct past changes in temperature and agricultural practices of pre-Viking and Viking societies in Southeastern Norway during the period between 200 and 1300 CE. The periods 200–300 and 800–1300 CE were warmer than the 300–800 CE period, which is known as the "Dark Ages Cold Period". This cold period was punctuated by

century-scale more temperate intervals, which were dominated by the cultivation of cereals and hemp (before 280 CE, 420–480 CE, 580–700 CE, and after 800 CE). In between, cold intervals were dominated by livestock farming. The results demonstrate that the pre-Viking societies changed their agricultural strategy in response to climate variability during the Late Antiquity.

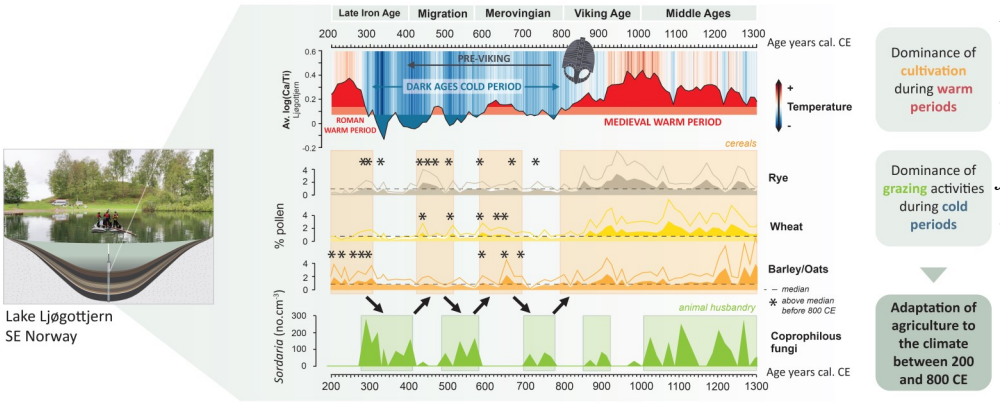



*Figure 4.7. Graphical abstract showing the results from the lake study.*

**8) Update and projects from the CLIPT stable isotope lab**

The CLIPT lab has provided analytical support to over 30 projects over this last year, with plans to continue expanding its user base in 2022. In the latter half of 2021, UiO provided funding for the purchase of two new cutting edge Picarro Cavity Ring Down Spectroscopy instruments. This will expand our analytical capabilities to include $\delta^{18}O$ and $\delta^{2}H$ on most natural waters, including marine, lacustrine, snow, rain, permafrost, glacial and rivers. A $CO_2/CH_4$ analyzer will enable us to continuously monitor atmospheric $\delta^{13}C$ in $CO_2$ and $CH_4$, either within controlled chamber experiments or the outside natural environment. The tentative delivery date is in the first quarter of 2022.

The water analyzer will open up many more possibilities for geologic studies, such as the recent CLIPT publication using $\delta^{18}O$ and $\delta D$ in waters to study the extreme environments associated with human migration corridors out of Africa during the last 150,000 years (Tabor, Jahren et al. 2021). The paper explores the geological and environmental factors that result in the most positive $\delta^{18}O$ and $\delta D$ values that have ever been reported for naturally occurring waters, along with the largest annual variability of streams documented (Fig. 4.8). Characterizations of extreme modern environments like these can provide analogues for what can be expected from ancient environments.

The year brought exciting new opportunities to the lab. We began an ambitious project that involves using carbon stable isotope measurements to reconstruct paleo $CO_2$ levels during the middle to late Devonian, a period that is lacking in $CO_2$ proxies. This time period is crucial for understanding how the development of land plants and their rapid colonization of land affected and changed the earth's $CO_2$ budget. With a group of CEED researchers, we embarked on fieldwork in September to the abandoned Russian coal mining town of Pyramiden, on Svalbard, where we successfully collected terrestrial Devonian age sedimentary rocks containing organic carbon. The preliminary stable isotope results look promising and we are on schedule to expand our sampling efforts in June 2022. In addition to the CLIPT lab members, CEED

researchers Mathew Domeier, Annique van der Boon, and Jean-Baptiste Koehl accompanied us, providing invaluable expertise with interpreting the stratigraphy and creating an age framework for our sampling.

We continued with multi-year projects, including a collaboration with Henrik Svensen investigating intra-ring carbon stable isotope patterns in 250 million year-old wood recovered from the Siberian Trap. Expanding on our preliminary dataset from 2020, the most recent analyses suggest extremely well-preserved stable isotope signals with the potential to provide unique paleoclimate data for a period of rapid climate change.
We also worked with Morgan Jones to analyze sediment layers from cores collected during an IODP expedition in the North Atlantic which will pinpoint the PETM, thus providing anchors for the age of the sediments. We also provided support for the Vikings lake study that was published this year.

While our primary projects this last year have been within CEED, we continued to support multi-disciplinary research, working with UiO researchers from across the scientific spectrum. For example, we co-authored a paper with Tor Eric Rusten and Petter Holland where we developed a method for studying carbon dynamics associated with tumor growth (Holland, Hagopian et al. 2021). This resulted in a method that enabled us to push the lower limits of sample sizes we can analyze, a technique we are now effectively applying to CEED projects such as the intra-ring Permian wood study.

With 2022, we look forward to continuing our support of CEED researchers, both with ongoing projects and potential new projects and anticipate the acquisition of the Picarro instruments will bring exciting new opportunities to the lab.

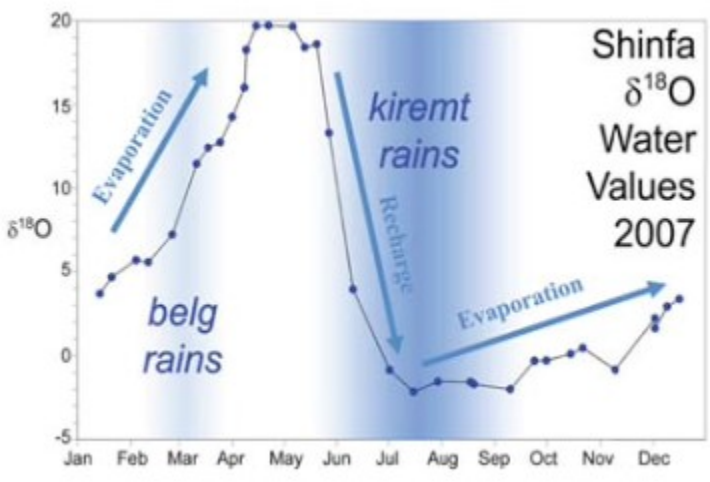



*Fig. 4.8. Plot illustrating the extremely high $\delta^{18}O$ values and high seasonal variability over the course of one year for the Shinfa River, Ethiopia.*

## Selected papers (CEED-affiliated in bold)


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**(**2021C), Explosive mud volcano eruptions and rafting of mud breccia blocks: Earth and Planetary Science Letters, v. 555, p. 116699.

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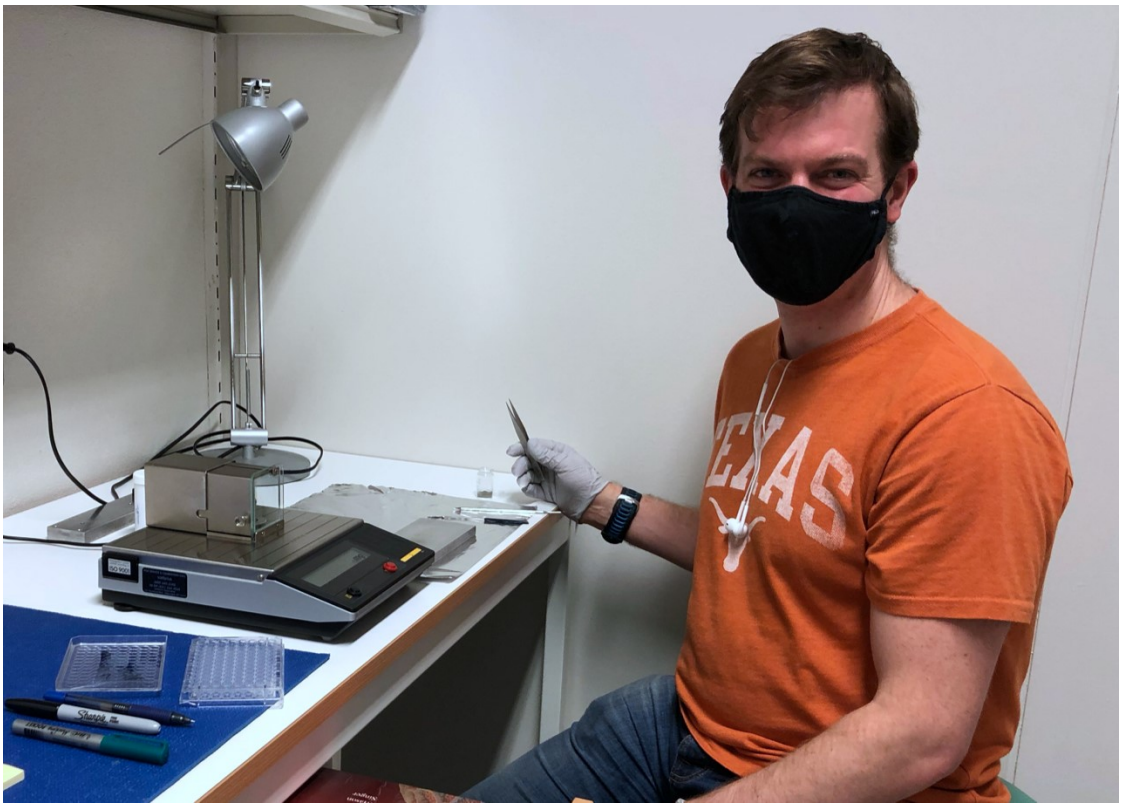
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*Morgan Jones (Earth Crises team) preparing IODP core samples for stable isotope analysis. Photo by: William Hagopian.*



*CEED conference December 2021. Members of the Earth Crises team. Photo by: Thea Heimdal.*

*Our mission is to understand the similarities and differences between Earth and the other terrestrial planets with the hypothesis that we can understand the dynamics of Earth and other planets within the same framework, but with different parameters. We extended this analysis to exoplanets.*
*The key factors in determining the style of mantle convection, surface tectonics and volcanism may be the amount of water or other volatiles in the system, and which steer physical properties. Composition as well as times and rates are thus essential for deciphering planetary processes during planet formation and evolution.*

**Martian crustal and aqueous processes with analogues of the PTAL collection**

In 2021, we finalised the Planetary Terrestrial Analogue Library (PTAL). It is a collection of rocks and spectral data aiming to support interpretation of remote sensing-obtained and in-situ data from Mars and small bodies of the Solar System [1]. PTAL comprise spectral data collected in the NIR, Raman and by LIBS, validated by XRD and microscopic characterization. Since September 2021 is PTAL public and freely accessible through www.ptal.eu. The physical collection of rocks is available for further studies upon request. PTAL consists of 106 rock samples from 19 diverse localities on Earth [1], collected with the intention of covering best the known composition of martian crust and a wide range of geological processes on Mars. Apart from igneous lithologies, PTAL contains samples from diverse surface alteration environments and a range of climatic environments. Caution though, no terrestrial rock can be perfect analogue for Mars, meeting both criteria of composition and formation processes, because of inherent differences between the two planets, e.g. Fe and Mn content or volatile abundances. A few samples [discussed in 2] have been selected as ExoMars rover surface operation simulation samples or as 'Mission Samples' for instrument analytical comparison.

**Volatiles in martian magmas – insight from orbital observations and from meteorites**

Mars oldest surface is characterised by vast deposits of Fe,Mg-phyllosilicates, supporting broadly accepted liquid water to have once been more ubiquitous. Using terrestrial analogues, we proposed plausible formation environments for phyllosilicates in Oxia Planum – the future landing-site area of the ExoMars rover – for which the Fe,Mg-phyllosilicates spectrally match best vermiculite [2]. On Earth, vermiculite forms by alteration of biotite (Fe-rich mica) or chlorite. On Mars, the presence of large quantities of these minerals is difficult to reconcile, because it typically requires highly differentiated protolith. Coexisting olivine and the lack of typical processes (crustal recycling) challenges pathways on how on Mars such vast deposits of vermiculite could have formed. Now we screened terrestrial analogues using constraints from martian meteorites to identify potential protolith and/or environmental conditions that could allow vermiculite to form. We have focused on rocks from the kimberlite-carbonatite family, because they contain olivine and phlogopite

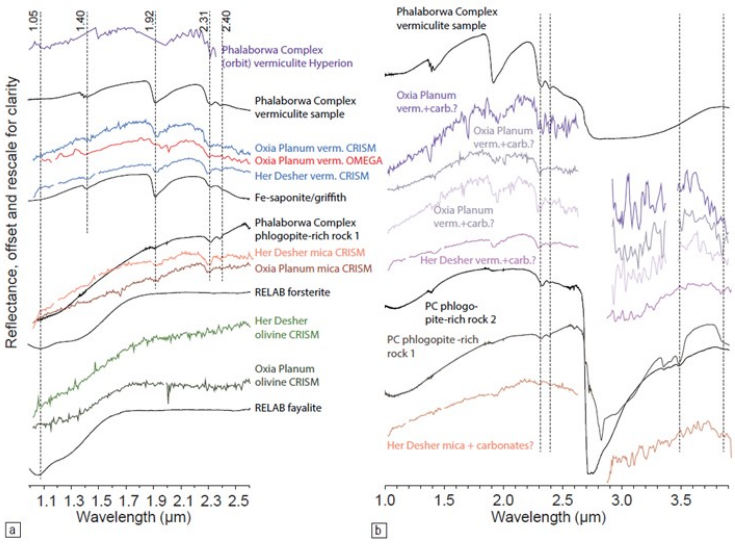



*Fig. 5.1. Comparison of NIR measurement for Earth sample (Palaborwa Complex) and remotely sensed martian surface (Oxia Planum and Her Desher Vallis).*

(Mg-rich mica), i.e. precursor for vermiculite. We could match terrestrial Kimberlites using NIR spectroscopy with Oxia Planum and other type locations of vermiculite on Mars. We have found an excellent spectral match, implying that kimberlite-carbonatite lithologies were highly likely primary rocks at these plains. Photogeological studies showed that kimberlitic-like magma emplacement on these martian plains is the favoured mechanism to form rocks that predated what is now vermiculite-rich plains.

One particular group of the martian meteorites, nakhlites, provide geochemical signatures suggesting a low degree of partial melting from a depleted mantle source. Nakhlites are basaltic in composition, not kimberlitic, however, we have identified that Cl concentrations in the primary melt were high enough to affect late stages of igneous evolution. Halite concretions enclosed in igneous mesostasis are associated with Fe-rich pyroxene overgrowing cumulate augite. It implies that igneous fluids and degassing have played a significant role in the evolution of these rocks and led to the formation of fluid alteration minerals. It is therefore likely, that on a global scale, such processes were connected to emplacement of alkali-rich and volatiles-loaded magmas, such as needed to form complexes currently represented by vermiculite plains.

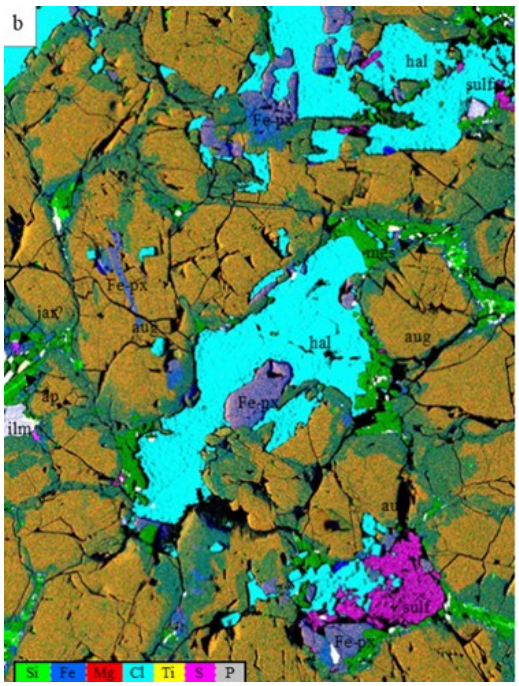



*Fig. 5.2. Montage of EDX elemental maps of Nakhla, a martian meteorite. Halite segregations, up to 1 mm in size and sulphate nodules are present in evolved, late stage mesostasis. The texture of halite suggests it formed at the igneous-hydrothermal stage of rock formation. The close association of Fe-rich orthopyroxene with halite indicates the strong influence of volatiles, namely Cl, on compositional evolution of the system .*

For terrestrial kimberlite-carbonatite magmatism, it is accepted that it requires minuscule partial melting of the metasomatized mantle. Support for the existence of such conditions on Mars comes from martian meteorites. This finding implies that Noachian magmas on Mars had larger quantities of volatiles, and rather complex petrogenesis. Our work [3] will be of interest for future in situ investigations of Oxia Planum by ExoMars2022 that could verify our hypothesis of kimberlite-alike rock formation on Mars.

**Planet internal dynamics and their tectonic surface expressions – YFF: PLATONICS**

We investigated the effects of composite rheology (co-existing creep mechanisms) in numerical models of mantle dynamics and plate-like behavior. The presence of dislocation creep locally reduces mantle viscosity and affects the strength of subducting slabs and how they drive surface plate motions [4]. In addition, we incorporated dynamic grain-size evolution (GSE) into these models [5]. GSE can modify the structure of deep mantle plumes by causing a relatively viscous interior of the plume conduit where grains can grow anomalously fast. GSE can also leave its marks in the lithosphere by causing zones of relatively reduced grain size, and thus reduced strength that can guide the development of new subduction. Both effects are to be explored in detail.

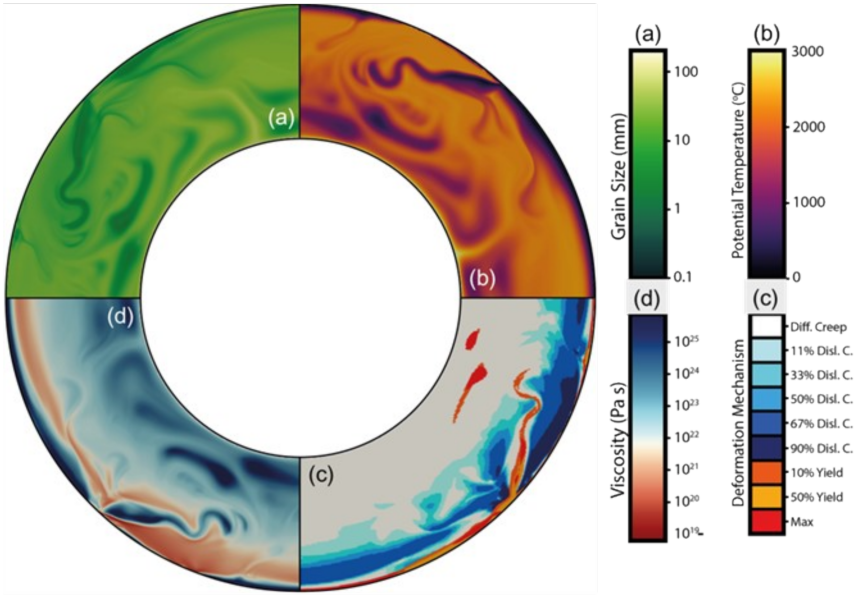



*Fig. 5.3. Snapshot of the different fields of convection model with GSE showing subduction and upwelling (plume): (a) Grain size, (b) Potential temperature, (c) Deformation mechanism, (d) Viscosity. All fields are computed in the entire annulus, but here just one quadrant of the solution is shown (and accordingly rotated) for visualization purposes. The figure shows our advances achieved [4,5].*

Venus, the target of several recently selected space missions, will be analyze on how our new model with GSE relates to different dynamics under Earth's and Venus' conditions, thereby contributing to the divergent evolution of both planets. A review of our knowledge of Venus' mantle dynamics and evolution has been prepared in relation to a workshop of the International Space Science Institute [6]. For the application to icy satellites, we started with an initial comparison of convection with uniformly distributed (classical internal heating) and heterogeneously distributed heat sources (arising from tidal heating) with relevance for Jupiter's satel-

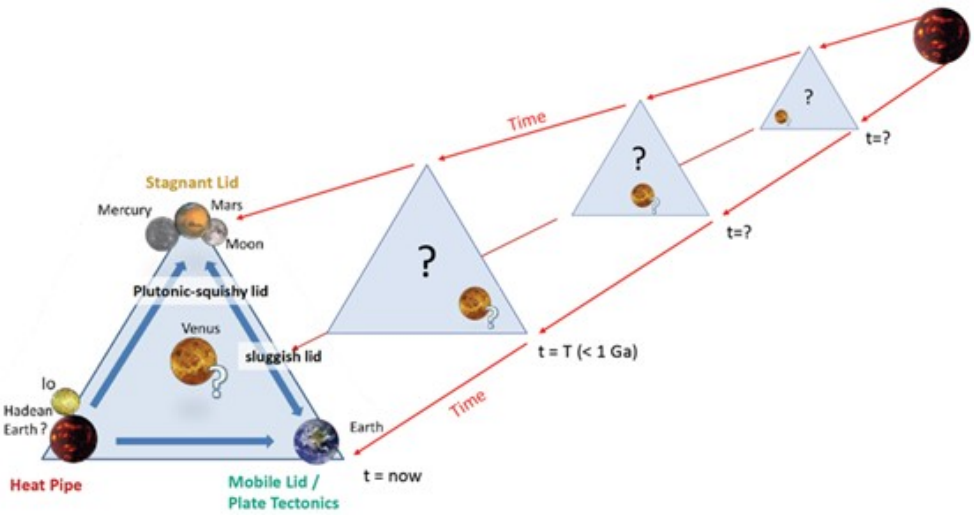



*Fig.5.4. Conceptual scheme of Venus' interior evolution from an unknown magma-ocean state to the (poorly constrained) present-day state, with likely active tectonism and volcanism that differ from the terrestrial style. These processes are all reviewed in [6]*

lite Europa, but the effects on the internal dynamics are minor, at least under stagnant lid conditions. We are implementing additional deformation mechanisms relevant for ice for exploring their effects in our GSE model as a next step. Together with the Earth Computing group at CEED (*Crameri, Heyn, Conrad*), we are improving the treatment of the lower model boundary, and better representation of the structure of the ice-liquid ocean interface (Europa) and the core -mantle boundary (Earth). On dynamics and evolution of Earth's supercontinents [7], work is continuing by systematically extracting quantitative measures of tectonic plates from geodynamic models and by using them to understand Earth's plate energetics (with *Capitanio*, Monash University) and as statistical constraints for novel approaches in paleomagnetism (with *Domeier*'s *youngCEED* workshop team). All our simulations use Norwegian supercomputers operated by UNINETT Sigma2.

**Exoplanets – Statistics, Formation and Evolution**

Planets are ubiquitous across the Galaxy. Our ambition is to understand the emergence and evolution of planets and planetary systems as a generalizable physical process and a natural outcome of star formation. A holistic picture should involve characterizing individual exoplanets as well as their interaction with their environment, including other planets in the same system and the host star. Our group investigates observable parameters describing and influencing exoplanet interior structure and composition, exoplanet system architecture and evolution, as well as host star properties [8]. We interpret the statistics of exoplanet populations with theoretical predictions and numerical simulations. For example, vetting several Exoplanet Data Depositories allows for studying the exoplanet population, separating rocky versus volatile rich planets, based on their mass-radius relation.

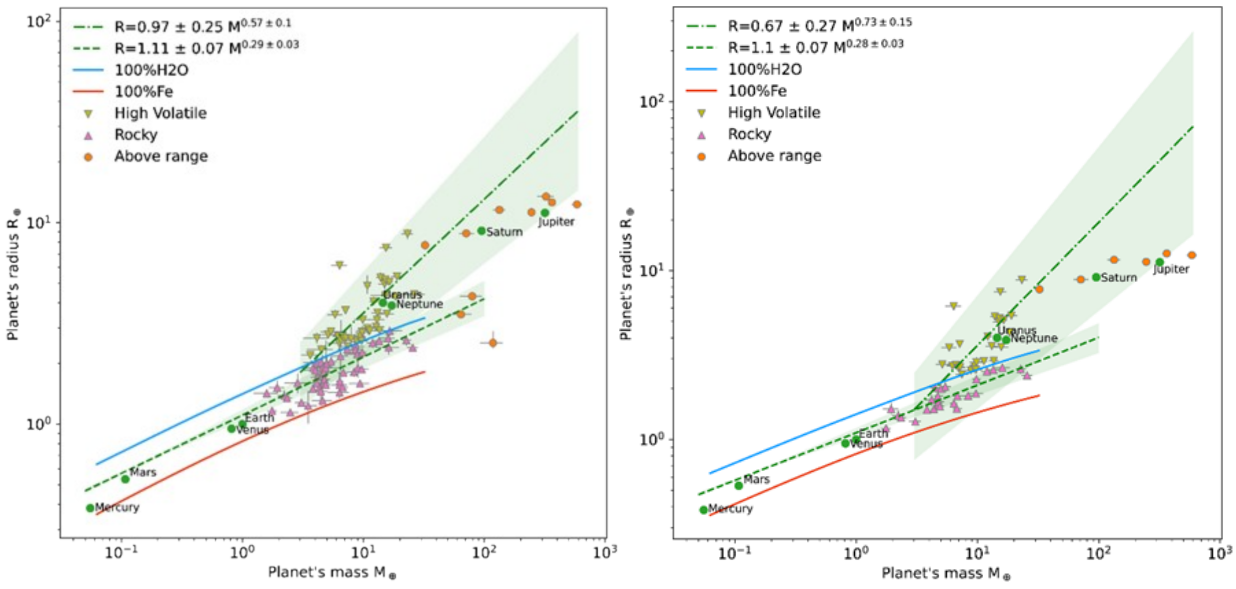



*Fig. 5.5. Mass-Radius relations for rocky and volatile-rich populations separated by the pure water line (blue, and red pure iron line according to [9]). The green dotted and dash-dotted lines represent fitting functions, the light-green envelopes represents the ±1σ regions of the fit. We show different sets based on the uncertainties we allow for the populations (right) ErrM/M = 50% and ErrR/R = 50%; (left) or more strict ErrM/M = 30% and ErrR/R = 10%.*

**Exoplanets's host stars**

Stars play a pivotal role in shaping the course of development for their exoplanet systems. Building blocks of planets inherit their composition from the same molecular cloud that formed the host star, the chemical makeup of the star should govern the internal structure and mineralogy, thermal evolution, and atmospheric constituents of its exoplanets. Small stars (i.e., <~0.7 Msun, also called red dwarfs) dwarf sun-like stars in number and host the majority of habitable-zone exoplanets currently known (also due to detection advantages). Observational and modeling challenges so far limited measurements of the nature of small stars, specifically their chemical composition. We are developing state-of-the-art methods to measure the abundances of chemical elements in red dwarfs through high-resolution spectroscopy. Using the latest atmosphere models and atomic data applied to high-quality spectra from the CARMENES survey, they elucidated, for the first time, a robust way to study the element vanadium in these types of stars using a dozen hyperfine-split lines [10]. In the same work, we identified a weakness in many previous chemical studies of sun-like stars that led to spurious results. In another work, we modelled iron and titanium spectral lines to infer fundamental properties of these stars, and pointed out clear limitations in current metallicity measurements of red dwarfs by showing significant inconsistencies between results from previous studies [11]. Furthermore, we are continuing to study a number of other elements in red dwarfs in a similar manner [12]. This type of measurements will be critical to understanding the exoplanet populations around the most common type of stars in the Galaxy.

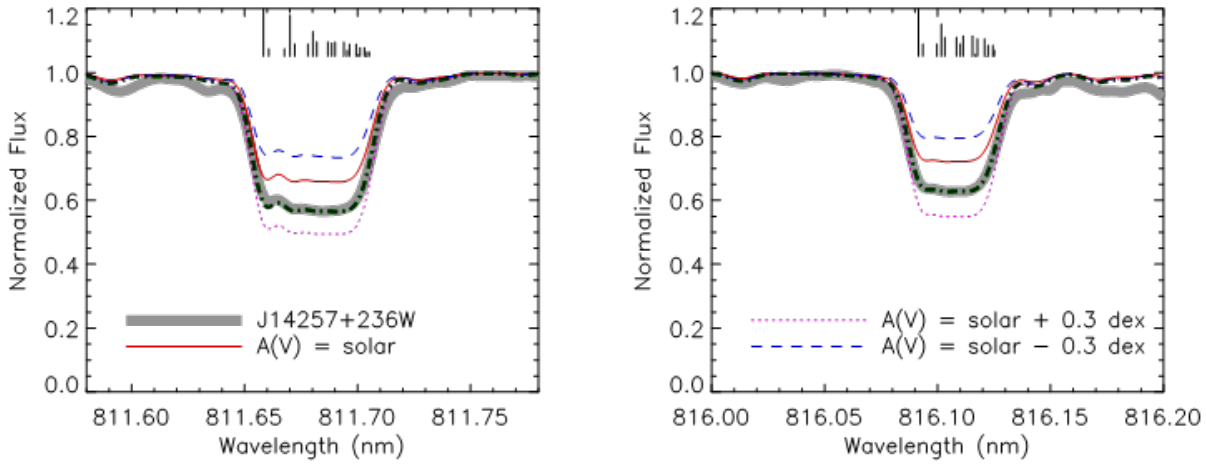



*Fig. 5.6: Hyperfine-split neutral vanadium lines in high-resolution red dwarf spectra, well-reproduced by model synthetic spectra with super-solar vanadium abundance [12].*

**Building Earth-like exoplanets**

We are now at the dawn of a new era of space telescopes surveying and detecting exoplanets, which provides exciting new opportunities to discover exoplanets with Earth-like orbits and sizes. Improved understanding of planetary system dynamical evolution can contribute to the theoretical foundations prepared for interpretations of the results from these missions. Therefore, we are working on building planetary systems, which will contain Earth-like exoplanets similar to the ones already observed. She is using the existing software for running numerical N-body simulations of late planet formation around lower mass stars, not very different from our Sun. Most currently known exoplanets orbit this type of stars. These simulations use Norwegian supercomputers operated by UNINETT Sigma2.

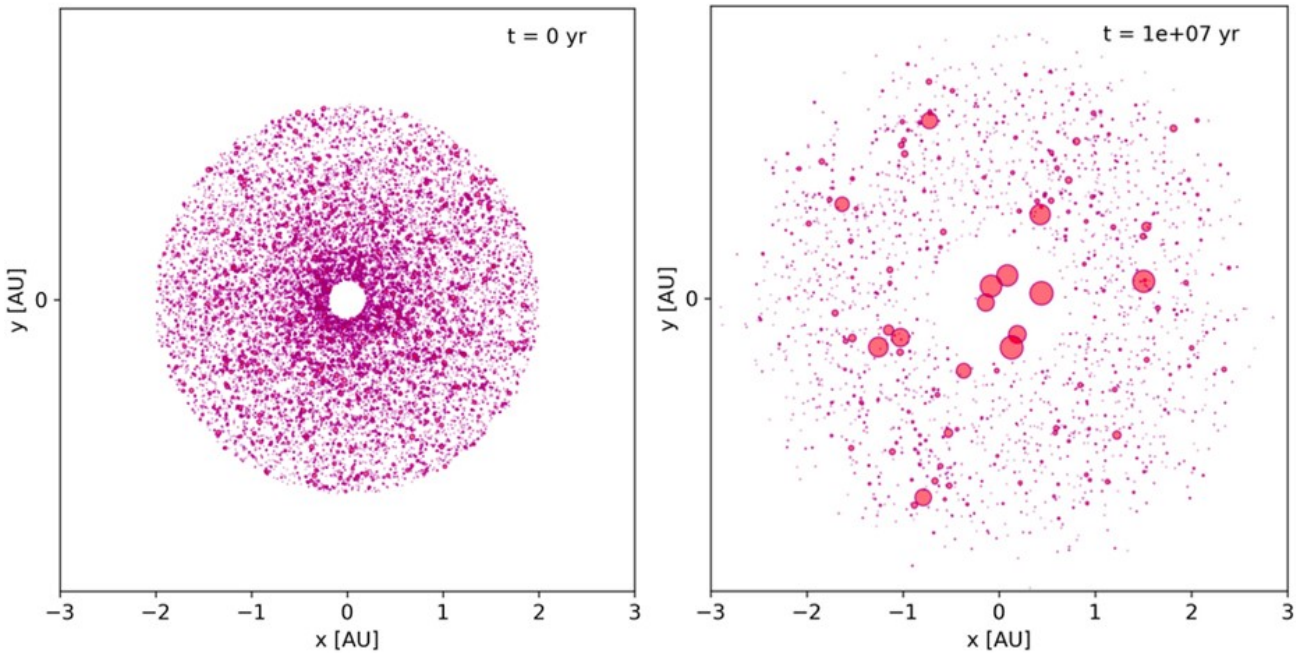



*Fig. 5.7: Example of 10 million years of planet formation simulation. Time is 0 yr on the left, and 10 million years on the right. Small bodies (in purple) formed in a protoplanetary disk around a young star are colliding and growing into larger bodies (in red), eventually forming planets.*

**Rotational Mass Shedding from Asteroid (6478) Gault**

Relic of the planet formation process in the solar system are small bodies dominantly found in the main asteroid belt (between Mars and Jupiter) and beyond Neptune. The main belt asteroid (6478) Gault turned out to have been intermittently active since 2013. Gault's irregular but repeated episodes of mass loss spread over many years are inconsistent with an origin by impact ejection, which would be, presumably, impulsive and singular. Its multiple short-duration dust releases, uncorrelated with perihelion, also rule out water ice sublimation as the cause of activity. By elimination, that leaves rotational instability as the most likely cause of mass loss in Gault. The most basic test of this hypothesis is to measure Gault's rotation period; however, Gault's considerable dust activity through 2019-2020 precluded clean measurement of the rotation of its nucleus. We [13] took advantage of Gault's bare state in mid-2020 to observe the object in the absence of near-nucleus dust. Our observations were consistent with a nucleus rotation period of 2.55 +/- 0.1 hour. In addition, Gault's small lightcurve amplitude, and the low-velocity ejection of large particles, are strongly reminiscent of asteroid (101955) Bennu. Like Bennu, Gault is probably a rubble- pile asteroid shaped like a top. We also showed that the Froude number Fr, defined here as the ratio between centrifugal force at the equator and gravitational force, could be a useful predictor of the onset of mass loss in fast-spinning rubble asteroids. Observational data indicate that mass loss starts at Fr □ 0.5, and once this threshold is reached, there is a large spread of activity level. The Froude number is useful for identifying those asteroids whose activity can be adequately explained by rotational instability, without the need for other less common mechanisms.

**Cratering Chronology and the History of the Solar System**

Crucial for all comparative studies is the accurate timing and sequence of events. This requires a solar system wide time frame. Our continuous effort resulted in two studies [14, 15]. We provided, based on Monte Carlo impact simulations of late accretion onto the Moon and Mars and present an updated chronology based on new dynamical simulations of three different projectile sources, thereby estimating the age of highly-siderophile element retention in the lunar mantle from late accretion [14]. Further, using detailed spectral mapping, cratering statistics and impact basin ejecta column estimates we document a new and very different stratigraphic relationship for the Apollo 14 landing site [15]. As a result, such stratigraphy reattributes the (majority of) Apollo 14 samples to Orientale rather than to Imbrium Basin, and implies that Orientale Basin is about 3.92 Gyrs old, 200 million of years older than previously suggested. Now, the youngest lunar basin formed at the onset of recorded mare volcanism, rather than amidst. This time shift also changes constraints on early planetary and solar-system processes, such as the intensity of impact bombardment, and pleads for revision of the crater-statistics based surface ages of other planetary bodies.

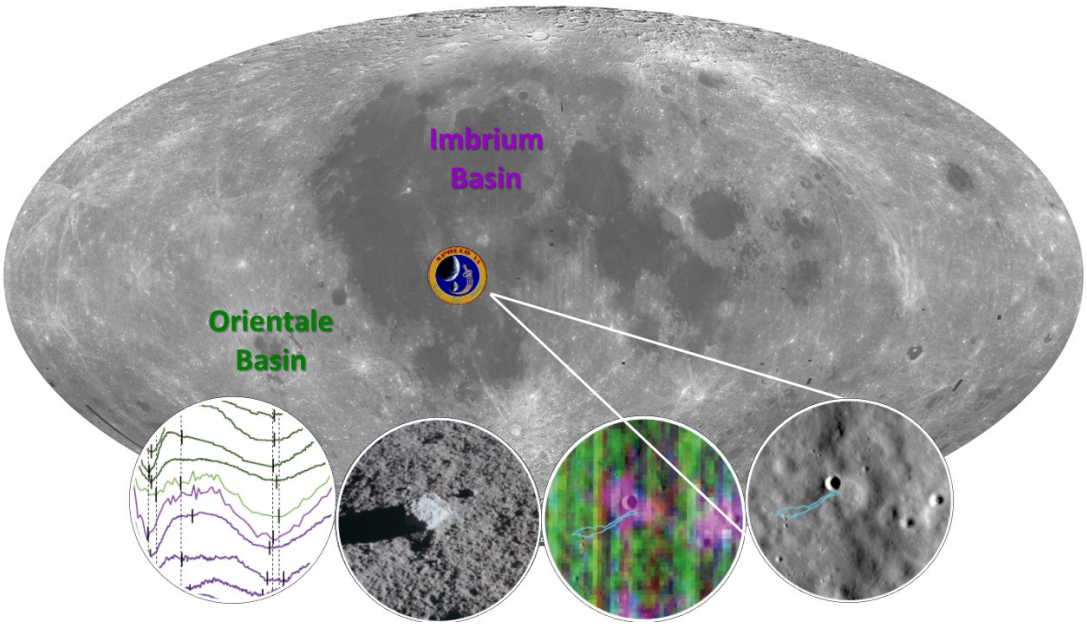



*Fig. 5.8. The Surface of the Moon (Mollweide projection). Insets from left to right: spectral detections of samples; photo of one key lunar sample (14305) used in the spectral analysis; spectral interpretation (green shows the surficial layer previously not detected), and a satellite image of the Apollo 14 Landing Site including astronauts' track (cyan).*

*These data sets were used [15] to show that most rocks collected by the Apollo 14 crew actual stem from the Orientale Basin and not as commonly believed from Imbrium Basin.*

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# 6. Earth Laboratory

*The Earth Laboratory Team focuses on research in paleomagnetism and its applications to paleogeographic reconstructions, plate tectonics, and the behavior of the Earth's magnetic field in the geological past. In 2021, we conducted several studies aimed at refining paleogeographic models for the Mesozoic, Paleozoic and Neo-Mesoproterozoic, exploring the magnetic field in the Devonian, and developing novel methodologies for constraining absolute plate motions using paleomagnetic data. Researchers of our team were actively involved in a number of collaborative projects with other CEED teams, as well as national and international collaborations, and authored thirteen peer-reviewed publications. Here we present a selection of the results from 2021 that correspond to the most significant outcomes of our research activities.*

## Paleomagnetism and Paleogeography

***Early Permian configuration of Pangea.*** From late Carboniferous to early Jurassic time (~320-200 Ma), virtually all landmasses of the Earth were assembled in a single supercontinent known as Pangea. There is a broad consensus that from late Permian time and until its breakup in the early Jurassic, Pangea was in a configuration that juxtaposed the eastern margin of North America against western Africa, called "Pangea A" (Fig. 6.1a). Yet, the earlier history of the supercontinent is less certain, and some paleomagnetic studies suggested that Pangea had formed in a different configuration, which was eventually transformed into Pangea A during the early to middle-Permian. Several alternative models for this original, late Carboniferous to early Permian configuration of Pangea have been proposed, but the only persistent alternative among them is "Pangea B," which places the Gondwana blocks (Africa, South America, India, Australia and Antarctica) approximately 4000 km to the northeast with respect to their position in Pangea A (Fig. 6.1a).

The transformation from Pangea B to Pangea A requires a more than 3500 km displacement along a ~6000 km-long intracontinental boundary separating Gondwana and the Laurussian blocks (North America, Greenland, Baltica and Siberia), which cannot be reconciled with geological record. Our new paleomagnetic-geochronologic investigation of early Permian volcanic rocks from central Morocco (Domeier et at., 2021) aimed at addressing this controversy. The objective of this study was to determine the paleolatitude of Morocco (and thus that of the larger landmass of Gondwana) in early Permian time, which is of critical importance to an ongoing debate concerning the shape/geometry of the early Pangea. Our investigation provided new U-Pb geochronological constraints on the studied rocks, confirming them to have been emplaced between 305 and 277 Ma. The paleomagnetic analysis of these rocks revealed that Morocco occupied an equatorial latitude during this time (Fig. 6.1b), which permits that the Pangean landmass was assembled in a Pangea A configuration already by the early Permian, and do not necessitates invocations of Pangea B. We do not find strong paleomagnetic and geologic support for Pangea B and conclude that the Pangea A configuration has likely persisted over the entire lifespan of the supercontinent.

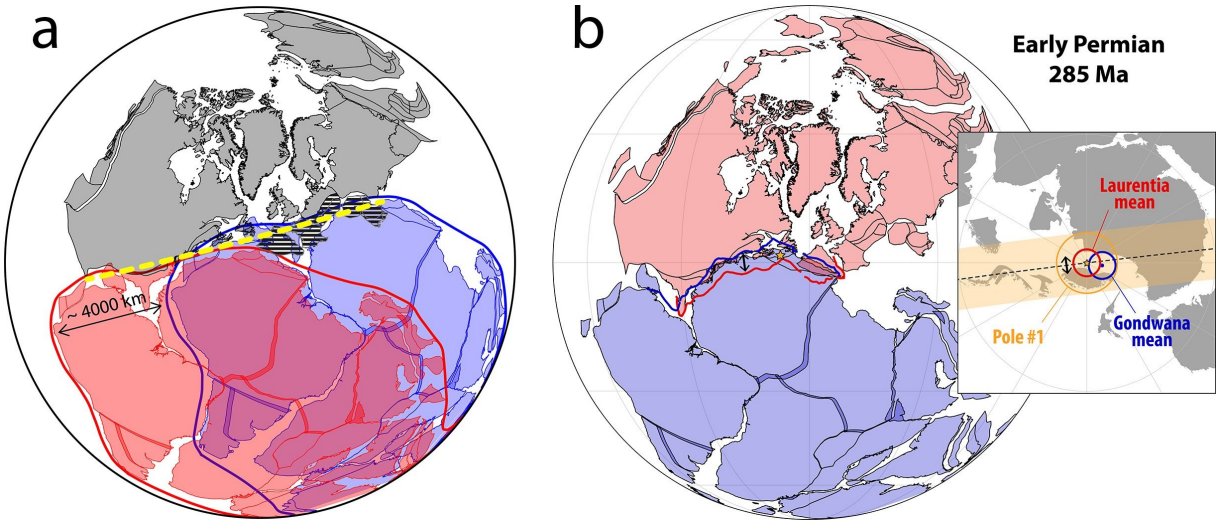



*Fig. 6.1. (a) Alternative positions of Gondwana, relative to a fixed Laurussia (grey blocks) in a Pangea A (red Gondwana) vs. Pangea B (blue Gondwana) configuration at ~300 Ma. The dashed yellow line schematically traces the zone of the megashear that would be required to transform Pangea B to Pangea A. (b) Early Permian reconstructions of Pangea in an 'A-type' configuration at 285 Ma. Laurussia (red blocks) was reconstructed using the APWP of Torsvik et al. (2012); Gondwana (blue blocks) was reconstructed using the paleomagnetic pole from Moroccan volcanics (inset, Pole #1, Domeier et al. (2021)). The thick red (blue) lines along the central Atlantic margins show the reconstructed modern continent ocean boundaries of North America (northwest Africa and northern South America) to provide an estimate of the maximum possible pre-breakup extent of the continent. Orange star shows the sampling area.*

***The origin of the Iapetus Ocean.*** The opening of the Iapetus Ocean was one of the most significant tectonic events of the late Neoproterozoic seguing into the beginning of the Phanerozoic (~700-530 Ma), which marked the final disintegration of the core constituents of the supercontinent Rodinia (Laurentia, Baltica and Amazonia). Yet, the exact timing and manner of opening of this ocean have remained unclear and debated. The study of Mathew Domeier and his co-workers sought to clarify this picture by conducting an exhaustive review of the presently-available paleomagnetic and geologic evidence which constrains this event (Robert et al., 2021). The analysis of the paleomagnetic data revealed that while some proposed models of Rodinia disintegration and Iapetus opening can be rejected, there remains great uncertainty owing to limitations in the data available. From the geological review, it can be likewise shown that some models can be dismissed, but that there remains significant uncertainty given the limited observations available. However, by considering the paleomagnetic and geologic constraints jointly, we were able to further constrain the possibilities and present a tectonic model that is self-consistent with these collected observations. In this model, the breakup of Laurentia, Baltica and Amazonia occurred in several phases, involving the spalling of marginal terranes from Laurentia and the successive opening of several oceans, including a composite "Iapetus Ocean" (Fig. 6.2). The first phase of continental breakup occurred between eastern Laurentia and western Amazonia at 750–700 Ma, leading to the opening of the Puncoviscana Ocean. This was followed by the opening of the eastern branch of the Iapetus Ocean, between Laurentia and Baltica, at ~590 Ma, which may have been instigated by emplacement of the Central Iapetus Magmatic Province (CIMP). The western branch of Iapetus subsequently opened at ~550 Ma by the detachment of marginal terranes from eastern Laurentia, following a protracted phase of rifting.

Hence, the Iapetus Ocean actually represents a compound oceanic system comprised of several distinct ocean basins that opened successively.

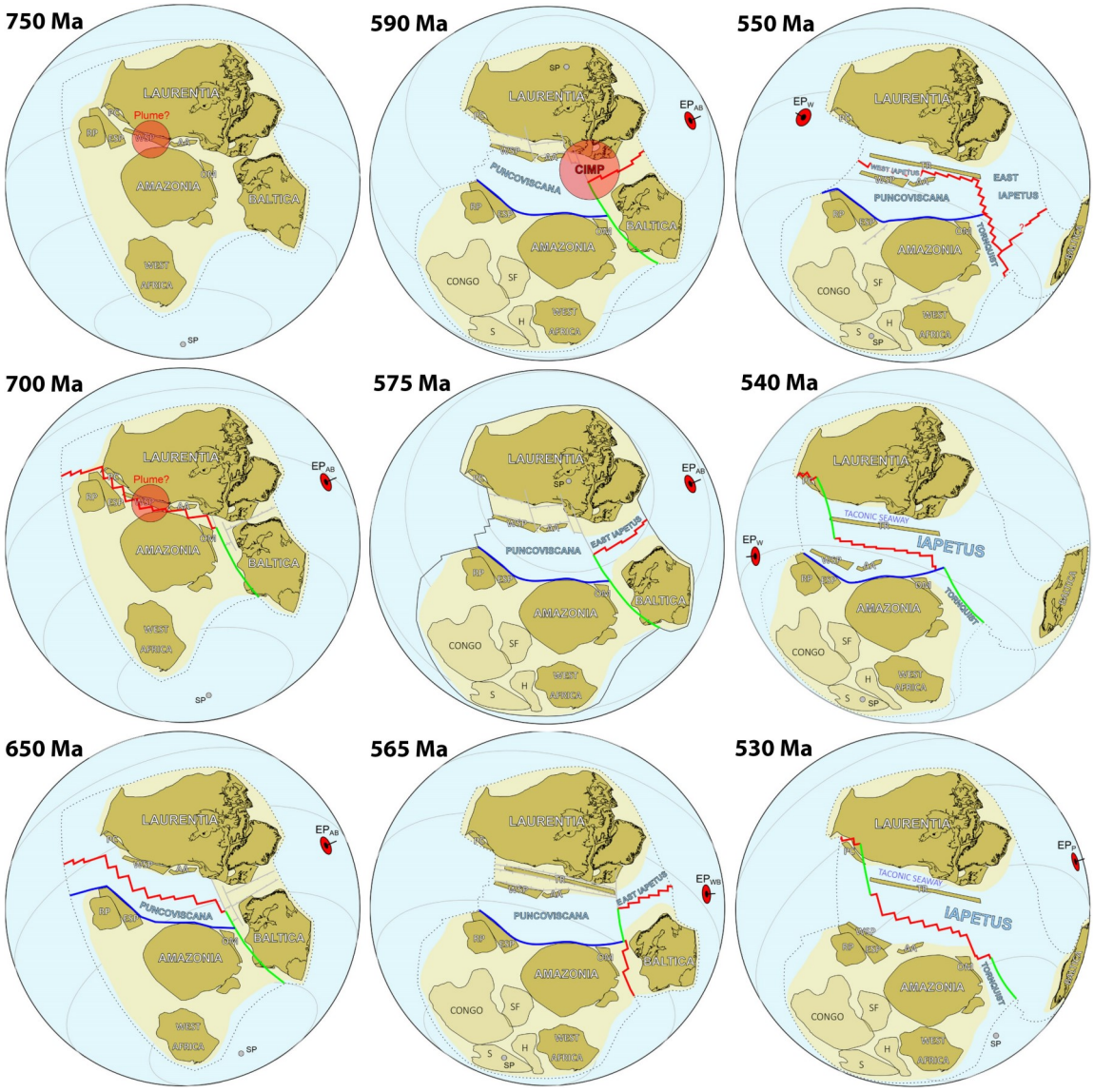



*Fig. 6.2. Snapshots of the regional plate model of Robert et al. (2021) illustrating the evolution of the Iapetus system from 750 to 530 Ma. Reconstructions are displayed with respect to fixed to Laurentia. Grid lines (gray) indicate the latitude predicted by paleomagnetic data; the South Pole is shown as a gray dot. Mid-ocean ridges are shown by red lines, transform faults are in green and subduction zones are in blue; intracontinental fault systems are shown in gray. The Central Iapetus Magmatic Province (CIMP) is illustrated by a large light red circle along with another presumed plume-related magmatic province at 750–700 Ma.*

***Paleogeography of Baltica in a Rodinia supercontinent context.*** A paleogeographic study led by Evgeniy Kulakov reported new 40Ar/39Ar geochronology and paleomagnetic data obtained from rocks from three areas within the Precambrian Sveconorwegian orogen (Southern Norway) that represent three distinct domains and record progressively younger orogenic events from east to west. Geochronological data, coupled with detailed rock magnetic analyses, indicate that studied rocks cooled down and acquired the natural remanent magnetization at approximately 1090 Ma, 1000 Ma and 900 Ma, respectively.

Paleomagnetic measurements yielded three high-quality paleomagnetic poles, suggesting a considerable revision of the Meso-Neoproterozoic APWP for Baltica. From a comparison with nearly coeval paleomagnetic poles for Laurentia, a new paleogeographic model for the relative configuration of Laurentia and Baltica has been proposed for the ~1250-930 Ma interval (Fig. 6.3). This model differs from previously published reconstructions in that it reconstructs Baltica with the noticeable latitudinal gap from the eastern Laurentian margin at 1090 Ma (Fig. 6.3c), and thus does not support the classical Baltica-Laurentia fit within the Rodinia supercontinent. The younger poles (1000 and 900 Ma), when used together with the coeval paleomagnetic data from Laurentia do not support the traditionally envisaged Meso- to Neoproterozoic Baltica-Laurentia relationship either (Figs. 6.3d, e). Overall, the new data do not lend support to the close connection between the two continents during the proposed Rodinia tenure but instead emphasize the problems with the traditional paleogeographic reconstructions of Rodinia. The new data are consistent with the geological record within the Sveconorwegian orogen, which indicates that the orogeny developed at or behind active continental margins. While Baltica and Laurentia may have resided at similar latitudes between 1000 and 900 Ma, there is no geologic and paleomagnetic evidence for placing them next to each other. A manuscript describing these findings has been submitted for publication in Precambrian Research (Kulakov et al., 2021a).

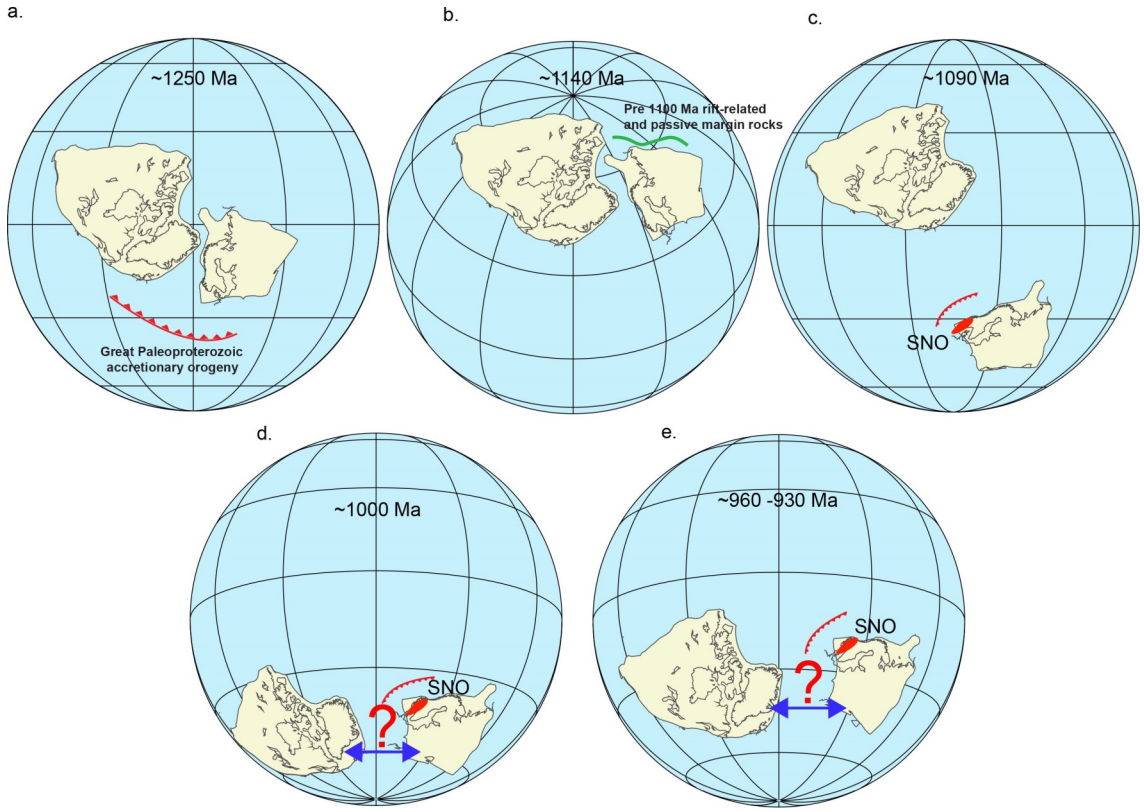



*Fig. 6.3. Paleogeographic model for the Baltica-Laurentia relationship for the ~1250-930 Ma time interval. Red area at the southwestern (present-day coordinates) part of Baltica shows the area of Sveconorwegian orogeny. Blue arrows and question marks in panels (d) and (e) indicate that longitudinal separation is unknown. The model is based on the geological record and supported by available paleomagnetic data (Kulakov et al., 2021a).*

***Jurassic fast polar shift rejected by a new paleomagnetic pole from southwest Greenland.*** A selective compilation of paleomagnetic data indicates that a vast amount of rapid polar motion occurred in Late Jurassic time. The over 30° polar shift that accumulated during a relatively short time interval (~160–145 Ma) suggests an episode of fast true polar wander (TPW) and was referred to as the Jurassic "monster polar shift" by some workers (Fig. 6.4a). The rates of the monster shift exceed all theoretical TPW limits and, if true, suggest rather exotic mantle regime. In the study of Kulakov et al. (2021b), we examined the Jurassic monster polar shift by virtue of a new paleomagnetic and 40Ar/39Ar geochronology study of Mesozoic coast-parallel dykes exposed in southwest Greenland. Our new and previously published geochronological data indicate that the southwest Greenland dykes were emplaced during a prolonged period centered at 147.6 ± 3.4 Ma. The paleomagnetic pole calculated from 40 site-mean paleomagnetic directions falls between the reference poles that were originally used to define the monster shift, suggesting much smaller amount of polar motion during the Late Jurassic (Fig. 6.4b). The pole position is consistent with the apparent polar wander paths (APWPs) for Europe, indicating the robustness of this result, which effectively eliminates the mismatch between the APWPs for Laurentia and Europe (Fig. 6.4c). Collectively, our new high-quality paleomagnetic pole and an updated global APWP do not support the fast Jurassic polar shift, but indicate steady polar motion with moderate rates of about 0.7°/Myr. Our critical reassessment of the monster polar shift indicates that it is likely an artifact of paleomagnetic and geochronological data that were previously used to argue for its existence. We conclude that the hypothesis of the Late Jurassic polar monster shift can be rejected.

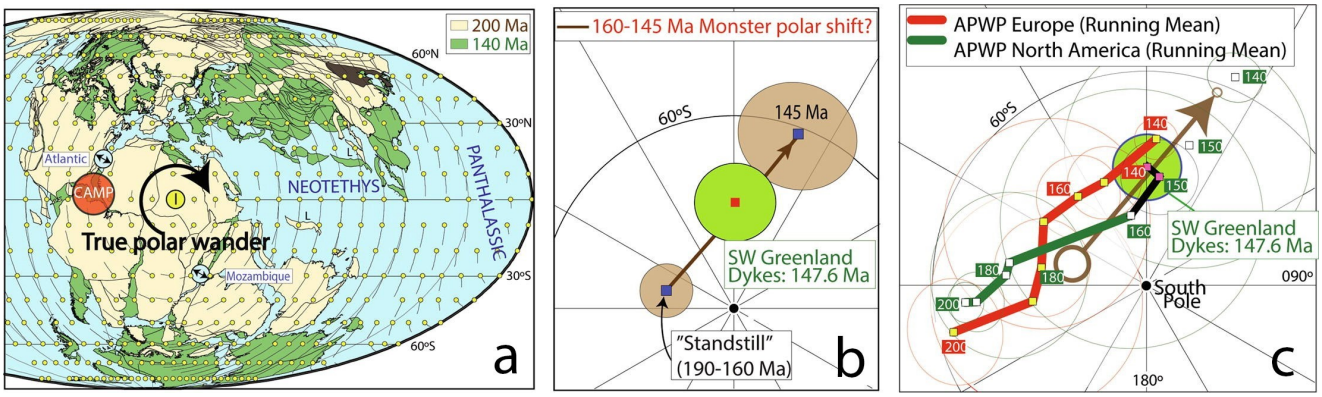



*Fig. 6.4. (a) Paleogeographic reconstructions between 200 Ma (pale yellow shading) and 140 Ma (green shading). The difference between the two maps is to a large extent attributed to a phase of clockwise TPW (Torsvik et al., 2012). TPW motions are shown as black lines connected to yellow dots with the sense of motion from the yellow dot toward the tail. (b) The reference paleomagnetic poles (blue squares with tan 95% uncertainty regions) defining fast Jurassic monster shift (~160-145 Ma, brown arrow) compared to the new pole from Greenland dykes (red square with green 95% uncertainty region). (c) APWPs for Europe and North America (Torsvik et al., 2012) compared to the Greenland pole. All poles in panels (b) and (c) are in in North American coordinates.*

***Paleomagnetic field in the Devonian.*** The Devonian period (~360-420 Ma) has long been a problematic time interval for paleomagnetic studies. Paleomagnetic data from the Devonian are generally difficult to interpret due to pervasive magnetic overprints and poor preservation of the primary magnetic signal observed in both sedimentary and igneous rocks. As a result, Devonian APWPs and paleogeographic reconstructions based on them have large uncertainties. The geomagnetic polarity in the Devonian is also poorly constrained. The available paleointensity estimates suggest that the field was much weaker than the modern field, which may have been accompanied by many polarity reversals. A study led by Annique van der Boon presented new paleomagnetic data from three middle to upper Devonian sedimentary sections from Poland (~360 Ma), Germany and Canada (~390 Ma). Although no significant heating and remineralization affected these rocks, all studied samples showed secondary magnetic overprints, which made it challenging to interpret the data, and in many cases it was not even possible to retrieve the primary magnetic directions.

A comparison with published magnetostratigraphic studies from the Devonian, a detailed review of the polarity patterns presented in different versions of the Geomagnetic Polarity Time Scale and the available estimates for the strength of the magnetic field suggest that the field during the Devonian might have been weak and in part non-dipolar, so that obtaining reliable primary paleomagnetic data from Devonian rocks can be extremely challenging. Independent evidence from malformed spores around the Devonian-Carboniferous boundary (~360 Ma) suggests that the terrestrial extinction connected to the Hangenberg event was caused by increased UV-B radiation, supporting the weak field hypothesis. A plausible reason for a weak and possibly non-dipolar field during the Devonian could have been true polar wander acting to maximize core-mantle heat flow in the equatorial region during this time interval. A paper presenting a detailed review of paleomagnetism in the Devonian and exploring the possible reasons for the scarcity of high-quality paleomagnetic data for this time interval has been submitted to Earth Science Reviews (van der Boon et al., 2021a).

***An optimization method for paleomagnetic Euler pole analysis.*** While paleomagnetic data directly record the paleolatitude and paleo-meridian orientation of ancient continents, they do not provide paleolongitude constrains, which remains the greatest uncertainty in pre-Cretaceous paleogeographic reconstructions. The Paleomagnetic Euler Pole (PEP) method (Fig. 6.5) presents a means to estimate longitudinal motions in the spin-axis (i.e. paleomagnetic) reference frame. The analysis assumes that if a given plate rotate for some interval of time about a stable Euler Pole (EP), then a set of perfectly resolved paleomagnetic poles from that plate, spanning that interval, will trace out an arc about the EP. Following that rationale, the PEP method seeks to fit a sequence of paleomagnetic poles from a given plate to a series of arcs that express the time-dependent motion of the plate about sequential EPs. However, the PEP technique has seen limited application and has struggled with issues of subjectivity. Researcher Leandro Gallo and his co-workers have developed a novel unsupervised searching algorithm for the PEP analysis and presented an optimization approach to PEP analysis that addresses these deficiencies. Based on unsupervised learning techniques, the method uses the Dijkstra's algorithm on a sequence of paleomagnetic poles for finding the shortest path between two given nodes. The shortest path solves an optimization problem and represents the sequence of Euler vectors that keep the misfit small, while connecting the two ends by optimizing the goodness of fit. A multi-platform software implementation of this method, which can be run through a web browser, has been made available to the community (https://mybinder.org/v2/gh/LenGallo/PEPy/HEAD). A manuscript describing this novel methodology (Gallo et al., 2021) has been submitted for publication to Computers and Geosciences and is available as a preprint at EarthArXiv (https://doi.org/10.31223/X58900).

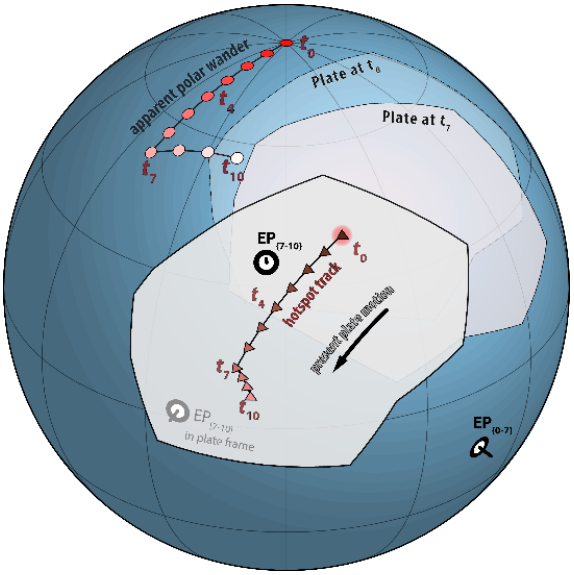



*Figure 6.5. Cartoon illustrating the relationship between an apparent polar wander path (APWP; red circles), a hotspot track (red triangles) and the Euler poles (EP; black poles) describing the kinematics of the host plate (grey polygon with static boundaries for simplicity), which gave rise to them over some interval of time $t_0 - t_{10}$. A sequence of paleomagnetic poles and/or hotspot volcanoes may be inverted to solve for the location of the corresponding EP .*

**Interdisciplinary research and collaboration**

In addition to the studies described above, the members of the Earth Laboratory team participated in a number of collaborative projects during 2021, working together with other CEED teams (Dynamic Earth, Earth Modelling, Earth Crises, and Deep Earth) and within broader national and international collaborations. Researcher Mathew Domeier contributed to several projects, including (1) an interdisciplinary investigation of the evolution the Irati-Whitehill Sea, an epicontinental sea that covered a vast area of southern Gondwana in Permian time (Bastos et al., 2021), (2) development of a model for spatiotemporal variations in Earth's surface heat loss over the past 400 Ma (Karlsen et al., 2021), (3) a study that presented new paleogeographic and degassing parameters for long-term carbon cycle models (Marcilly et al., 2021), and (4) a paleomagnetic project that provided new constraints on the Cambrian (~500 Ma) position and orientation of proto-South America within the Gondwana supercontinent (Temporim et al., 2021). Domeier also co-authored two book chapters that presented reviews of Phanerozoic paleogeography and true polar wander (Torsvik et al., 2021a) and linkages between the deep Earth and the atmosphere, most importantly, those related to the eruption of large igneous provinces (Torsvik et al., 2021b). Researcher Annique van der Boon was actively involved in producing a new, quality-assessed compilation of global data on the intensity of the Earth's magnetic field (PINT database) (Bono et al., 2022), led a study on a possible link between the Middle Eocene Climatic Optimum (~45 Ma) and Neotethys continental arc volcanic activity (van der Boon et al., 2021b), and was a key participant in the "Magnetic to the Core" project, which explored ways of communicating paleomagnetism to the general public through hands-on experiments (van der Boon et al., 2021c). Researcher Evgeniy Kulakov collaborated with his colleagues from NGU on a field and geochronology study of the Rogaland Anorthosite Province and the spatially associated Bjerkreim–Sokndal layered intrusion in the Sveconorwegian Orogen. Researcher Jean-Baptiste Koehl and his co-authors published three papers presenting field and geophysical studies on the tectonic history and deformation in Svalbard (Koehl, 2021; Koehl et al., 2021, 2022).

**Field work**

In 2021, the Earth Laboratory group organized three field work trips: one trip to the Egersund area in western Norway to collect samples of Ediacaran dikes (~615 Ma) for paleomagnetic and paleointensity studies, and two trips to the Pyramiden area on Svalbard to collect Middle-Late Devonian sedimentary rocks for both paleomagnetism and $CO_2$ proxy estimates (Fig. 6.6). The collected samples are currently being processed in the lab.

**National Geomagnetic Laboratory**

The Earth Laboratory team runs and manages a Norwegian national geomagnetic laboratory (the Ivar Giæver Geomagnetic Laboratory, www.iggl.no). Similarly to 2020, the laboratory operated in a reduced capacity this year due to coronavirus restrictions that limited the number of visiting researches, limited technical support and related issues with the instrument maintenance (ca. 50% workload compared to 2019). Nonetheless, several research projects were able to use the infrastructure. A summary of these projects is presented in Table 6.1.

*Table 6.1. Summary of research projects that used the geomagnetic laboratory in 2021 (CEED members in **bold**).*

| |
|---|
| *Paleomagnetism of the Triassic Nicola Group, Quesnellia terrane (western Canada) and paleogeographic implications (**Mathew Domeier**, Stephen Johnston, University of Alberta, Canada, and Mitch Mihalnyuk, British Columbia Geological Survey, Canada).* |
| *Paleomagnetic and rock magnetic measurements of Middle Devonian sediments from Mimerdalen, Svalbard (**Annique van der Boon, Mathew Domeier**)* |
| *Paleomagnetism and geochronology of the Proterozoic mafic dikes in southwestern Greenland (**Evgeniy Kulakov**, Lars Eivind Augland, Department of Geosciences, UiO, and Trond Slagstad, NGU)* |
| *Self-reversal of thermal remanent magnetization in Greenland dikes: Causes and implications (**Evgeniy Kulakov**)* |
| *Absolute paleointensity recorded by ~1.7 Ga dykes from southwestern Greenland (**Evgeniy Kulakov**)* |
| *Ediacaran field behavior and tectonics from the Avalonia zone of eastern Newfoundland, Canada (Boris Robert, GFZ Potsdam, Germany, **Mathew Domeier**)* |
| *Ediacaran paleointensity study of Egersund dikes, Norway (**Evgeniy Kulakov, Mathew Domeier, Assia Meijer**)* |
| *The Neoproterozoic geomagnetic field: New insights from a high-resolution study in South China (Justin Tonti-Filippini, LMU, Germany)* |
| *Magnetic properties of high-entropy ferromagnetic alloys (Anthoula Poulina, Aleksander Amble Larsen, Department of Physics, UiO)* |
| *Magnetic properties of biologically produced palladium nanoparticles (Ana Lucia Campana Perilla, Pavlo Mikheenko, Department of Physics, UiO)* |

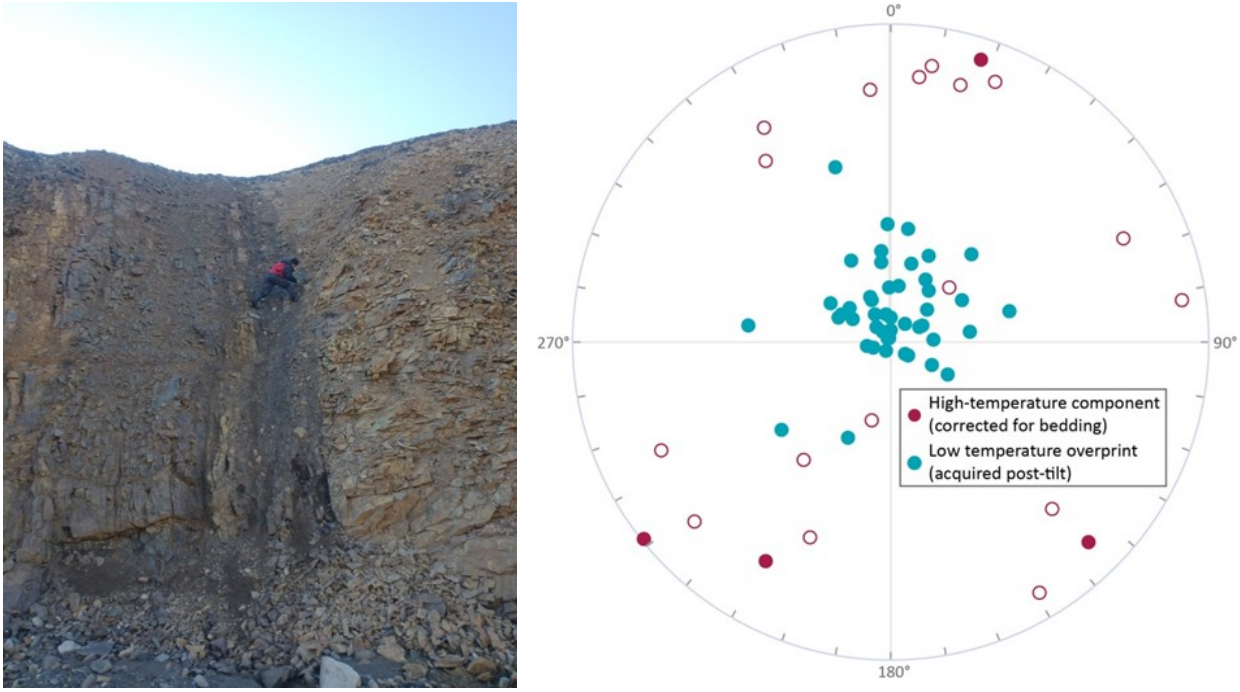



*Fig. 6.6. Left: Mathew Domeier sampling Middle Devonian sediments near Pyramiden, Svalbard. Right: Equal area plot of preliminary data of the Middle Devonian (Svalbard). High-temperature components in purple (presumably Middle Devonian magnetizations) show an extreme spread in data, typical for Ediacaran data sets. Low-temperature components in green cluster around a recent magnetic field direction. Closed (open) circles denote positive (negative) magnetic inclinations.*

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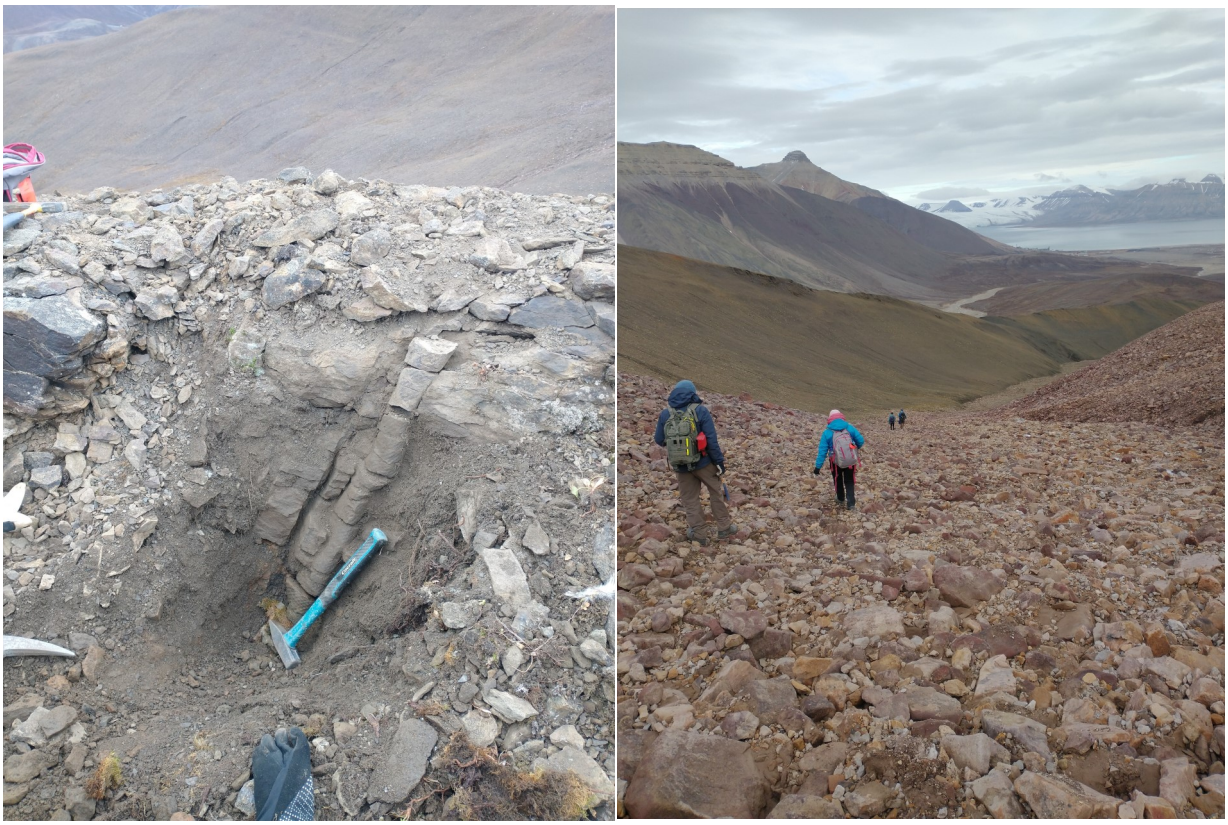
**Photos from the field:**



Drilling Ediacaran dikes around Egersund



Collecting hand-samples from Devonian sedimentary rocks outside Pyramiden, Svalbard



Left: Devonian forest in Svalbard, Right: sampling team walking around Mimerdalen (Svalbard) with Devonian and Carboniferous sedimentary rocks in the background.

## Young CEED 2021: *Frontiers in Quantitative Paleogeography*

In 2018, CEED experimented with a new initiative to engage and promote research driven by early career researchers: a 'Young CEED Workshop'. The concept was to provide support for a team of young researchers to physically gather for a week in order to discuss and brainstorm new ways to tackle important outstanding problems in Earth science. The first workshop, which took place in November 2018, enabled the formation of an interdisciplinary team of 14 people who came together to tackle the problem of subduction zone initiation (SZI). This first workshop was highly successful, and led to several conference presentations, a publication in *Nature Commmunications* (Crameri et al. 2020) and the construction of an online database (szidatabase.org) that has already had a clear impact on the wider Earth science community.

Following from the success of Young CEED 2018, CEED supported a subsequent Young CEED Workshop in November 2021 (originally planned for November 2020, but postponed as a consequence of the restrictions imposed by the Covid-19 pandemic), which was dedicated to the exploration and advancement of new frontiers in quantitative paleogeography. This focus was motivated by several outstanding problems in the construction of state-of-the-art paleogeographic models in 'deep' geologic time (before about 200 million years ago). A first problem is that deep-time paleogeographic models are underpinned by paleomagnetic data, but standard approaches in paleomagnetic analysis omit many known (and important) uncertainties—thereby undermining the quantification of error in paleogeographic models. A second problem is that the estimation of paleolongitude in deep time remains difficult and contested, and has resulted in a dizzying array of contrasting paleogeographic models in the recent literature. A third problem is that although many paleogeographic models are constrained by paleomagnetic and geologic observations, they largely ignore crucial insights provided by observational and theoretical geodynamics (or they use such insights inconsistently).

With the aim to devise new approaches to overcome these important problems through transdisciplinary engagement and open discussion, CEED-based workshop organizers Mathew Domeier, Leandro Gallo, Annique van der Boon, Grace Shephard and Ágnes Király gathered together 10 additional young scientists (together spanning 9 institutions and 10 nationalities) with complimentary expertise in paleogeography, paleomagnetism, geodynamics, geology, statistics and data science. Owing to continued Covid-19 restrictions, 5 participants were not able to physically attend the workshop held in Drøbak, Norway, and so the workshop was conducted in a hybrid (physical-digital) way. The workshop opened with several days of presentations and open discussion, followed by group work toward concrete objectives identified during the first day's discussions.

A number of exciting insights and strategies emerged from the workshop, which are actively being furthered by continued collaboration amongst the Young CEED '21 team members. Ongoing work includes: 1) the development of methods to execute paleomagnetic analysis at the site-level (rather than the study-level), enabling trans-hierarchical uncertainty propagation and a much richer exploration of the information available in paleomagnetic datasets; 2) the expansion and application of emerging paleomagnetic Euler pole (PEP) analysis frameworks, which hold the promise of enabling quantitative paleolongitude estimates from existing paleomagnetic datasets, and 3) the formulation of statistical inferences on plate motions derived from Earth-like geodynamic models (which self-generate plate tectonic behavior) to be integrated into

paleogeographic model construction routines. To facilitate these new methodological advancements, the Young CEED ’21 Workshop also began construction on a database of site-level paleomagnetic results from North America for the last 60 million years. This database will serve to provide an initial case study for proof-of-concept demonstrations, but is designed to be extensible so that subsequent efforts can broaden its scope in both time and space.

Although only a few months have passed since the kick-off of the workshop, some preliminary results of this developing collaborative effort will be presented at the general assembly of the European Geosciences Union (EGU) this spring (Domeier et al. 2022). Stay tuned for further updates and presentations of this rapidly evolving collective work!

*10 of the 15 international young scientists who participated in the Young CEED 2021 Workshop (not*

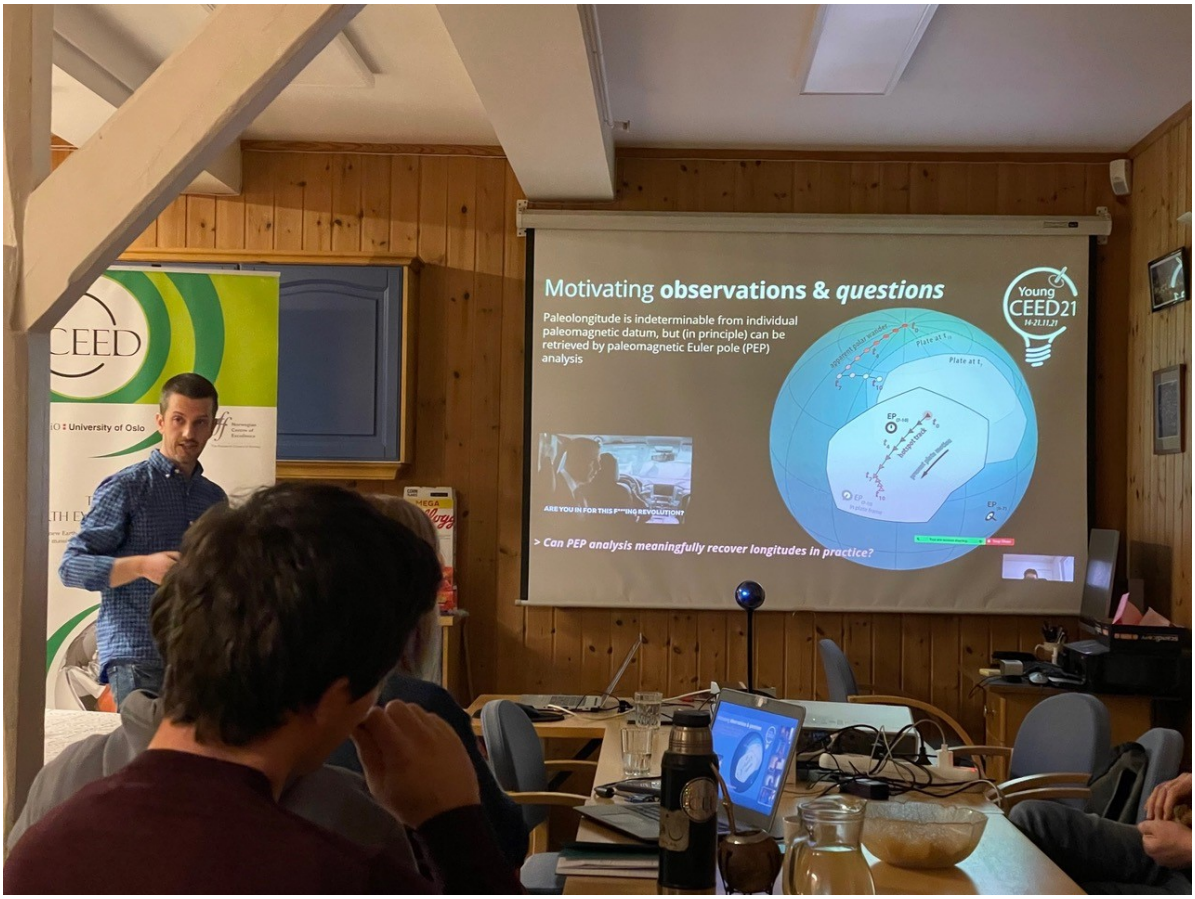



*shown are digital attendees Athena Eyster, Derya Gürer, Nicholas Swanson-Hysell, Lei Wu and Yiming Zhang).*

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*YoungCEED21 workshop in Drøbak featuring leader Mat Domeier. Photo by: Grace Shephard.*



*“Tollboden”, the venue for YoungCEED21. Photo by: Grace Shephard.*

# 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 her PhD or postdoctoral work has made a significant contribution to research in Geosciences.*

*The committee members for 2021 were Professor **Anny Cazenave**, LEGOS-CNES Toulouse, France and Professor **Claudio Faccenna,** Università Roma TRE and University of Texas at Austin.*

***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:*** **Callegaro, S., Svensen, H. H., Neumann, E. R.**, Polozov, A. G., Jerram, D. A., Deegan, F. M., ... & Melnikov, N. V. (2021). Geochemistry of deep Tunguska Basin sills, Siberian Traps: correlations and potential implications for the end-Permian environmental crisis. Contributions to Mineralogy and Petrology, 176(7), 1-30.

For 2021, the award had one winner: **Louise Mary Vick** from the Arctic University of Norway (UiT). She was recognised at a conference at The Centre for Earth Evolution and Dynamics (CEED), University of Oslo, on 2.12.2021.

Louise Mary Vick was recognized for *having received national and international recognition within the field of geohazards and engineering geology.* The international committee for the Else-Ragnhild Neumann Award for Women in Geosciences concluded that Louise Mary Vick deserves recognition due to her research within geosciences, more specific in the research field geohazards and engineering geology. The committee found the nomination letter very strong and convincing.

The winner was nominated by **Matthias Forwick,** head of department at the institute for geosciences UiT .

ELSE-RAGNHILD
NEUMANN
AWARD
FOR WOMEN IN GEOSCIENCES

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

**Louise Mary Vick** took her PhD. in Earth Sciences in Engineering Geology in 2015, at the University of Canterbury, New Zealand. Her Ph.D. focused on modelling and hazard analysis of the earthquake-triggered rockfalls on the Port Hills in Christchurch, following the Canterbury earthquake sequence. Vick later worked an as Engineering Geologist and Environmental Scientist in private companies, and came to UiT The Arctic University of Norway in 2017. Here she worked as a Postdoctoral Fellow, Researcher and now from June 2020 as Associate Professor.



*Louise Mary Vick, the winner of the 2021 Else-Ragnhild Neumann Award.*

*Photo by: Kai Mortensen.*

**About Louise Mary Vick**

"Her work is important, and based on different type of observations including remote sensing and modelling. It has clear societal implications, and the winner spends a significant part of her time to serve the community.

The prize winner has received national and international recognition within the field of geohazards and engineering geology. Her work is innovative and highly relevant to advance the understanding of the behavior of unstable mountain slopes in a changing climate."

**Selected, recent publications:**


Rouyet, L., Lilleøren, K. S., Böhme, M., **Vick, L. M.,** Delaloye, R., Etzelmüller, B., ... & Blikra, L. H. (2021). Regional morpho-kinematic inventory of slope movements in Northern Norway. *Frontiers in Earth Science*, 9.

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# Outreach highlights

Another academic year has passed with the COVID pandemic continuing to disrupt personal and professional lives. However, CEED's outreach efforts still persevered, mostly via digital formats but also some in-person contributions. Outreach initiatives by CEED members, and the scientific community at-large, are important, not only because exciting, new research is continually being generated, often with public-funding, but also because more and more of the wider public has turned to digital means to source news and updates. This was reflected in the number of subscribers/followers to our social media channels which nearly doubled across all platforms in 2021. More broadly, at a time of misinformation and societal unrest, promoting the scientific method, peer-reviewed results as well as highlighting diverse scientific voices is crucial. As we enter the final year of CEED maintaining our outreach is still as relevant as when we first began. CEED had a strong online presence across internal and internal websites, and social media, and as in previous year's there has been a mix of both individual and group-driven outreach initiatives.

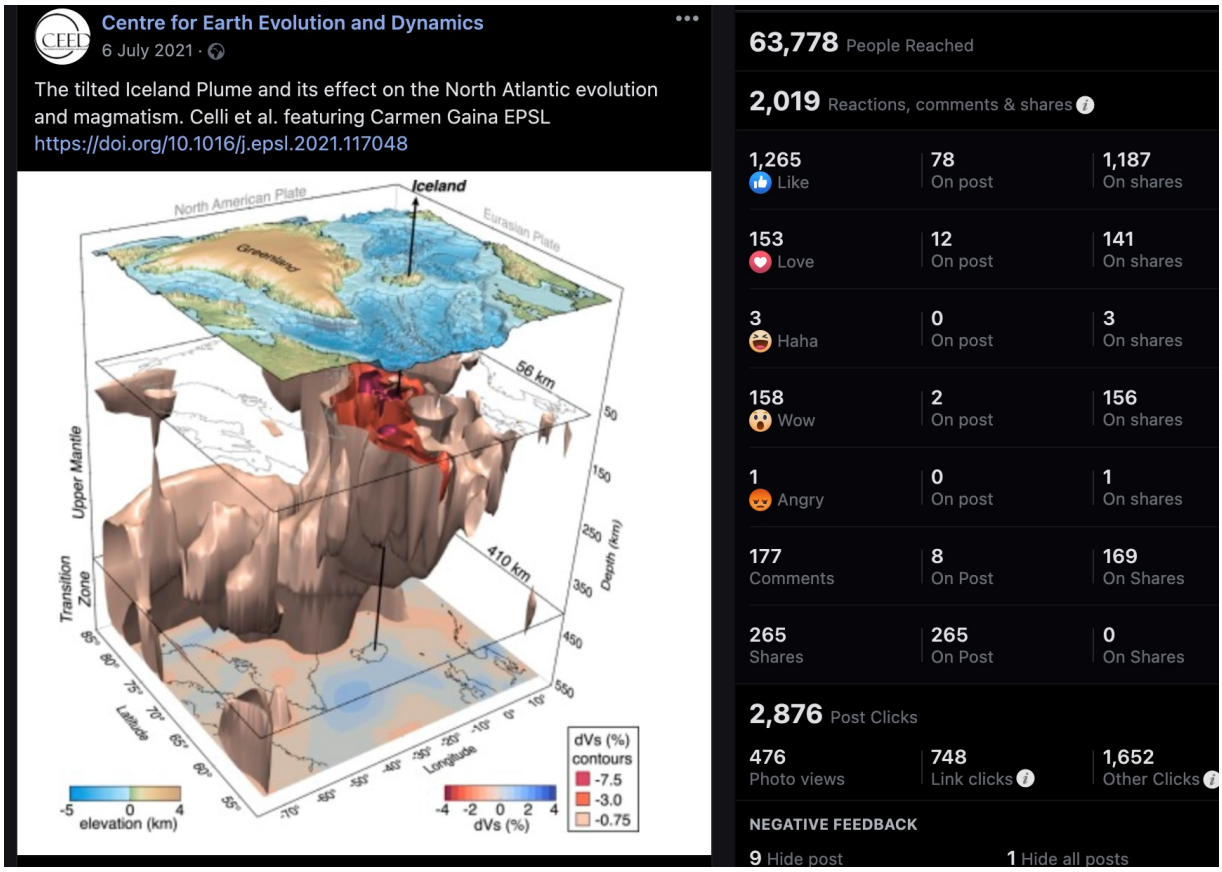



*Image 1: A screenshot of some of the statistics behind the CEED facebook account. This "viral" image was by far the most widely seen post with over 63,000 people reached and 2,000 interactions (usually posts are sitting around 10 interactions). Despite its overwhelming number of likes and "wow" reactions, true to social media platforms, there was at least one "angry" reaction.*

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 including Titan.uio.no. In the Norwegian media, avenues include NRK (radio, TV and online), TV2, forskning.no and geoforskning.no . We hope to make the final year of CEED a successful one for outreach; so please follow and interact with our accounts for our final 12 months!

**Selected highlights of outreach events from 2021 include:**

- A figure (Image 1) from the paper Celli et al. 2020 (EPSL) showing the Iceland plume from a seismic tomography model, was by far the most interacted post across CEED's social media domains and highlighted the power of images.
    - Sighting of the meteor on June 25th 2021 and related coverage lead mostly by Agata Krzesińska was a highlight in Norwegian media. There were even several public field searches in Finnemarka for the meteorite along with the Red Cross (Image 2).
    - Recent IODP Drilling expedition 396 to the mid Norwegian margin (Image 3) including Morgan Jones and Sverre Planke included near daily coverage in geoforskning.no by Ronny Setså
    - Krister Karlsen's 2021 GRL paper on Earth's heat loss featured across a number of large media outlets and was highly interacted with by the public.
    - Henrik Svensen gave numerous talks about the nature and history of the Oslo region throughout the year.
    - Razvan Caracas opened an exhibition "Moon Impact - a geological story related" to his IMPACT ERC project and has so far been seen in Romania and Bulgaria.
    - A webinar on the Mount Fagradalsfjall volcanic eruption - AGU reported it was one of the largest attended webinars of its kind (over 300 attendees) and it has since been watched on YouTube 1500 times. Involved Morgan Jones, Grace Shephard, Carmen Gaina, and members of the NOR-R-AM project.
    - A new series of educational postcards from volcanoes has been written by Dougal Jerram. The set of twelve postcards, which can be sent out to children weekly, follow a journey by a young child and his dog exploring the world of volcanoes.
    - "Scientific Communication" one-week course run with the DEEP School for the first time, involving Grace Shephard, Henrik Svensen, Fabio Crameri, Karen Mair (GEO) and a number of international guests.
    - You can find many more events listed in "In the media and Outreach" section .



*Image 2: Searching for the meteorite that fell near Lier, south of Oslo, on 25th June. Photos by Alexander Minakov.*




*Image 3: From the IODP Expedition 396 to the Norwegian margin co-led by Sverre Plank (here celebrating his birthday onboard). Images from various posts featured in geoforskning.no .*

**Some statistics from social media and outreach in 2021:**

The CEED Blog – 8 blog articles published

Facebook - 1231 likes/followers, 110 individual posts

Twitter - 1401 followers, 100 original tweets

Instagram – 191 followers, 16 posts

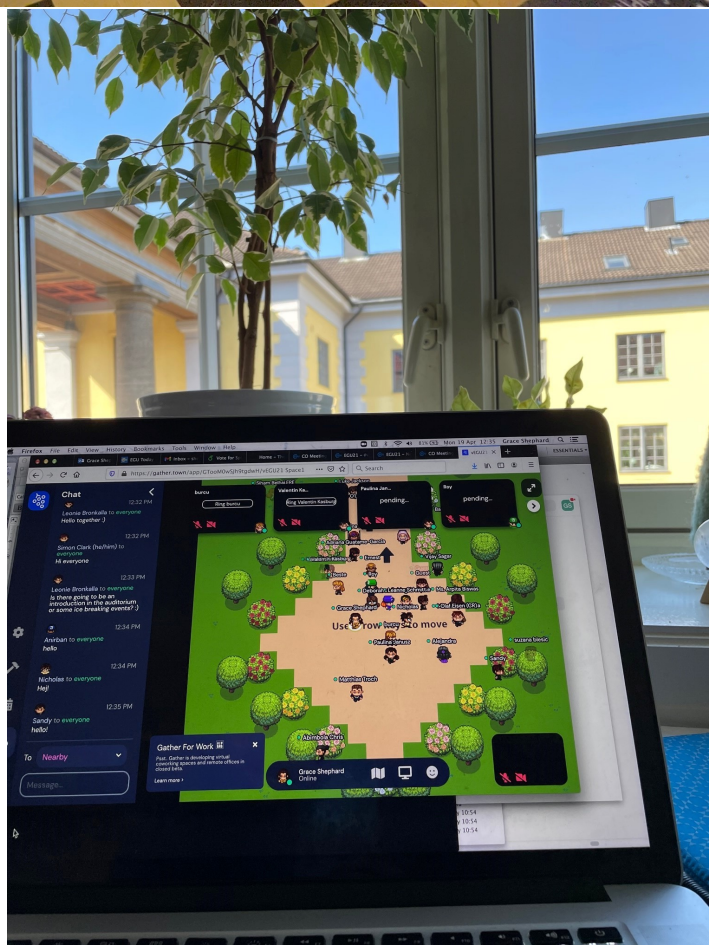
YouTube – 124 subscribers, 2 videos

**CEED Outreach team members:**

Grace Shephard (Coordinator), Trine-Lise Knudsen Gørbitz (CEED webpage), Gunn Kristin Tjøfløt (GEO), Valentina Magni (CEED Instagram).



*Svalbard early career workshop, photo by: Grace Shephard.*




*Joining the EGU21 conference networking from home , photo by: Grace Shephard.*

***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* ***Sara A. Nettum*** *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-DEEP9506 Mineralogy of planetary surfaces and biosignatures (10 – 14.05)**

Course responsible: Agata Magdalena Krzesinska and Benjamin Bultel from CEED.

This Special Topics course series explores state-of-the-art principles, methods, and techniques within selected topics in DEEP research school themes. During this course we introduced the basics of how we can study mineralogy of extraterrestrial bodies and how to retrieve information on biosignatures from this. This was a fully digital course by Zoom.

23 participants: 4 master students, 2 postdoc, 17 PhD candidates, 2 of the participants were from CEED

**Deformation processes - An intensive course offered at the University of Tromsø (UiT), (1 – 5.03)**

Course responsible: Holger Stunitz.

An intensive DEEP course (5 ECTS) to learn about how Plate Tectonics operate by localizing deformation at plate boundaries on all scales. In order to understand and model plate tectonics, we need to understand the fundamental processes of deformation operating in the Earth. The objective of this course was to teach these processes and how they are manifested in rocks.

The course was attended by 4 PhD candidates.

**GEO-DEEP9200 Deep Earth and Planetary Mineralogy and Dynamics (12 – 17.04 and 3—14.05)**

Course responsible: Reidar Trønnes.

The course treats Earth and planetary differentiation to form core, mantle and crust and gives insights into the seismic structure, heat production, heat flow and convective dynamics of the Earth. The melting and subsolidus phase relations and mineral physics of silicate rocks and Fe-dominated alloys are central to our understanding of Earth and planetary dynamics and evolution. The identification of primordial, melt-depleted and deeply recycled crustal material by radiogenic isotope systematics will also be reviewed.

April 12-17: 14 participants, 1 of them from CEED.

May 3-14: 62 participants, 3 of them from CEED.

**GEO-DEEP9505 Heat Transfer between Rock Units (6 – 10.09)**

Course responsible: Holger Stunitz (UiT).

This Special Topics course series explores state-of-the-art principles, methods, and techniques within selected topics in DEEP research school themes. This course focused on the physics principle of heat transfer in solid materials and the consequences of the processes on the tectonic development of crustal and mantle rocks.

The course was attended by 5 participants, 1 of them was from CEED.

**GEO-DEEP 9501 Earth Magnetism and Paleogeography (4 – 8.10)**

Course responsible: Pavel V. Doubrovine assisted by Evgeniy V. Kulakov, Mathew Domeier. Featured lecture: Prof. Trond H. Torsvik and Petter Silkoset (lab instructor).

The course provides a comprehensive overview of the Earth magnetism at the present time (geomagnetism) and in the geologic past (paleomagnetism). The main focus of the course is applications of paleomagnetism to paleogeographic reconstructions and motions of lithospheric plates. It also to discuss recent advances in our understanding of the evolution of geomagnetic field in the context of the Earth dynamics at the planetary scale.

5 Participants: 2 master students and 3 Phd candidates. 2 of the participants were from CEED.

**GEO-DEEP9300 Lithosphere and Asthenosphere: Composition and Evolution (1 – 5.11)**

Course responsible: Profs. Valerie Maupin and Clint Conrad assisted by Florence Dela Cruz Ramirez, Agnes Kiraly, and Maaike F. Weerdesteijn.

This course deals with the composition and evolution of the crust, lithospheric mantle and asthenosphere. Seismic imaging techniques and interpretation of tomographic images in terms of composition and physical properties will be coupled with recent results in petrology, geochemistry and geodynamical modelling to review recent advances in our understanding of the evolution and present state of the continental as well as oceanic lithosphere.

10 PhD candidates attended the course and 3 of them were from CEED.

## DEEP generic and scientific courses

### Writing with results

DEEP and Mathew Stiller-Reeve offered an online course on "writing with results", each Tuesday for 6 weeks from the 2 February 2021.

During the course, PhD candidates had the opportunity to bring a piece of their own writing and work on it intensely throughout 6 weeks. The point of this course 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. The foundational lectures during week 1 covered issues like cutting clutter, using active voice, and planning structure. During the rest of the course, we used a recurring process to develop the different sections. This included discussions, brainstorming, planning, writing, and editing. We also developed forums for peer-to-peer reflection and collaboration.

The course was attended by 11 PhD candidates. 1 of the participants was from CEED.

### Intensive course in Science Illustration (22 – 26.03)

DEEP and Pina Kingman offered a short intensive course; 5 days with 19 participants. 5 of the participants were from CEED

This course introduced the theory and method of how to visually represent a 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 would be helpful throughout the whole career. This course was a fully digital course by Zoom.

### DEEP method courses: Introduction to MATLAB (25 – 28.10)

Course responsible: Valentina Magni assisted by Agnes Kiraly

This intense course for beginners aims at giving a basic knowledge of programming with MATLAB. The main goal is for the participants to become comfortable enough with MATLAB so that they will know its potential and they will be able to understand scripts, create their own, and continue learning and keep using it on their own.

8 participants: 2 master students and 6 PhD candidates. 1 of the participants was from CEED.

**Science Communication - knowing and reaching your audience ( 8 – 10.11)**

Course responsible: Grace Shephard assisted by Elodie Chabrol, Fabio Crameri, Hazel Gibson, Philip Heron, Sam Illingworth, Anne Hope Jahren, Karen Mair, Henrik Svensen, Eivind Torgersen, and Paul Voosen

This course is intended to provide an overview on why it is important to disseminate your scientific results and how it can be successfully achieved. It also highlights the diversity of channels and audiences by providing examples to: What is science communication? To whom are you trying to reach? And how can you go about this? For this course, we have an exciting line-up of science communicators, including scientists, journalists, authors, artists, poets, and social media coordinators. They share their personal and professional experiences in science communication, and provide tips for getting your own work out there. Our guest lecturers (also in-person or online) include those from the University of Oslo and internationally. The three half-day sessions will include a combination of lectures, discussions, group work and activities.




*Participants of the DEEP Science Communication Course led by Grace Shephard.*

## 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 |
|---|---|---|---|
| GEO1100 Jordens utvikling | Autumn 21 | 10 | **H.H. Svensen,** T. Berntsen, K.S. Lilleøren, A. Bryn |
| GEO2140 Solid Earth Geophysics | Spring 21 | 10 | **A.J. Breivik** |
| GEO2300 Physical processes in the geosciences | Autumn 21 | 10 | J. Lacasce, **V. Maupin**, T. Vikhamar, B. Schäfer, L. Keetz |
| GEO3000 Bachelor-oppgave i geologi | Spring 21 | 10 | K.S. Lilleøren, **H.H. Svensen** |
| GEO-AST3410/4410 Planetology | Autumn 21 | 10 | **S.C. Werner,** V. Hansteen |
| GEO4120 Near-Surface Geophysics | Autumn 21 | 10 | **A. Breivik/** K. Muller, A. Alexander, T. Eiken |
| GEO4218 Basin Formation and Development | Autumn 21 | 10 | **J. I. Faleide,** J. Jahren, F. Tsikalas, **S. Gac** |
| GEO4240 Seismic Interpretation | Spring 21 | 10 | **J.I. Faleide,** I.A. Anell, M. Hassaan |
| GEO4360 Field methods in hydrogeology | Spring 21 | 5 | A. Sundal, A. Popp, P. Aagard, H. Hellevang, L.-A. Erstad, C. Sena, **A.** |
| GEO4630/9630 Geodynamics | Autumn 21 | 10 | **C. Conrad** |
| GEO4840/9840 Tectonics | Spring 21 | 10 | L. Menegon, O. Galland, **G. Shephard,** H. J. Kjøll, **M. M. Domeier** |
| GEO-DEEP9200 Deep Earth and Planetary Mineralogy and Dynamics | Spring 21 | 5 | **R. Trønnes** |
| GEO-DEEP9300 Litosphere and Asthenosphere: Composition and Evolution | Spring 21 | 5 | **V. Maupin, C. Conrad / F. Ramirez, A. Kiraly, M. Weerdesteijn** |

## Table 1 cont.
## Teaching by CEED staff at UiO

| | | | |
|---|---|---|---|
| GEO-DEEP9501 Special Topics on Dynamics and Evolution of the Earth and Planets: Earth Magneism and Pale- | Autumn 21 | 5 | **P. Dubrovine, E. Kulakov, M. Domeier. T. H. Torsvik, P. Silkoset** |
| GEO-DEEP9506 Special Topcs on Dynamics and Evolution of the Earth and Planets: Mineralogy of Planetary Surfaces and Biosignatures | Spring 21 | 5 | **A. M. Krzesinska, B. Bultel** |



*Clouds above the ZEB building where CEED is located. Photo by: Grace Shephard.*

## Appendices



*Ella W. Stokke defended her PhD in January 2021.*

**PhD student projects** (**bold**: finished in 2021 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,** Makke | UiO |
| Beloša, Lea | The Role of Fracture Zones in Geodynamic Processes. * Co-supervisors: **A. Breivik, R. Trønnes, A. Mazzini,** and **S. Callegaro** | Main supervisor **C. Gaina,** see * | UiO |
| Harrington, Elise M. | Evaporites on Mars: An in-depth study of past water-rock interaction in Paleolakes | **S. Werner, A. Krzesinska, B. Bultel** | 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. Heim-** | 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 |
| Werdesteijn, Maaike | 3D glacial isostatic adjustment modeling for Greenland using magnetotelluric constraints on | **C. Conrad**, K. Selway | RCN |

**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. |

## Master student projects with one or more supervisors at CEED

**Bold:** finished in 2021

| Name | Topic | CEED-supervisor(s) |
|---|---|---|
| Bondevik, Lars Harstad | Extensional fault growth in high-resolution seismic data | S. Planke |
| **Christiansen, Vetle** | **Potential for analysis of microseismicity from a single-station record at the Åknes unstable rockslope** | V. Maupin |
| **Diaz Meza, Sergio A.** | **Detection and Location of Tremor signals: A case study from East Java, Indonesia** | V. Maupin |
| Eliassen, Gard L. | Structural evolution of the Sele High and Ling Depression | J. I. Faleide |
| Herrem, Amailie S. | Basin infill of the Realgrunnen Subgroup in the Tiddlybanken area: Influenced by salt halokinesis and local tectonism | J. I. Faleide |
| Labes, Aliénor M. P. | Morphologies and gas emissions from the Gobstan-Shamakhy mud volcano province, Azerbaijan | A. Mazzini |
| **Lisicia, Karlo** | **Petrological and Geochronological investigation of the Lundy granite and its role in the North Atlantic Igneous Province (NAIP)** | M. Jones |
| Lundahl, Jenny N. B. | Modelling of acoustic wave propagation in the ocean in the presence of a laterally varying ice layer | V. Maupin |
| Mamenova, Elena | Qualitative and quantitative study of known exoplanets and exoplanetary systems | S. Werner |
| **Meakins, Max W. J.** | **Understanding offshore flood basalt sequences using onshore analogues with application to permanent CO2 storage: Examples from the Faroe Islands** | S. Planke |
| **Meza Cala, Juan C.** | **Late Mesozoic-Cenozoic tectono-stratigraphic evolution of the Vesterålen margin, offshore Northern Norway** | J. I. Faleide |

**Master student projects cont.**

**Bold:** finished in 2021.

| Name | Topic | CEED-supervisor(s) |
|---|---|---|
| **Rosenqvist, Marija P.** | **CO2 sequestration in volcanic margin basalt sequences: A high-resolution reservoir model based on an analog study of the Faroe Islands Basalt Group** | S. Planke |
| **Viken, Thomas** | **Paleomagnetism of Silurian to Carboniferous magmatic rocks in the Orkney Islands** | M. Domeier, |
| Wang, Helene | Mapping heterogeneous water storage within the Earth's mantle | C. P. Conrad, M. Domeier, G. E. Shephard, V. Magni |



*Semester start 2021, photo by: Grace Shephard.*

## 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 | Collaboration | A. Mazzini |
| Brazil | Collaboration, joint publication, visiting student | H. Svensen, T.H. Heimdal |
| Canada | Research cooperation | 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 | Collaboration | C. Gaina |
| 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 | Lab work; Joint publication (s), collaboration | J. Dougal, R. Trønnes, T.H. Torsvik G. Shephard, V. Maupin, F. Crameri, C.E. Mohn, V. Magni |
| 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 8th CEED birthday symposium: Earth and Life Evolution (**C. Gaina, T-LK. Gørbitz)** |
| 1.11 | Research in Svalbard: APECS workshop 2021 **(G. Shephard,** S. Akhmetkaliyeva, Y. Zaika) |
| 14.11-21.11 | Yound CEED 2021 **(F. Crameri, V. Magni, M. Domeier, G. Shephard)** |
| 2.12 | Ups and Downs on Planet Earth **(T. H. Torsvik, T-L. K. Gørbitz),** |
| 8.12-10.12 | The Christmas Symposium new@CEED-21 **(T-L. K. Gørbitz)** |




*Illustration made for the 8th birthday symposeum by: Grace Shephard.*

| Work shops, lab work, research stay outside UiO | | |
|---|---|---|
| Nov 1st-5th | Workshop "Empirical and Ab Initio Thermodynamic Models of Minerals and Melts". Athens, Greece | Speaker: R. Caracas |
| Nov 7th-23rd | Labwork at University of Utrecht, Netherlands. | Organizer: M. Vickers |
| Nov 24th-26th | Workshop “Svalbard Rock Vault Paleoclimate Days”. UNIS, Longyearbyen, Svalbard. | Speaker: M. Vickers |
| Dec 11th-24th | Labwork at University of Utrecht, Netherlands. | Organizer: A. van der Boon |

| Field work in Europe | | |
|---|---|---|
| July | Field survey at Formiche Island, Tyrrhenian Sea, Italy. Geophysical and sampling survey at fluid emission sites | A. Mazzini |
| Sept-Oct | Training Through Research Cruise (TTR-20), Arctic Ocean. Glacimarine landforms & focused fluid discharge | A. Mazzini |
| Oct 5th-8th | Paleomagnetism fieldwork - Middle Devonian field strength | A. van der Boon |
| **Field work in Norway** | | |
| May-June | Sampling Oslo Rift sills. Petrology and geochemistry of the early magmatism in the Oslo Rift. | S. Callegaro, H. H. Svensen, T. H. Heimdal |
| Aug 9th-13th | Paleomagnetism reconaissance, Ringerike. | A. van der Boon |
| Sept 1st-13th | Magnetostratigraphy and CO2 proxy sampling. Pyramiden, Svalbard | A.H. Jahren, B. Hagopian, M. Domeier, J-B. Koehl, A. van der |

## Project funding in 2021

| UiO project # | Projects, project leader | Total funding in |
|---|---|---|
| 100050001 | 123272 Centre for Earth Evolution and Dynamics, Gaina (2013-23), | 29 548 |
| 100061001 | 246929/F20 Clim-VoTe, ISP-Geofag, Niscancioglu (2015-20) | 126 |
| 100083001 | 249040/F60 DEEP Research school, Werner (2016-23) | 2 954 |
| 100264001 | 276032 Platonics, Rolf (2018-22) | 2 382 |
| 100345001 | 288449 Magpie, Conrad (2019-23) | 2 529 |
| 100521001 | 301096 Maples, Callegaro (2020-23) | 2 538 |
| 100566001 | 309477 Nor-R-Am II, Gaina (Intpart 2020-23) | 220 |
| 100263001 | 275191/F20 VIKINGS: Volcanic Eruptions and their Impacts on Climate, Environment, and Viking Society in 500-1250 CE, Krueger. (2018-23) | 1 746 |
| 100660001 | 228107/E30 ARCEx, Faleide. (2018-21) | 3 150 |
| 100145101 | 314742/F20 Anima, Kiraly. (2021-25) | 644 |
| | 323531/F20 ERC-incentive, Domeier (2021) | 500 |
| 100688101 | 322421/E40 Strain Partitioning and Decoupling in Hornsund during the Ellesmerian and Eurekan orogenies, Koehl. (2021) | 95 |
| 102596101 | 328697/E40 Research in Svalbard: An APECS workshop, Shephard. (2021-22) | 200 |
| 102880101 | 326238/F20 Polaris, Shephard. (2021-25) | 13 |
| 102820101 | 325567/F20 HIDDEN, Caracas. (2021-25) | 315 |
| 103080101 | 325984/F20 DYPOLE, Faleide. (2021-25) | 20 |
| | 328597/F20 Bouldering, tilleggsfinansiering, Prieur. (2021-23) | 82 |
| 690591 | RO-NO-2019-0428 Baja Mare, Gaina (EØS, with Romania 2020-23) | 179 |
| 690604 | 456924 Poles together, Augland (EØS with Poland 2020-23) | 1 032 |
| 102545101 | 101025975 Tango, Gallo. (MSCA 2021-2023) | 426 |
| 102824101 | 101030364 Bouldering, Prieur. (MSCA 2021-2023) | 247 |
| | Developing and applying probabilistic inversion frameworks for the advancement of paleogeographic reconstruction, Torsvik/Domeier. (Peder Sather Grant 2021-2023) | 171 |
| 102822101 | 101024218 Icecap. Vickers. (MSCA 2021-2023) | 233 |
| UiO funding | Strategy grant (2013-22) in kkr | 2 000 |
| UiO funding | UiO contribution (Egenandel) | 11 945 |

** in kkr*

## Invited guest lectures at CEED

1. Early Triassic nutrient limitation and productivity crises in the Boreal realm—implications for recovery from the Latest Permian Extinction, Nov. 25, 2021 16:15-17:00, Zoom by Stephen E. Grasby from Geological Survey of Canada. Hosted by Henrik Svensen.
2. The symphony of tectonics, magmatism and geothermal reservoirs unveiled by multi-scale magnetotelluric imaging, Nov. 18, 2021 13:15-14:00, Aud. 3 by Friedemann Samrock from ETH Zurich. Hosted by Maik Neukirch.
3. The dynamics of volcanic conduits: views from the inside and outside, Nov. 11, 2021 13:15-14:00, Zoom, by Katharine Cashman from the University of Bristol. Hosted by Henrik Svensen.
4. Recovery of Earth after the Moon-forming giant impact, Nov. 4, 2021 13:15-14:00, Zoom, by Simon Lock from Caltech. Hosted by Razvan Caracas.
5. Satellite Measurements of Sea Level Change: What are they telling us about the future? Oct. 28, 2021 13:15-14:00, Aud. 3, by Steve Nerem from the University of Colorado. Hosted by Maaike Weerdesteijn/Clint Conrad.
6. Crustal earthquakes triggered by ice mass changes: where, when and why, Oct. 21, 2021 13:15-14:00, Zoom, by Rebekka Steffen from Geodesy at Lantmäteriet. Hosted by Maaike Weerdesteijn/Clint Conrad.
7. Geodynamic modelling applied to earthquake seismology, Oct. 14, 2021 10:15-11:15, Aud. 3, by Iris van Zelst from the German Aerospace Center. Hosted by Fabio Crameri.
8. Probing the subsurface with infrasound, Oct. 7, 2021, 13:15-14:00, Aud. 3, by Quentin Brissaud from Norsar. Hosted by Valerie Maupin.
9. The Ancient Climate of Mars: Was the Ambient Climate “Warm and Wet” or “Cold and Icy”? Sep. 30, 2021, 13:15-14:15, Aud. 3, by James Head from Brown University. Hosted by Stephanie Werner.
10. Computational Mineral Physics: Challenges and Opportunities, Sep. 23, 2021 15:15-16:15, Zoom, by Renata Wentzcowitch from the Columbia University in the City of New York. Hosted by Reidar Trønnes.
11. Treasure maps, sustainable development, and the billion-year stability of cratonic lithosphere, Sep. 9, 2021 13:15-14:15, Zoom, bu Mark Hoggard from ANU. Hosted by Valentina Magni.
12. Deep volatiles and deep melting: Experimental insights into the behavior of H2O & CO2 in the deep upper mantle, May 27, 2021, Zoom, by Davide Novella from the University of Padova. Hosted by Razvan Caracas.
13. Tectonics and surface processes interactions: insights from selected sedimentary basins and numerical models, May 20, 2021 14:15-15:00, Zoom, by Attila Balázs from ETH, Zurich. Hosted by Ágnes Király.
14. Potential impact of anthropic and natural erosion on tectonic deformation and seismicity during the seismic cycle, May 6, 2021 13:15-14:00, Zoom, by Philippe Steer from the University of Rennes. Hosted by Sebastien Gac.
15. On the effects of planetary rotation on the dynamics of a terrestrial magma ocean, Apr. 15, 2021 14:15-15:00, Zoom, by Christian Maas from the University of Münster. Hosted by Tobias Rolf.
16. Volcanic outgassing rates predicted by mantle convection simulations coupled with melting and gas speciation models: from early Earth to rocky exoplates, Apr. 8, 2021 14:15-15:00, Zoom, by Lena Noack from the Freie Universität Berlin. Hosted by Tobias Rolf.

17. Subduction initiation and the (ultra)high-pressure rock cycle, Mar. 25, 2021 14:15-15:00, Zoom, by Stefan Schmalholz from the University of Lausanne. Hosted by Sergei Medvedev.
18. Deformation of poly-mineralic materials and their effect on extensional processes at lithospheric scale-, Mar. 11, 2021 15:15-16:00, Zoom, by Suzon James from Texas State University. Hosted by Sebastien Gac.
19. Early Eocene magmatism following subduction initiation along the Bonin forearc: An up-to-date model, Mar. 4, 2021 13:15-14:00, Zoom, by Daniel Coulthard from Massey University, NZ. Hosted by Fabio Crameri.
20. From micro-continents to microplastics—recent R/V Falkor adventures in the Coral and Tasman Seas, Feb. 26, 2021 10:00-11:00, Zoom, by Derye Gürer from the University of Queensland. Hosted by Ágnes Király.
21. The Slab Puzzle of the Alpine-Mediterranean Region: Insights from Surface Wave Tomography, Feb. 25, 2021 13:15-14:00, Zoom, by Thomas Meier fro the University of Kiel. Hosted by Valerie Maupin.
22. Assessing the role of the Deccan Traps in the end-Cretaceous mass extinction, Feb. 11, 2021 15:15-16:00, Zoom, by Blair Schoene from Princeton University. Hosted by Morgan Jones.
23. Variable water input controls evolution of the Lesser Antiles Volcanic arc, Jan. 21, 2021 13:15-14:00, Zoom, by George Cooper from the University of Cardiff. Hosted by Valentina Magni.
24. Distribution & Mobility of Hydrogen in the Earth's Lithosphere, Jan. 14, 2021 13:15-14:00, Zoom, by Sylvie Demouchy from the University of Montpellier. Hosted by Razvan Caracas.

The Wilson lecture is an annual public lecture within the fields of Geosciences, arranged by CEED. The lecture for 2021 was unfortunately cancelled due to the Covid-19 pandemic.




*The sun setting on CEED, photo by: Grace Shephard.*

## Scientific publications *: young CEED scientist as first author: 17

1. Alaminia, Z., Tadayon, M., Griffith, E. M., Solé, J., & **Corfu, F.** (2021). Tectonic-controlled sediment-hosted fluorite-barite deposits of the central Alpine-Himalayan segment, Komsheche, NE Isfahan, Central Iran. Chemical Geology, 566, 120084.
2. Allan, N. L., Conejeros, S., Hart, J. N., & **Mohn, C. E.** (2021). Energy landscapes of perfect and defective solids: from structure prediction to ion conduction. Theoretical Chemistry Accounts, 140(11), 1-16.
3. **Austrheim, H., Corfu, F.,** & Renggli, C. J. (2021). From peridotite to fuchsite bearing quartzite via carbonation and weathering: with implications for the Pb budget of continental crust. Contributions to Mineralogy and Petrology, 176(11), 1-14.
4. Bagge, M., Klemann, V., **Steinberger, B.,** Latinović, M., & Thomas, M. (2021). Glacial-Isostatic Adjustment Models Using Geodynamically Constrained 3D Earth Structures. Geochemistry, Geophysics, Geosystems, 22(11), e2021GC009853.
5. Bandyopadhyay, D., Ghosh, B., Guilmette, C., Plunder, A., **Corfu, F.,** Advokaat, E. L., ... & van Hinsbergen, D. J. (2021). Geochemical and geochronological record of the Andaman Ophiolite, SE Asia: From back-arc to forearc during subduction polarity reversal?. Lithos, 380, 105853.
6. Barrett, R. S., Bellwald, B., Talling, P. J., Micallef, A., Gross, F., Berndt, C., ... & Krastel, S. (2021). Does retrogression always account for the large volume of submarine megaslides? Evidence to the contrary from the Tampen Slide, offshore Norway. Journal of Geophysical Research: Solid Earth, 126(2), e2020JB020655.
7. Bastos, L. P. H., Rodrigues, R., Pereira, E., Bergamaschi, S., Alferes, C. L. F., **Augland, L. E., ... & Svensen, H.** H. (2021). The birth and demise of the vast epicontinental Permian Irati-Whitehill sea: Evidence from organic geochemistry, geochronology, and paleogeography. Palaeogeography, Palaeoclimatology, Palaeoecology, 562, 110103.
8. Batchelor, C. L., Bellwald, B., **Planke, S.,** Ottesen, D., Henriksen, S., Myklebust, R., ... & Dowdeswell, J. A. (2021). Glacial, fluvial and contour-current-derived sedimentation along the northern North Sea margin through the Quaternary. Earth and Planetary Science Letters, 566, 116966.
9. Bellwald, B., **Planke, S.,** Polteau, S., Lebedeva-Ivanova, N., **Faleide, J. I.,** Morris, S. M., ... & Castelltort, S. (2021). Characterization of a glacial paleo-outburst flood using high-resolution 3-D seismic data: Bjørnelva River Valley, SW Barents Sea. Journal of Glaciology, 67(263), 404-420.
10. Berntell, E., Zhang, Q., Li, Q., Haywood, A. M., Tindall, J. C., Hunter, S. J., ... & Brady, E. C. (2021). Mid-Pliocene West African Monsoon rainfall as simulated in the PlioMIP2 ensemble. Climate of the Past, 17(4), 1777-1794.
11. Brasser, R., Mojzsis, S. J., Werner, S. C., & Abramov, O. (2021). A new estimate for the age of highly-siderophile element retention in the lunar mantle from late accretion. Icarus, 361, 114389.
12. Bredow, E., & Steinberger, B. (2021). Mantle Convection and Possible Mantle Plumes beneath Antarctica-Insights from Geodynamic Models and Implications for Topography. Geological Society, London, Memoirs, 56.
13. Bretones, A., Nisancioglu, K. H., Jensen, M. F., Brakstad, A., & Yang, S. (2022). Transient Increase in Arctic Deep-Water Formation and Ocean Circulation under Sea Ice Retreat. Journal of Climate, 35(1), 109-124.
14. Budzyń, B., Sláma, J., Corfu, F., Crowley, J., Schmitz, M., Williams, M. L., ... & Włodek, A. (2021). TS-Mnz–a new monazite age reference material for U-Th-Pb microanalysis. Chemical Geology, 572, 120195.
15. ***Callegaro, S., Svensen, H. H., Neumann, E. R.,** Polozov, A. G., Jerram, D. A., Deegan, F. M., ... & Melnikov, N. V. (2021). Geochemistry of deep Tunguska Basin sills, Siberian Traps: correlations and potential implications for the end-Permian environmental crisis. Contributions to Mineralogy and Petrology, 176(7), 1-30.
16. Capriolo, M., Marzoli, A., Aradi, L. E., Ackerson, M. R., Bartoli, O., **Callegaro, S.,** ... &

Szabó, C. (2021). Massive methane fluxing from magma–sediment interaction in the end-Triassic Central Atlantic Magmatic Province. Nature Communications 12, 5534 (https://doi.org/10.1038/s41467-021-25510-w).

17. **Caracas, R.,** Kobsch A, Solomatova NV, Li Z, Soubiran F, Hernandez JA, 2021. Analyzing Melts and Fluids from Ab Initio Molecular Dynamics Simulations with the UMD Package. J. Vis. Exp. 175, e61534
18. Celli, N. L., Lebedev, S., Schaeffer, A. J., & **Gaina, C. (**2021). The tilted Iceland Plume and its effect on the North Atlantic evolution and magmatism. Earth and Planetary Science Letters, 569, 117048.
19. Corseri, R., **Planke, S., Faleide, J. I.,** Senger, K., Gelius, L. J., & Johansen, S. E. (2021). Opportunistic magnetotelluric transects from CSEM surveys in the Barents Sea. Geophysical Journal International, 227(3), 1832-1845.
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*The "team" of CEED personnel that participated in the "Search for the Devonian"-field trip that took place on Svalbard, near Pyramiden, in September of 2021. From left: Mathew Domeier, William Hagopian, Anne Hope Jahren, Annique van der Boon and Jean-Baptiste Koehl.*

## Outreach activities

**TV; radio; newspapers and magazines**

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57. Svensen, Henrik Hovland. Et vindu til den dype tiden: Erfaringer fra et geologisk-kunstnerisk samarbeid. [Talk] Snø og isdekte alper: Kunst og vitenskap; 2021-11-03

58. Svensen, Henrik Hovland. Geological highlights in Oslo - Excursion. [Excursion] Geologisk vandring i Oslo sentrum; 2021-09-07

59. Svensen, Henrik Hovland. Geologien i Oslo området. [Talk] Medlemsforedrag, Røyken Rotary; 2021-04-26

60. Svensen, Henrik Hovland. Lærdommer fra fortidens masseutryddelser og klimaendringer. [Talk] Gjesteforedrag hos NFR, Miljø og klimaavdelingen; 2021-05-11

61. Svensen, Henrik Hovland. Om Kolsås og rombeporfyr. [Talk/Discussion] The Mountain Body project; 2021-08-21

62. Svensen, Henrik Hovland. Oslos geologiske historie med fokus på leire. [Talk and excursion] Foredrag ved Kunsthøgskolen i Oslo; 2021-09-28

63. Svensen, Henrik Hovland. Tanker om faget. [Talk] Samling for geografilærere i Sogn og fjordane; 2021-06-01

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*Physics building in Autumn, photo by: Grace Shephard*

## Abstracts (talks & posters at conferences)

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2. B. Heyn, and C.P. Conrad, “Plume-induced heat flux anomalies and the associated thinning of the continental lithosphere”, AGU Fall Meeting, New Orleans, USA, Dec. 2021.
3. B. Larsen, Rune; Sørensen, Bjørn Eske; Planke, Sverre; Tegner, Christian; Grant, Thomas. Untold Tales From the Deep Dark Crust: Understanding the Lower Crustal Architecture of a LIP Forming System. American Geophysical Union, Fall Meeting; 2021-12-11 - 2021-12-18 UiO NTNU
4. Bajard, Manon Julietto Andree; Ballo, Eirik Magnus Gottschalk; Høeg, Helge I.; Bakke, Jostein; Støren, Eivind N.; Loftsgarden, Kjetil; Iversen, Frode; Hagopian, William Martin; Jahren, Anne Hope; Svensen, Henrik Hovland; Krüger, Kirstin. Instability or adaptation of the pre-Viking society to the climate variability of the Late Antiquity?. Geological Winter Meeting 2021; 2021-01-06 - 2021-01-08 UiB UiO
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6. Baker, Don R.; Callegaro, Sara; Renne, Paul R; De Min, A.; Whitehouse, Martin J.; Marzoli, A. Don’t blame it on Fluorine: Low F concentrations in Deccan Traps magmas straddling the extinction interval estimated from in situ analyses on clinopyroxene. Goldschmidt Conference; 2021-07-04 - 2021-07-09 UiO
7. Ballo, Eirik Gottschalk; Bajard, Manon Juliette Andree; Bakke, Jostein; Støren, Eivind Wilhelm Nagel. Using CT scans to count varves in Lake Sagtjernet. Winter Conference 2021; 2021-01-06 - 2021-01-08 UiO UiB
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12. Boukaré CÉ, Badro J, Brodholt JP, 2021. Thermodynamics in the Fe-Si-O system up to 300 GPa. Goldschmidt Conf., 2c02-1720.
13. Brodholt JP, Wang W, Li Y, Walter MJ, 2021, Can core formation constrain the amount of water in the mantle? AGU Fall Meeting, MR24A-03.
14. Brotz, Petr; Hauber, Ernst; Conway, Susan; Luzzi, E.; Mazzini, Adriano; Noblet, A.; Jaroš, J.; Markonis, Y.. The Formation of the Kilometre-Sized Flows in Chryse Planitia (Mars). 52nd Lunar and Planetary Science Conference; 2021-03-15 - 2021-03-19 UiO
15. Brotz, Petr; Hauber, Ernst; Conway, Susan; Luzzi, E.; Mazzini, Adriano; Noblet, A.; Jaroš, J.; Markonis, Y.. The Formation of the Kilometre-Sized Flows in Chryse Planitia (Mars). EPSC2021-77; 2021-09-13 - 2021-09-24 UiO

16. Bultel B., Krzesińska A.M., Loizeau D., Lanz C., Poulet F., Austrheim H.O., Bjerga A., Harrington E., Viennet J.C., Dypvik H., Werner S.C., 2021. Leka Ophiolite Complex as analogy to the serpentinization-carbonation system on Mars. European Geosciences Union General Assembly: abstract EGU2021-12057.
17. Callegaro S., Svensen H.H., Neumann E.-R., Polozov A., Jerram D.A., Deegan F.M., Planke S. Geochemistry of low-Ti Siberian Traps sills from the Tunguska Basin bears evidence of magma-crust interaction. Goldschmidt Conference 2021 (Lyon, virtual).
18. Callegaro, Sara; Baker, Don R.; Marzoli, Andrea. Quantifying S in silicate melts from their crystal cargo: data and applications. NGF Vinterkonferansen 2021; 2021-01-06 - 2021-01-08 UiO
19. Callegaro, Sara; Svensen, Henrik Hovland; Jerram, Dougal Alexander; Neumann, Else Ragnhild; Deegan, Frances M.; Polozov, Alexander; Planke, Sverre. Geochemistry of low-Ti Siberian Traps sills from the Tunguska Basin bears evidence of magma-crust interaction. Goldschmidt 2021; 2021-07-04 - 2021-07-09 UiO
20. Capriolo, Manfredo; Callegaro, Sara; Dal Corso, Jacopo; Newton, Robert J.; Baker, Don R.; Renne, Paul R; Marzoli, Andrea. Synchrotron light X-ray microtomography reveals a crystalline mush within the deep plumbing system of Large Igneous Provinces. Goldschmidt Conference; 2021-07-04 - 2021-07-09 UiO Capriolo, M., Marzoli, A., Aradi, L. E., Callegaro, S., Dal Corso, J., Newton, R. J., Mills, B. J. W., Wignall, P. B., Bartoli, O., Baker, D. R., Youbi, N., Remusat, L., Spiess, R., and Szabo, C.: Deep CO2 from the Central Atlantic Magmatic Province during the end-Triassic mass extinction, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11189, https://doi.org/10.5194/egusphere-egu21-11189, 2021.
21. Conrad, Clinton Phillips. Global Mantle Flow Patterns and the Time Dependence Dynamic Topography at Earth's Surface and CMB. 4D Deep Dynamic Earth Science Meeting 2021; 2021-09-28 - 2021-09-28 UiO
22. Conrad, Clinton Phillips. Sea Level and the Solid Earth. GeoCenter Danmark; 2021-09-03 - 2021-09-03 UiO
23. Conrad, Clinton Phillips. Tectonic Reconstructions of Past Sea Level, Dynamic Topography and the Deep Water Cycle. University of Münster, Institute of Geophysics; 2021-06-14 - 2021-06-14 UiO
24. Crameri, F., Shephard, G., and Heron, P.: The "Scientific colour map" Initiative: Version 7 and its new additions, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11208, https://doi.org/10.5194/egusphere-egu21-11208, 2021.
25. Crameri, Fabio. A trans-disciplinary and community-driven database to unravel subduction zone initiation. University of Cambridge Bullard Seminar, virtual, 2021-01-27
26. Crameri, Fabio. How to prevent misuse of colour in science communication. OpenPlanetary Lunch Seminar, virtual, 2021-09-07
27. Crameri, Fabio. How to prevent misuse of colour in science communication. University of Hawaii TGIF Seminar, virtual, 2021-02-26
28. Crameri, Fabio. How to use colour in science communication. UMR Géoazur Seminar, virtual, 2021-01-25
29. Crameri, Fabio. Modelstanding ocean-plate tectonics. University of Kentucky Rast-Holbrook Seminar, virtual, 2021-09-08
30. Crameri, Fabio. The advantage, availability, and application of Scientific colour maps. Michigan State University SeismoLab Seminar, virtual, 2021-02-02
31. Crameri, Fabio. The misuse of colour in science communication. University of Oslo GeoHyd Seminar, virtual, 2021-01-29
32. Dowding EM, Seminar: 'It's a Trap! Environment and biogeography of Siberia across the Frasnian-Famennian', Palaeontology Society Conference.

33. EPSC 2021-230 Bultel et al. Leka Ophiolite Complex as analogy to the serpentinization-carbonation system on Mars.
34. EPSC2021-105 Veneranda et al. Planetary Terrestrial Analogues Library (PTAL): online database platform and spectroscopic tools.
35. EPSC2021-349 Krzesinska et al. Spectral study of Fe-rich vermiculite bearing rocks and implications for mineralogy of Oxia Planum, ExoMars 2022 Rover landing site
36. EPSC2021-627 Werner et al. PTAL – The Planetary Terrestrial Analogues Library for interpreting spectroscopic data
37. Evgeniy Kulakov, Trond Helge Torsvik, Pavel V Doubrovine, Lars Eivind Augland, Trond Slagstad, Morgan Ganerod and Stephanie C. Werner (2021). PALEOMAGNETISM AND U-PB GEOCHRONOLOGY OF PROTEROZOIC MAFIC DYKES IN SW GREENLAND. AGU 2021 Fall meeting. New Orleans, USA
38. Faleide, Thea Sveva; Braathen, Alvar; Lecomte, Isabelle; Mulrooney, Mark Joseph; Midtkandal, Ivar; Bugge, A.J; Planke, Sverre. Exploring extensional fault interpretations from seismic reflection data of various resolution substantiated by seismic modelling.. Norwegian Geological Winter Meeting; 2021-01-08 - 2021-01-10 UiO UiB
39. Hernandez, Jean-Alexis Robert. Constraints on the crystallization kinetics in shock-compressed MgSiO3. 3rd DyCoMax workshop.
40. Heyn, Björn Holger; Conrad, Clinton Phillips. Plume-induced heat flux anomalies and the associated thinning of the continental lithosphere. AGU Fall Meeting; 2021-12-13 - 2021-12-17 UiO
41. Huang D, Brodholt JP, Sossi P, Li Y, Murakami M, 2021. Nitrogen speciation in the terrestrial magma ocean at mantle conditions from ab initio simulations AGU Fall Meeting, MR15A-0058.
42. Kajanto, Karita Anneli; Nisancioglu, Kerim Hestnes. The role of icebergs in a Greenland fjord. BCCRPolar Greenland Workshop; 2021-10-28 - 2021-10-29 UiO UiB
43. Kiraly, A. - Dynamic interactions between subduction zones - Invited talk at the German-Swiss Geodynamics Workshop
44. Kiraly, A. - Slabs, edges , and gaps - Invited talk at AGU Fall meeting (session DI021 – Unusual subduction processes)
45. Kiraly, Agnes. Dynamic interactions between subduction zones. German-Swiss Geodynamics Workshop 2021; 2021-08-29 - 2021-09-01 UiO
46. Kiraly, Agnes. Slabs, edges, and gaps. American Geophysical Union Fall Meeting 2021; 2021-12-13 - 2021-12-17 UiO
47. Koehl, Jean-Baptiste P.; Cooke, Frances Ann; Plaza-Faverola, Andreia. Formation of a transform-parallel oceanic core complex along an inherited Timanian thrust, and impact on gas seepage in the Fram Strait. Tectonic Studies Group 50; 2021-01-05 - 2021-01-08 UiO UiT
48. Koehl, Jean-Baptiste P.. Impact of Timanian thrusts on Arctic Tectonics (ArcTec). Meeting with Lundin Petroleum Norway; 2021-03-19 - 2021-03-19 UiO
49. Koehl, Jean-Baptiste P.. Impact of Timanian thrusts on Arctic tectonics. CEED Seminars; 2021-03-26 - 2021-03-26 UiO
50. Koehl, Jean-Baptiste P.. Impact of Timanian thrusts on the Phanerozoic tectonic history of Svalbard. Norwegian Petroleum Directorate seminar; 2021-04-21 - 2021-04-21 UiO
51. Koehl, Jean-Baptiste Philippe. Seismic study of major faults in Svalbard and the Barents Sea. Institute for Geophysics, Polish Academy of Science (IG PAS) Seminar; 2021-12-03 - 2021-12-03 UiT UiO
52. Krzesińska A.M., Bultel B., Loizeau D., Craw D., April R., Poulet F., Mineralogy, Aqueous Alteration and Biosignature Preservation Potential of Oxia Planum, ExoMars2022 Landings Site as Inferred from Spectral Characterization of Terrestrial Analogues. European Geoscience Union General Assembly: abstract EGU2021-841

53. Lindström, Sofie; Callegaro, Sara; Davies, J.; Tegner, Christian; van de Schootbrugge, Bas; Krarup Pedersen, Gunver; Youbi, Nasrrddine; Sanei, Hamed; Marzoli, Andrea. Tracing volcanic emissions from the CAMP volcanism in the sedimentary and biotic record. EGU General Assembly 2021; 2021-04-19 - 2021-04- 30 UiO
54. Livio Ruggiero, Alessandra Sciarra, Gianfranco Galli, Adriano Mazzini, Claudio Mazzoli, Maria Chiara Tartarello, Fabio Florindo, Gary Wilson, Sabina Bigi, Raffaele Sassi, Jacob Anderson, and Giancarlo Ciotoli. First measurements of 222Rn and 220Rn activities in soil in Taylor Valley, Antarctica. Session NH8.5, EGU General Assembly 2021, EGU21-51001, Wien 9–30 April 2021
55. M.F.M. Weerdesteijn, C.P. Conrad, A. Hollyday, J. Austermann, and R. Gassmöller, "Extending the open-source code ASPECT to solve the sea level equation on a heterogeneous Earth", AGU Fall Meeting, New Orleans, USA, Dec. 2021.
56. M.F.M. Weerdesteijn, C.P. Conrad, J.M. Reusen, R. Steffen, and J. Naliboff, "Solid earth uplift due to contemporary ice melting above low-viscosity regions of Greenland's upper mantle", AGU Fall Meeting, New Orleans, USA, Dec. 2021.
57. Machado Garcia, Aurora; Bellwald, Benjamin; Midtkandal, Ivar; Anell, Ingrid; Planke, Sverre; Sternai, Pietro; Myklebust, Reidun. Sedimentary Processes and Deposits of the Last Glaciation at the North Sea Fan, Offshore Norway. Mid-European Geomorphology Meeting 2021; 2021-11-06 - 2021-11-09 UiO
58. Magni V.: Magmatism from the onset to the end of a subduction zone - Keynote speaker at GeoMod 2021, Utrecht
59. Magni V.*, Prada M., Naliboff J. & Gaina C. : Ridge jumps and mantle exhumation in the Tyrrhenian back-arc basin - Invited talk at Società Geologica Italiana Symposium (online)
60. Magni V.*, Prada M., Naliboff J. & Gaina C. : Rift jump and microcontinent formation in back-arc settings - EGU2021 (online)
61. Magni, Valentina. Magmatism from the onset to the end of a subduction zone. GeoMod; 2021-09-19 - 2021-09-23 UiO
62. Manjón-Cabeza Córdoba, Antonio; Rolf, Tobias; Arnould, Maëlis. Systematics of the mobile-lid regime with grain-size evolution. German-Swiss Geodynamics Workshop; 2021-08-30 - 2021-09-01 UiO
63. Marcilly, Chloe M.; Torsvik, Trond Helge; Domeier, Mathew Michael; Royer, Dana L.. Refining key parameters for long-term carbon cycle models. Norsk geologisk forening - vinterkonferanse 2021; 2021-01-06 - 2021-01-08 UiO
64. Marcilly, Chloe M.; Torsvik, Trond Helge; Domeier, Mathew Michael; Royer, Dana L.. Revising key parameters for long-term carbon cycle models. EGU 2021; 2021-04-19 - 2021-04-30 UiO
65. Medvedev, Sergei; Faleide, Jan Inge; Hartz, Ebbe Hvidegård. Cenozoic reshaping of the Barents Shelf: Influence of erosion, sedimentation, and glaciation. EGU General Assembly; 2021-01-19 - 2021-04-30 UiO
66. Medvedev, Sergei; Faleide, Jan Inge; Hartz, Ebbe Hvidegård. Cenozoic reshaping of the Barents-Kara shelf: Influence of erosion, sedimentation, and glaciation. The Geological Society of Norway Winter conference; 2021-01-06 - 2021-01-08 UiO
67. Medvedev, Sergei; Hartz, Ebbe Hvidegård. Lithosphere response to localized erosion: Model and case studies. GSA annual meeting; 2021-10-10 - 2021-10-13 UiO
68. Michalek, Jan; Atakan, Kuvvet; Rønnevik, Christian; Indrøy, Helga; Ottermøller, Lars; Natvik, Øyvind; Langeland, Tor; Daae Lampe, Ove; Fonnes, Gro; Cook, Jeremy; Christensen, Jon Magnus; Baadshaug, Ulf; Kierulf, Halfdan Pascal; Grøtan, Bjørn Ove; Olesen, Odleiv; Dehls, John; Maupin, Valerie. EPOS-Norway Portal. Find, access, share

and use data across the globe: Infrastructure solutions for Earth System Sciences at EGU General Assembly 2021; 2021-04-19 - 2021-04-30 UiO NGU UiB NORCE NORSAR

69. Nisancioglu, Kerim Hestnes; Morée, Anne; Sun, Tianyi; Bretones, Anais Magali; Straume, Eivind Olavson; Gebbie, Geoffrey. Cancellation of the precessional cycle in 18O records during the Early Pleistocene. EGU General Assembly 2021; 2021-04-26 - 2021 -04-30 UiB UiO
70. Rolf, Tobias; Arnould, Maëlis. Tectonic regime control by strain-induced plastic weakening in global-scale mantle convection simulations. German-Swiss Geodynamics Workshop; 2021-08-30 - 2021-09-01 UiO
71. Rolf, Tobias; Arnould, Maëlis. Tectonic regime variety and stability in mantle convection with strain-induced weakening. European Geosciences Union General Assembly; 2021- 04-19 - 2021-04-30 UiO
72. Rolf, Tobias. Understanding Plate Tectonics at Large: a modelling tale of mantle convection, lithospheric weakness, and supercontinents. GeoKolloquium; 2021-02-18 - 2021-02-18 UiO
73. Rolf, Tobias. Venus' mantle evolution through time. Venus' Evolution Through Time; 2021-09-13 - 2021-09-17 UiO
74. Ruggero, Livio; Sciarra, A.; Galli, G.; Mazzini, Adriano; Mazzoli, Claudio; Tartarello, M; Florindo, F.; Wilson, G.; Bigi, Sabina; Sassi, R.; Anderson, J.; Ciotoli, Giancarlo. First measurements of 222Rn and 220Rn activities in soil in Taylor Valley, Antarctica. EGU General Assembly 2021, EGU21-51001, Wien 19-30 April 2021.; 2021-04-19 - 2021-04-30 UiO
75. Scubert B.A., Jahren A.H. Separating the effects of CO2 and water stress on carbon isotope discrimination in C3 land plants. American Geophysical Union Fall Meeting, New Orleans, LA, Dec 13-17, 2021
76. Shephard, G. E., Gaina, C., Pozdnakova, A., Wilson Rowe, E., Kapoor, N., Jønnum, S., Kleivane, S. H., Lindalen, T., Niklasson, K., Bjerknes, A., Kvernmo, T. M., Knudsen, K. A., Lomell, L., Drevsjø, S., and Skjelkvåle, B. L.: An Arctic transformation; from an in-person international summer school to a digital MOOC , EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12584, https://doi.org/10.5194/egusphere-egu21 -12584, 2021.
77. Shephard, Grace; Houser, Christine; Hernlund, John W; Valencia-Cardona, JJ; Trønnes, Reidar G; Wentzcovitch, RM. (Keynote) Detecting the spin crossover in ferropericlase. Am. Geophys. Union Fall Mtg. DI14A-01. Am. Geophys. Union Fall Meeting Abstr. 2021 UiO
78. Shephard, Grace. Carmen Gaina, Alla Pozdnakova, Elana Wilson Rowe, Nita Kapoor, Siri Jønnum, Svein Harald Kleivane, Turi Lindalen, Karoline Niklasson, Audun Bjerknes, Trine Merete Kvernmo, Kristine Aall Knudsen, Brit Lisa Sjelkvåle, Mikkel Kornberg Skjeflo. A Changing Arctic – summer school and MOOC. Svalbard Science Conference, Fornebu 2-3 November 2021
79. Shephard, Grace. From the surface to deep and back again: Introducing the POLARIS project. Hammer talk, Department of Geosciences 24th November 2021
80. Shephard, Grace. Iceland’s tectonic and geodynamic setting. NOR-R-AM and AGU Fagradalsfjall Webinar Online 10th June 2021
81. Shephard, Grace. Polar Subduction. ESA 4-D Earth Meeting. Online 28-29th September 2021.
82. Shephard, Grace. Scientific Communication: some practicalities and tips. CHESS School Local meeting, Voksenålia 29th October 2021
83. Shephard, Grace. Scientific life during the pandemic, an early and senior career perspective CHESS Annual meeting, Raddisson Hotel. Oslo 7-9th June 2021
84. Svensen, Henrik Hovland. Et vindu til den dype tiden: Erfaringer fra et geologisk-kunstnerisk samarbeid. Snø og isdekte alper: KUnst og vitenskap; 2021-11-03 UiO

85. Svensen, Henrik Hovland. Geological highlihts in Oslo - Excursion. Geologisk vandring i Oslo sentrum; 2021-09-07 UiO
86. Svensen, Henrik Hovland. Lærdommer fra fortidens masseutryddelser og klimaendringer. Gjesteforedrag hos NFR, Miljø og klimaavdelingen; 2021-05-11 UiO
87. Svensen, Henrik Hovland. Om Kolsås og rombeporfyr. The Mountain Body project; 2021 -08-21 UiO
88. Svensen, Henrik Hovland. Oslos geologiske historie med fokus på leire. Foredrag ved Kunsthøgskolen i Oslo; 2021-09-28 UiO
89. Svensen, Henrik Hovland. Tanker om faget. Samling for geografilærere i Sogn og fjordane; 2021-06-01 UiO
90. Svensen, Henrik Hovland. Under asfalten. Medlemsforedrag; 2021-02-16 UiO
91. Svensen, Henrik Hovland. Vulkaner og jordens revolusjoner. Seminar hos Cegal, Oslo; 2021-12-01 UiO
92. Swai, Violeth Charles; Kollsgård, Christine Tømmervik; Eilertsen, Vårin Trælvik; Braun, Carmen; Ballo, Eirik Gottschalk. XRF core scanning for paleoclimate reconstructions. XRF core scanning for paleoclimate reconstructions; 2021-09-27 - 2021-09-29 UiT UiO UiB
93. Tegner, Christian; Andersen, Torgeir Bjørge; Kjøll, Hans Jørgen; Brown, Eric L.; Hagen-Peter, Graham; Corfu, Fernando; Planke, Sverre; Torsvik, Trond Helge. A mantle plume origin for the Scandinavian Dyke Complex: a “piercing point” for 615 Ma plate reconstruction of Baltica?. EGU-General Assembly 2021; 2021-04-19 - 2021-04-20 UiO NGU
94. ter Schure, Anneke; Bajard, Manon Julietto Andree; Loftsgarden, Kjetil; Høeg, Helge Irgens; Ballo, Eirik Magnus Gottschalk; Bakke, Jostein; Støren, Eivind Wilhelm Nagel; Iversen, Frode; Kool, Anneleen; Brysting, Anne Krag; Krüger, Kirstin; Boessenkool, Sanne. Anthropogenic and environmental drivers of biological change in southeastern Norway during the Holocene. Ancient Biomolecules of Plants, Animals, and Microbes; 2021-03-29 - 2021-03-31 UiB UiO
95. ter Schure, Anneke; Bajard, Manon Julietto Andree; Loftsgarden, Kjetil; Høeg, Helge Irgens; Ballo, Eirik Magnus Gottschalk; Bakke, Jostein; Støren, Eivind Wilhelm Nagel; Iversen, Frode; Kool, Anneleen; Brysting, Anne Krag; Krüger, Kirstin; Boessenkool, Sanne. Disentangling anthropogenic and environmental drivers of biological change in southeastern Norway during the Holocene. Bioarchaeology Early Career Conference; 2021-03-25 - 2021-03-28 UiB UiO
96. Thea H. Heimdal, Yves Goddéris, Morgan T. Jones, Henrik H. Svensen (2021). Modeling the effects of carbon release from the Karoo Large Igneous Province (LIP). Goldschmidt,
97. Thea H. Heimdal, Henrik H. Svensen, Morgan T. Jones, Sara Callegaro, Yves Goddéris, Egberto Pereira (2021). Sediment-derived volatile release during LIP emplacements – the key to explain environmental/climatic impacts? AGU conference, PP31B-01
98. Trønnes RG, 2021: Chemical exchange between the protocore and the (basal) magma ocean. Goldschmidt Conf. 2cO3-1045.
99. Trønnes RG, Mohn CE, Hernandez JA, Guren MG, Grømer B, Baron MA, 2021: High-density residual Ca-perovskite in the lowermost mantle. Meeting, Royal Astron. Soc. and UK Studies of Earth's Deep Interior (RAS, UK-SEDI), Nov. 12.
100. Valeria Turino, Valentina Magni, Hans Jørgen Kjøll, and Johannes Jakob: The effect of magma poor and magma rich rifted margins on continental collision dynamics - EGU2021 (online)
101. van der Boon, A., Biggin, A., Hounslow, M., Thallner, D., Nawrocki, J., Wojcik, K., Paszkowski, M., Konigshof, P., Kabanov, P., Gouwy, S., Vandenberg, R., 2021. Why does magnetostratigraphy not work in the Devonian?, Magnetic Interactions 2021

102. van der Boon, A., Biggin, A., Hounslow, M., Thallner, D., Nawrocki, J., Wojcik, K., Paszkowski, M., Konigshof, P., Kabanov, P., Gouwy, S., Vandenberg, R., Bono, R., 2021, Devonian magnetostratigraphy: new data and old problems, vEGU2021

103. van der Boon, A., Biggin, A., Hounslow, M., Thallner, D., Nawrocki, J., Wojcik, K., Paszkowski, M., Konigshof, P., Kabanov, P., Gouwy, S., Vandenberg, R., Bono, R., 2021, Synthesis of palaeomagnetic datasets suggests that the geomagnetic field was persistently non-uniformitarian in the Devonian, vEGU2021

104. van der Boon, A., Biggin, A.J., Thallner, D., Hounslow, M.W., Bono, R., Wójcik, K., Paszkowski, M., Königshof, P., de Backer, T., Kabanov, P., VandenBerg, R., The Devonian magnetic field: weak and poorly understood, AGU Fall meeting, December 2021

105. Van Dijk, Evelien; Gundersen, Ingar Mørkestøl; Loftsgarden, Kjetil; Ballo, Eirik Gottschalk; Krüger, Kirstin; Iversen, Frode. Can we link volcanic impacts on the climate to a change in society?. CHESS annual meeting; 2021-06-07 - 2021-06-09 UiO

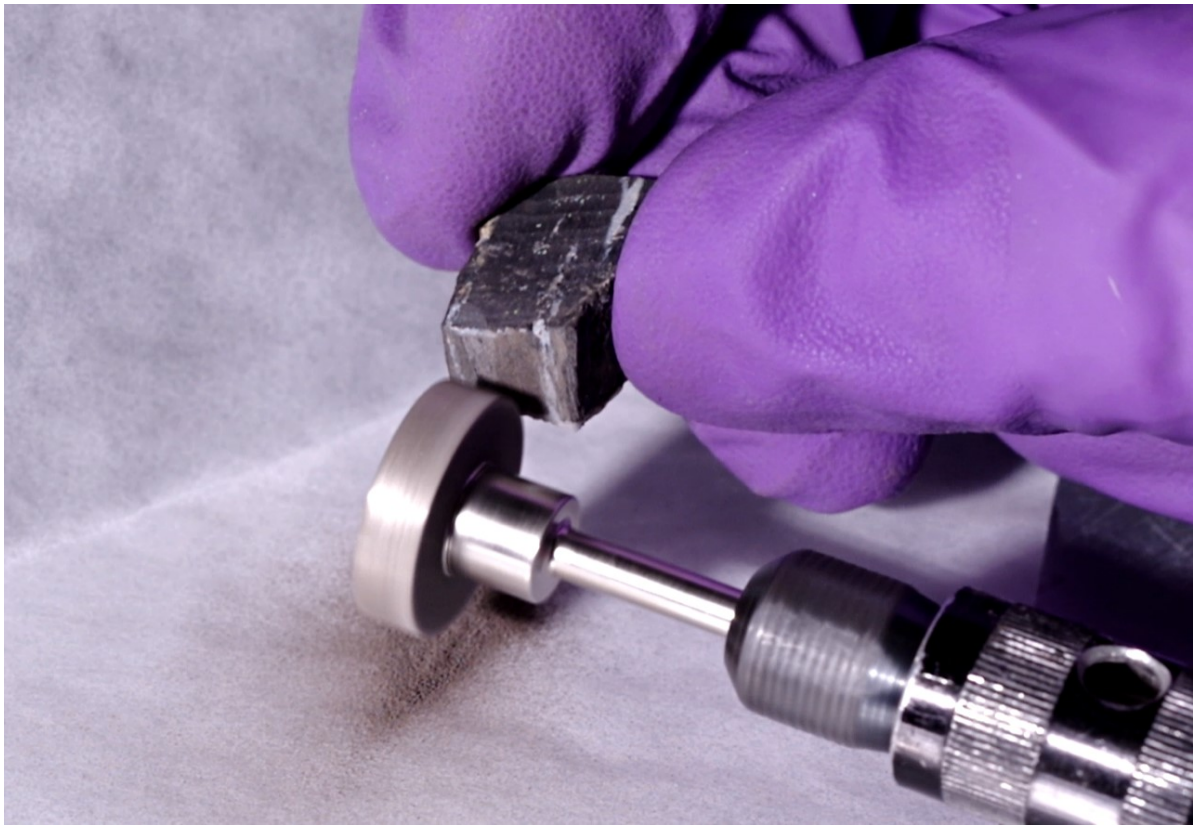
106. Wang W, Li Y, Brodholt JP, Walter MJ, Wu Z, 2021. Superionic iron-hydrogen alloys in Earth's inner core. Goldschmidt Conf., 2cO3-1055.

107. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Hollyday, A.; Austermann, J.; Gassmöller, R.. Extending the open-source code ASPECT to solve the sea level equation on a heterogeneous Earth. AGU Fall Meeting; 2021-12-13 - 2021-12-17 UiO

108. Weerdesteijn, Maaike Francine Maria; Conrad, Clinton Phillips; Reusen, J.M.; Steffen, R.; Naliboff, J.. Solid earth uplift due to contemporary ice melting above low-viscosity regions of Greenland's upper mantle. AGU Fall Meeting; 2021-12-13 - 2021-12-17 UiO

109. Williamson, M.-C., Shephard, G. E., and Kellett, D. A.: Contrasting styles of magmatism and rifting in the High Arctic LIP, Sverdrup Basin, Canadian Arctic, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12230, https://doi.org/10.5194/egusphere-egu21-12230, 2021.

110. Zuchuat, Valentin; Augland, Lars Eivind; Jones, Morgan Thomas; Twitchett, Richard; Rodríguez-Tovar, Francisco J.; Hammer, Øyvind; Senger, Kim; Betlem, Peter; Turner, Holly; Svensen, Henrik; Planke, Sverre. Facies changes, volcanism, and mass extinction conundrum: the Permian-Triassic boundary across the Barents Sea Shelf. 35th IAS International Meeting of Sedimentology; 2021-06-21 - 2021-06-25 UiO UNIS



*William Hagopian (Earth Crises Group, CLIPT Lab) sampling Late Permian permineralized wood for intra-ring stable carbon isotope analyses that will be used for paleoclimate reconstruction.*



*Thin section image of Late Permian permineralized wood showing exceptional cellular structure still intact.By: William Hagopain.*

**Professors, Researchers and Adjunct Professors**

| Name | Title | Period at CEED | Man months in 2021 |
|---|---|---|---|
| Abdelmalak, M. Mansour | Researcher | 01.06.19-31.05.22 | 12,0 |
| Andersen, Torgeir B. | Professor emeritus | 01.03.18-30.04.20 | |
| Augland, Lars Eivind | Researcher | 13.20.21-28.02.23 | 1,5 |
| Breivik, Asbjørn | Associate professor | 01.03.18-28.02.23 | 6,0 |
| Brodholt, John | Professor | 01.03.18-28.02.23 | 2,4 |
| Bultel, Benjamin | Researcher | 15.01.19-31.01.22 | 12,0 |
| Callegaro, Sara | Researcher | 22.09.20-28.02.23 | 12,0 |
| Caracas, Razvan | Researcher | 01.09.18-28.02.23 | 2,4 |
| Conrad, Clinton P. | Professor | 01.08.16-28.02.23 | 12,0 |
| Corfu, Fernando | Professor emeritus | | |
| Crameri, Fabio | Researcher | 01.01.21-31.12.21 | 2,4 |
| Domeier, Mathew | Researcher | 07.08.16-28.02.23 | 12,0 |
| Dubrovine,  Pavel | Researcher | 01.10.16-28.02.23 | 12,0 |
| Faleide, Jan I. | Professor | 01.03.18-28.02.23 | 3,6 |
| Gac, Sebastien | Researcher | 01.10.19-30.04.22 | 12,0 |
| Gaina, Carmen | Professor | 01.03.18-28.02.23 | 6,4 |
| Heyn, Björn Holger | Researcher | 15.09.16-28.02.23 | 12,0 |
| Jahren, A. Hope | Researcher | 01.09.16-28.02.23 | 12,0 |
| Jerram, Dougal | Researcher | 01.03.13-28.02.23 | 2,4 |
| Jones, Morgan | Researcher | 18.09.17-28.02.23 | 11,0 |
| Kiraly, Agnes | Researcher | 01.08.17-28.02.23 | 12,0 |
| Kruger, Kirstin | Professor | 01.11.18-28.02.23 | 1,2 |
| Krzesinska, Agata | Researcher | 15.10.20-28.02.23 | 12,0 |
| Kulakov Evgeniy | Researcher | 01.05.19-28.02.23 | 12,0 |
| Luu, Jane | Adjunct professor | 01.09.19-28.02.23 | 1,2 |
| Magni, Valentia | Researcher | 01.03.19-28.02.23 | 12,0 |
| Maupin, Valerie | Professor | 01.03.18-28.02.23 | 6,0 |
| Mazzini, Adriano | Researcher | 01.03.13-28.02.23 | 3,6 |
| Medvedev, Sergei | Researcher | 01.12.18-30.04.22 | 12,0 |
| Minakov, Alexander | Researcher | 01.10.20-28.02.23 | 12,0 |
| Mohn Chris E. | Researcher | 01.06.13-28.02.23 | 12,0 |
| Neumann, Else Ragnhild | Professor emerita | 01.03.13-28.02.23 | |
| Niscancioglu, Kerim Hestnes | Adjunct professor | 01.10.18-20.02.22 | 1,2 |
| Planke, Sverre | Adjunct professor | 01.07.18-28.02.23 | 1,8 |
| Prieur, Nils Charles | Researcher | 01.10.21-28.02.23 | 3,0 |
| Rolf, Tobias | Researcher | 01.12.18-31.05.22 | 10,5 |
| Schweitzer, Johannes | Adjunct professor | 01.09.15-28.02.23 | 2,4 |
| Selway, Kate | Researcher | 15.09.20-28.02.23 | 2,4 |
| Shephard, Grace | Researcher | 01.05.18-28.02.23 | 12 |
| Steinberger, Bernhard | Researcher | 01.05.16-28.02.22 | 2,4 |
| Straume, Eivind O. | Reseacher | 15.08.20-14.02.21 | 1,5 |
| Svensen, Henrik | Researcher | 01.05.16-28.02.23 | 12 |
| Torsvik, Trond H. | Professor | 01.03.18-28.02.23 | 11 |
| Trønnes, Reidar | Professor | 01.03.18-28.02.23 | 6 |
| Watson, Robin | Researcher | 01.12.18-28.02.23 | 1,2 |
| Werner, Stephanie | Professor | 01.03.18-28.02.23 | 6 |

**PhD candidates**

| Name | Funding Source | Period at CEED | Man months in 2021 |
|---|---|---|---|
| Ballo, Eirik | UiO | 24.09.18-31.04.22 | 8,0 |
| Beloša, Lea | UiO | 04.11.19-05.11.23 | 12,0 |
| Harrington, Elise | UiO | 26.08.19-28.02.23 | 12,0 |
| Hatalova, Petra | UiO | 03.05.21-28.02.23 | 8,0 |
| Jerkins, Anne E. | Project NNSN/Norsar | 01.01.20-28.02.23 | 12,0 |
| Karlsen, Krister S. | UiO | 01.08.17-26.09.21 | 9,0 |
| Marcilly, Chloé F.M. | UiO | 05.08.19-04.08.22 | 12,0 |
| Ramirez, Florence | NFR (SFF CEED) | 13.08.19-30.09.22 | 12,0 |
| Wang, Yijun | NFR (Project Anima) | 07.09.21-28.02.23 | 4,0 |
| Werdesteijn, Maaike | NFR (Project Magpie) | 28.05.19-15.11.22 | 12,0 |

**Postdoc fellowships**

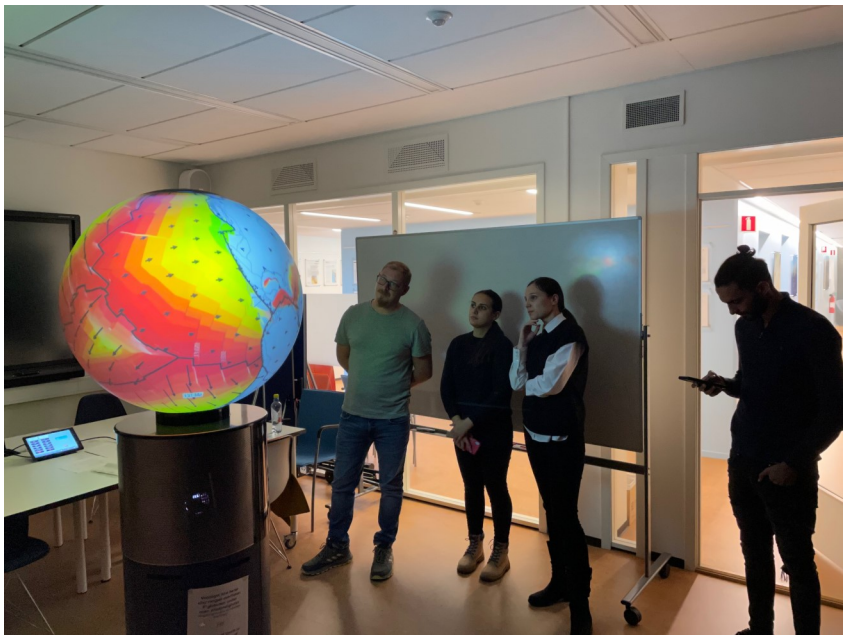
| Name | Funding Source | Period at CEED | Man months in 2021 |
|---|---|---|---|
| Bajard, Manon | NFR (project Vikings) | 03.09.18-31.08.21 | 8,0 |
| Capriolo, Manfredo | NFR (project Maples) | 01.08.21-28.02.23 | 5,0 |
| Cordoba, Antonio | NFR (project Platonics) | 16.11.20-30.03.22 | 12,0 |
| Dowding, Elizabeth | NFR (SFF CEED) | 26.04.21-28.02.23 | 8,0 |
| Gallo, Leandro | MSCA (project Tango) | 02.08.21-28.02.23 | 5,0 |
| Geng, Ming | NFR (SFF CEED) | 01.06.21-28.02.23 | 7,0 |
| Heimdal, Thea Hatlen | NFR (SFF CEED) | 07.01.19-26.03.22 | 12,0 |
| Hernandez, Jean-Alexis | NFR (SFF CEED) | 02.09.19-30.04.21 | 4,0 |
| Koehl, Jean-Baptiste | NFR (SFF CEED) | 18.01.21-28.02.23 | 11,5 |
| Neukirch, Maik | EEA (project Geysir) | 01.06.21-28.02.23 | 7,0 |
| Ozgurel, Ozge | NFR (SFF CEED) | 03.02.20-02.03.22 | 12,0 |
| Shan, Yu Tong | NFR (SFF CEED) | 16.08.21-28.02.23 | 4,5 |
| Stokke, Ella Wulfsberg | NFR (SFF CEED) | 15.02.21-20.02.23 | 10,5 |
| Van der Broon, Annique | NFR (SFF CEED) | 14.06.21-28.02.23 | 6,5 |
| Vickers, Madeleine Larissa | MSCA (project Icecap) | 18.10.21-28.02.23 | 2,5 |

**Techinical-administrative staff**

| Name | Title | Period at CEED | Man months in 2021 |
|---|---|---|---|
| Gørbitz, Trine-Lise | Head of Administration | 01.03.13-28.02.23 | 12,0 |
| Hagopian, William | Senior Engineer | 01.01.17-28.02.23 | 12,0 |
| Nettum, Sara Asgari | Senior Exectuive Officer | 01.12.20-28.02.23 | 12,0 |
| Silkoset, Petter | Senior Engineer | 01.01.16-28.02.23 | 12,0 |
| Sørlie, Anita | Senior Exectuive Officer | 15.06.16-28.02.23 | 8,4 |

# CEED: A CENTRE OF EXCELLENCE 2013-2023

*Basic research relevant to society and industry*







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