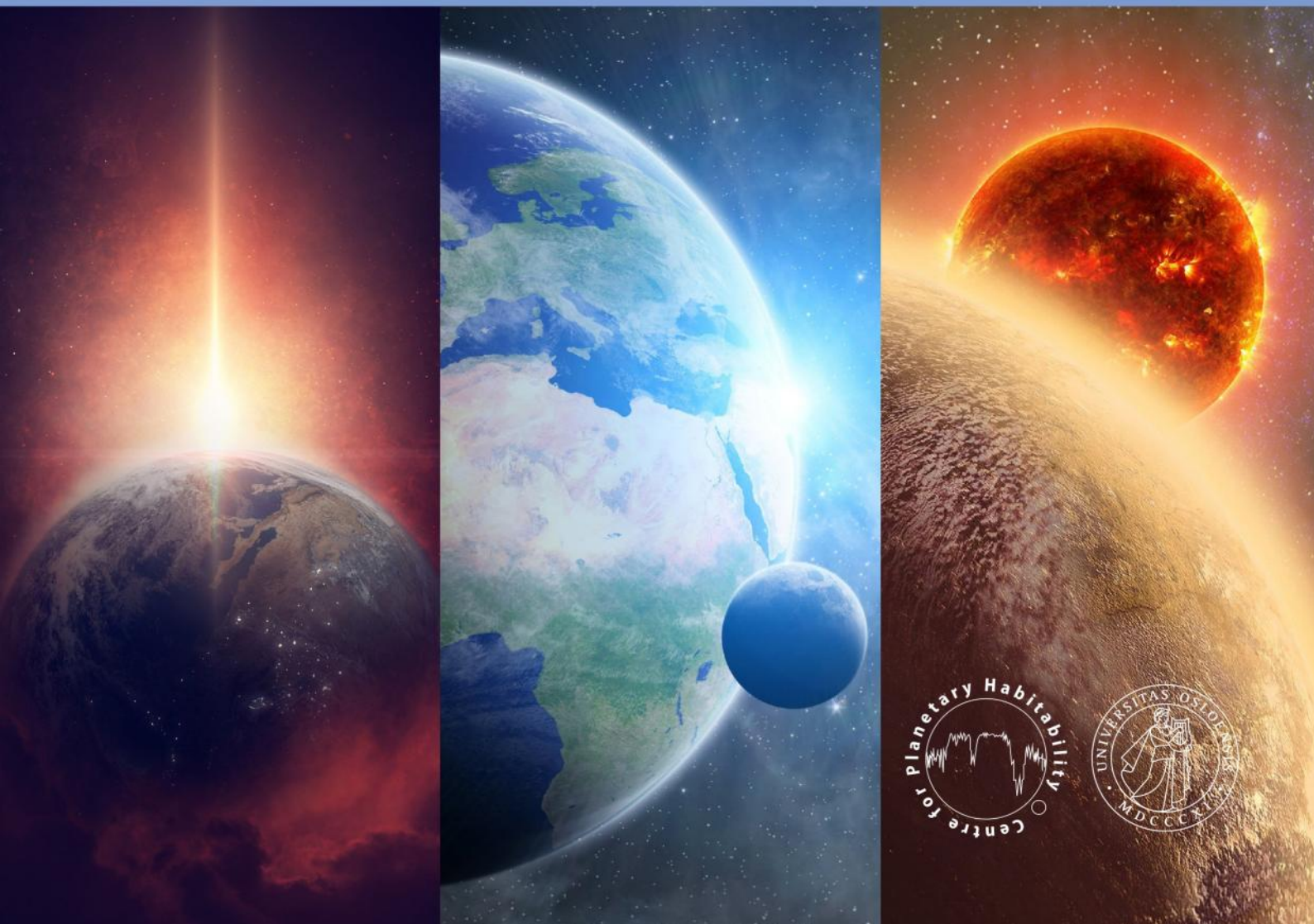


UNIVERSITY
OF OSLO

Centre for Planetary Habitability

Annual report 2025



PRIMARY OBJECTIVE:

Recognize and characterize the key conditions that make a planet habitable.

SECONDARY OBJECTIVES:

- (1) Establish absolute timelines for key events in the Solar System.
- (2) Characterize the initial physical and chemical conditions of habitability for life as we know it.
- (3) Explore how a planet's composition and interior influence its ability to nurture a biosphere.
- (4) Unravel correlative versus causal relationships among biotic and abiotic time-series.
- (5) Identify the drivers for greenhouse versus icehouse conditions.
- (6) Understand life-threatening tipping points and the fragility of habitability.
- (7) Recognize planets around other host stars that are or were potentially habitable.

Earth is the only planet on which life is known to have originated. Earth has abundant surface water, a large moon, a long-lived magnetic field, and plate tectonics. Yet, which of these and other characteristics are essential for long-term habitability? How have Earth's physical and chemical attributes, and thus our planet's proclivity for life, evolved? How can we recognize distant worlds around other stars that have been or could be habitable?

A Centre dedicated to research on the habitability of star-planet systems is the first of its kind in Norway, and PHAB was officially opened on 1st of July 2023.



ACHIEVEMENTS IN 2025

PHAB researchers published **84** papers in international journals (**9** in high-impact journals: PNAS, Science and Nature-indexed).

Yijun Wang (18.08.2025), **Lea Belosa** (27.08.25), **Ana Anzulovic** (29.08.2025) and **Juan Camilo Meza Cala** (31.10.25) successfully defended their PhD projects.

Amando Lasabuda was awarded the *Robert Mitchum Award* (2025) from the European Association of Geoscientists and Engineers (EAGE).

Jyotirmoy Paul was awarded the *Institute Medal* (2023-24) from the Indian Institute of Science for his Ph.D thesis. It was officially awarded to **Paul** in July 2025.

Nicole Obren was awarded the *Best PhD Oral Presentation Award* from the Natural History Museum, UiO.

Agata Krzesinska was awarded the NASA Honor Award for group achievement (2024-2025).

Konstantin Herbst and **Vincent Kofman** were elected as members of the PLATO Science Core Team (ESA).

Trond H. Torsvik was awarded a FRIPRO researcher project (GOE-PHAB) from the Research Council of Norway.

Stephanie C. Werner was awarded a ROMFORSK researcher project (GREP) from the Research Council of Norway and an ESA project (SER3NE).

Erik Asphaug was awarded a FRIPRO researcher project (GIANTS) from the Research Council of Norway.

Trond H. Torsvik and **Li Zeng** was awarded a TALENTUTLAND researcher project (WaterWorlds) from the Research Council of Norway.

Lee Hsiang Liow was awarded a Centre for Advanced Study Grant.

Razvan Caracas (DAWN) was awarded an ERC Advanced Grant.

PHAB conferred **The Else Ragnhild Neumann Award** for the 7th time to Gabrielle Emma Kleber, UiT.



PHAB-staff, guests and board members at the board meeting on 22.5.25

Photo: Jyotirmoy Paul



Organization

Scientific Advisory Board

Professor **Heike Rauer**
(chair), German Aerospace
Centre & Freie University
Berlin (Germany)

Professor **Donald Canfield**,
University of Southern
Denmark (*withdrew on*
29.09.25)

Professor **Jennifer**
McElwain, Trinity College
Dublin, Ireland

Professor **Paul Tackley**,
ETH Zurich, Switzerland

Professor **Ann Carine**
Vandaele, Royal Belgian
Institute for Space Aeronomy
(*from 1.11.25*)

PHAB is headed by a director, a co-director, six principal investigators (PIs) and an administrative coordinator. We also have a scientific advisory board and a Young PHAB Senate, which are involved in organizing scientific workshops, career development events and social programming. Centre activities are carried out in three research themes:

(1) PLANETS/EARLY EARTH

Addresses planet formation, evolution, and comparative planetology to identify the initial conditions for habitability and how a planet's composition and interior influence its ability to nurture a biosphere.

(2) MODERN EARTH

Addresses the geological and biological processes that led to our Modern Earth, starting from the dispersal of a supercontinent 750 million years ago, and accompanied by dramatic cooling events, unprecedented carbon-cycle fluctuations, and the rapid evolution of multicellular organisms.

(3) EXO-EARTHS

Takes comparative planetology beyond the Solar System to identify planets orbiting other stars that are, or have been, potentially habitable.

PHAB

Director: Professor **Trond**
H. Torsvik until 30.6.25,
then **Stephanie Werner**

Deputy Director: Professor
Stephanie Werner until
30.6.25, then **Trond H.**
Torsvik

Administrative
coordinator: **Trine**
Sannesmoen

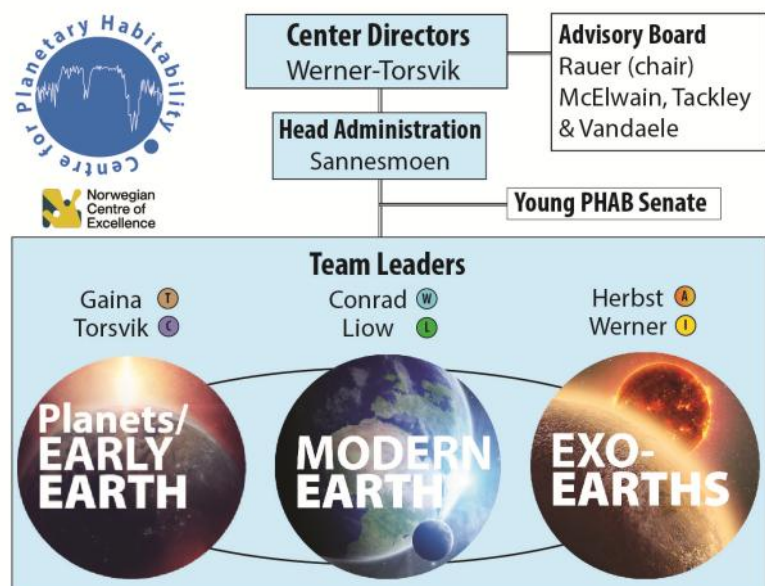
26 Professors, Associate
Professors and Researchers

12 Postdocs

7 PhD fellows

3 Technical-administrative
staff members

4 Professor emerita/emeritus



Each research theme is led by two PIs who also front specific research topics (Interior, I; Tectonics, T; Water, W; Atmosphere, T; Climate, C; Life, L).



*The oldest lavas and intrusions in eastern Iceland, near Dalatangi, July 2025.
Photos: Justin Tonti-Filippini*

Table of contents

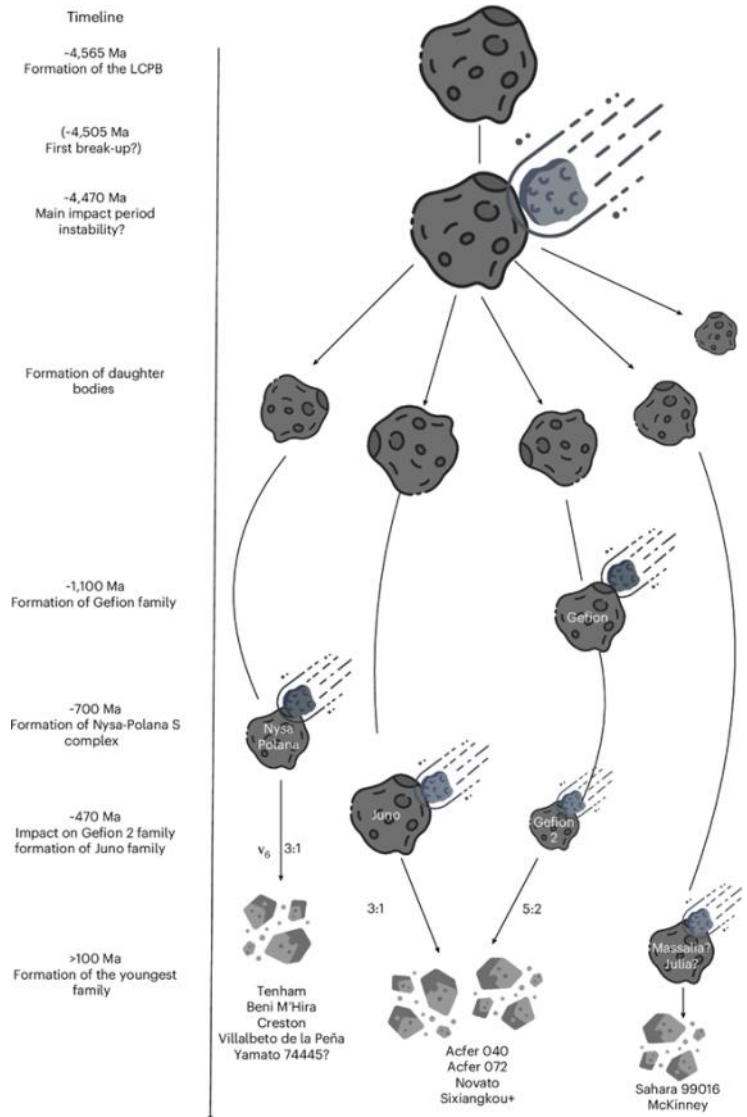
Objectives	3
Achievements	4
Organization	5
Research Highlights.....	8
From the Director.....	14
Activity by theme.....	16
Planets/Early Earth.....	17
Modern Earth.....	30
Exo-Earths.....	52
The Else-Ragnhild Neuman award	66
Outreach highlights.....	68
SOUP workshop.....	70
A PhD candidate's visit at FAU.....	72
Appendices	74
Master student projects.....	74
PhD candidate projects.....	75
International cooperation	76
Conferences organized by PHAB.....	77
Workshops, lab work, research stays outside UiO.....	78
Fieldwork.....	79
KEPLER Lecture Series.....	80
PHAB Scientific Seminar Series.....	82
Products	
Scientific publications.....	84
Outreach activities.....	90
Abstracts (talks and posters).....	92
Project funding.....	96
List of staff.....	98

Nature-indexed journals

A collisional history of the L chondrite parent bodies.

Ciocco, M., Roskosz, M., Doisneau, B., Deloule, E., Fiquet, G., Delbo, M. & Gounelle, M. (2025) Nature Astronomy 9, 1455–1463. <https://doi.org/10.1038/s41550-025-02615-6>

L chondrites are some of the most common meteorites retrieved on Earth. Their Ar–Ar collision ages indicate a major disruption of their parent body ~470 million years ago (Ma), which was followed by an intense meteorite shower on Earth that is linked to the Ordovician biological crisis. However, recent but previously scarce chronological and geochemical data on a few L chondrites hint at a more complex evolution of the parent body than a single, one-stage 470 Ma break-up. Ciocco et al. conducted a unique coordinated mineralogical and geochronological study on eight shocked L chondrites, which showed a wide distribution of collisional ages at 4,500, 4,470, ~700, 470 and ~10 Ma. The lower-limit sizes of the parent body derived from shock timescales, combined with the orbital parameters and the aforementioned ages of the meteorites, indicate a complex collisional cascade endured by the parent body of the L chondrites, pointing towards several L chondrite sources in the asteroid main belt, namely, the Nysa–Polana, Juno, Gefion 2 and potentially Massalia asteroid families.



Summary of the proposed collisional history of the L chondrite parent body.

Shaving continents into the oceans

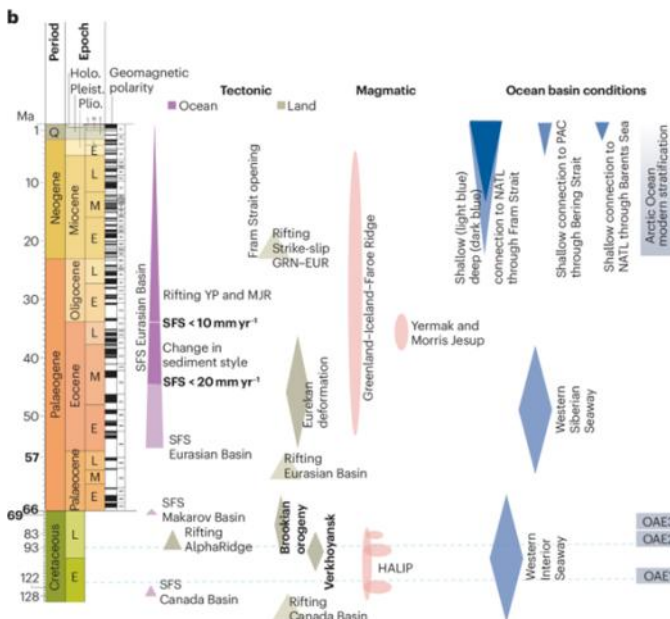
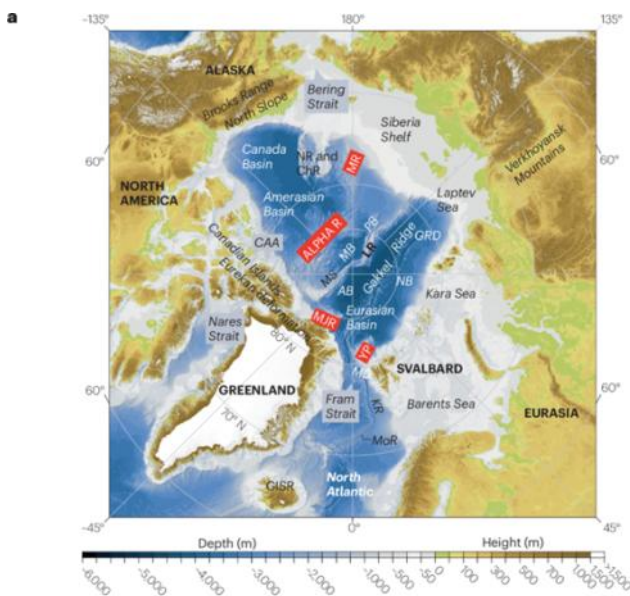
Gaina, C. (2025), Nature Geoscience 18, 1191–1192. <https://doi.org/10.1038/s41561-025-01845-7>

Complex numerical simulations show how slivers of continental crust in the ocean were shaved from continental margins and then transported by transform fault complexes. Once continents have started to drift apart, the space between them is filled by the floor of a new ocean, mostly comprising basaltic crust formed at a spreading ridge. Tiny fragments of continents may be trapped within this oceanic crust and sometimes transported far away from continental margins, by processes that are not fully understood. Gaina highlights the importance of numerical assessments on how narrow slivers of continental crust are both carved from these margins and carried away by oceanic transform (ridge segment-bounding, predominantly strike-slip) faults.

Arctic Ocean bathymetry and its connections to tectonics, oceanography and climate.

Gaina, C., Jakobsson, M., Straume, E. O., Timmermans, M., Boggild, K., Bünz, S., Schlindwein, V., & Døssing, A. (2025). *Nature Reviews Earth & Environment* 6, 211–227. <https://doi.org/10.1038/s43017-025-00647-0>

For at least the past 50 million years, the Arctic region has had a major role in regulating global climate regimes and their variations through time. Gaina et al. review the role of the Arctic oceanic basin and its complex bathymetry in controlling ocean circulation and marine cryosphere development. The spatial distribution and depth of various seafloor features, such as ocean gateways, submarine plateaus and continental shelves, influence the pathways of ocean currents, both today and in the past. The Arctic Ocean was an enclosed basin until the Early Eocene (56–48 million years ago), when the Eurasian Basin started to form and a shallow sea connected the Arctic to the Tethys Ocean. The connections with the North Atlantic and the global ocean through shallow and deep gateways prompted the transition from a global greenhouse to icehouse climate. However, the Arctic Ocean remains underexplored, as less than one-quarter of its seafloor is mapped in detail. Future integrated geoscience research, modern bathymetric mapping technology and active international programmes are needed to close these data gaps.



Key points

- Bathymetry controls ocean current pathways, especially along steep slopes, and influences ocean mixing, ventilation, and the horizontal and vertical distribution of temperature and salinity.
- In the Cretaceous period, when the first Arctic abyssal plain was forming 126 million years ago (Ma), the Arctic Ocean was confined between large land masses and their wide continental shelves.
- From 56 Ma, tectonic changes and mantle dynamics facilitated the opening of shallow and deep seaways within Eurasia and at its continental margins, initiating water exchange with the Tethys, North Atlantic and global oceans.
- A temporary deepening of the Barents Seaway in the Eocene at 50 Ma reduced the strength of the proto-Atlantic Meridional Overturning Circulation via freshwater fluxes from the Arctic, which suppressed dense-water formation at the northern limb of the overturning circulation.
- Bathymetric changes of the proto-Fram Strait, Barents Seaway and the Greenland–Iceland–Scotland Ridge together with decreasing atmospheric carbon dioxide probably influenced the climate transition from greenhouse to icehouse conditions at the Eocene–Oligocene Transition (34 Ma).

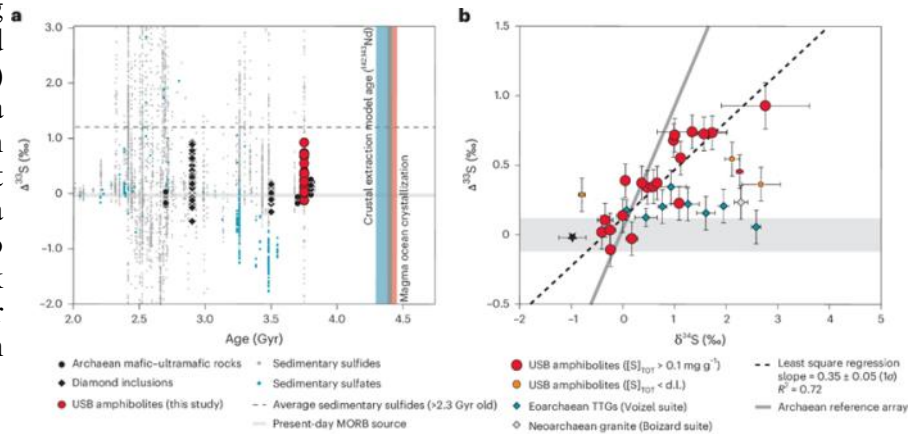
The key features and regions of the circum-Arctic, and main tectono-magmatic events and corresponding ocean basin changes of the Circum-Arctic region over time.

RESEARCH HIGHLIGHTS 2025

Early Archaean onset of volatile cycling at subduction zones

Caro, G., Grocolas, T., Bourgeois, P., Bouilhol, P., **Mojzsis, S. J.** & Paris, G. (2025) Nature Geoscience 18, 436–442. <https://doi.org/10.1038/s41561-025-01677-5>

The subduction of pelagic sediments and altered oceanic crust modulates the global cycle of volatile elements. Sulfate and carbonate fluids released when one plate descends beneath another modify the redox state of the mantle, and generate the return of water and reactive gases to the atmosphere and hydrosphere via arc volcanism, affecting planetary habitability over geologic timescales. However, the timing of the onset of subduction remains uncertain, hindering our understanding of how deep geochemical cycles operated on the early Earth. Caro et al. measured sulfur and neodymium isotope data on Eoarchaean mantle-derived rocks of the Innuksuac Complex in northern Québec, Canada, with petrological characteristics of arc magmas. These rocks exhibit anomalous sulfur isotopic compositions originally produced by photochemical reactions in the atmosphere more than 3.8 Gyr ago. Combined sulfur and neodymium isotope data suggest that these signatures were transferred to the Innuksuac mantle through devolatilization and partial melting of terrigenous sediments derived from a Hadean (4.3–4.4 Gyr ago) continental source, providing a record of an early continental margin subduction environment. This result pushes back direct evidence of a subduction-driven volatile cycle to the onset of the terrestrial rock record, approximately 1 Gyr earlier than previously inferred from diamond inclusions.



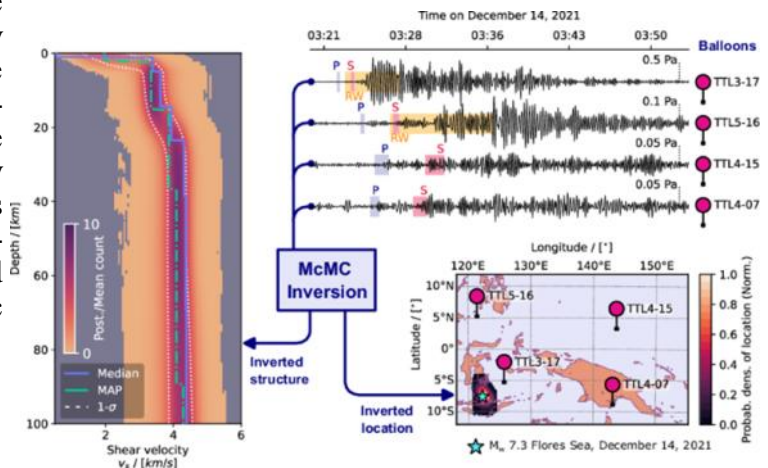
Sulfur isotope compositions in metalavas and granitoid gneisses of the Innuksuac Complex.

Balloon seismology enables subsurface inversion without ground stations.

Froment, M., Brissaud, Q., Näsholm, S. P., & **Schweitzer, J.** (2025). Communications Earth & Environment 6, #949. <https://doi.org/10.1038/s43247-025-02917-7>

Earth's interior structure is derived primarily from data recorded by ground-based seismometers. Such instruments would provide essential insight into the composition and evolution of Venus, but harsh surface conditions hinder their deployment. Balloon-borne seismology offers an alternative by capturing upper-atmospheric infrasonic signatures of seismic waves. Froment et al. show that subsurface seismic velocities and earthquake source location can be jointly inverted from balloon observations. They demonstrate this method using infrasound signals recorded by four stratospheric balloons following a major earthquake in the Flores Sea, Indonesia. A Bayesian inversion using Markov chain Monte Carlo sampling is implemented to account for trade-offs in the joint location and subsurface velocity estimation. The inverted seismic parameters are consistent with results obtained using ground-based seismometers. This demonstration of the ability to estimate source and velocity parameters without ground deployments motivates further development of seismo-acoustic mission concepts to Venus, and provides new opportunities for seismic exploration in remote Earth regions.

The data pipeline concept:



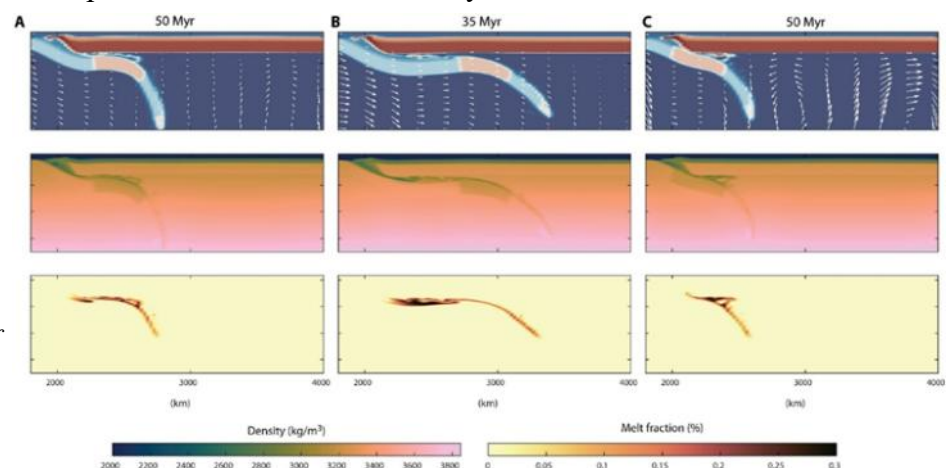
Science-indexed journals

Slab underthrusting is the primary control on flat-slab size.

Gianni, G., Gallo, L. C., Likerman, J., Echaurren, A., Gianni, C. R., & Faccenna, C. (2025). Science Advances 11 (28). <https://doi.org/10.1126/sciadv.adv8872>

Flat subduction, an intermittent phenomenon along active margins, arises from well-known causes, yet the mechanisms driving its expansion remain poorly understood. The prevailing view suggests that trenchward continental motion drives slab overthrusting, causing the flat slab to expand oceanward. Gianni et al. explored an alternative mechanism: underthrusting of the subducting plate through forward propagation of the flat-slab hinge. They directly evaluate both hypotheses through a kinematic analysis of trench and flat-slab motions using a global flat subduction database cast into multiple absolute plate motion models. Their results indicate that flat-slab expansion reflects distinct end-member processes, with forward propagation emerging as the dominant mode. They present a framework for flat-slab propagation that emphasizes the dynamic interaction between lower-plate motion and slab pull from adjacent subduction zones, an interplay validated through numerical modeling. These findings challenge conventional assumptions and underscore the need to reconsider the role of lower-plate kinematics in flat-slab dynamics.

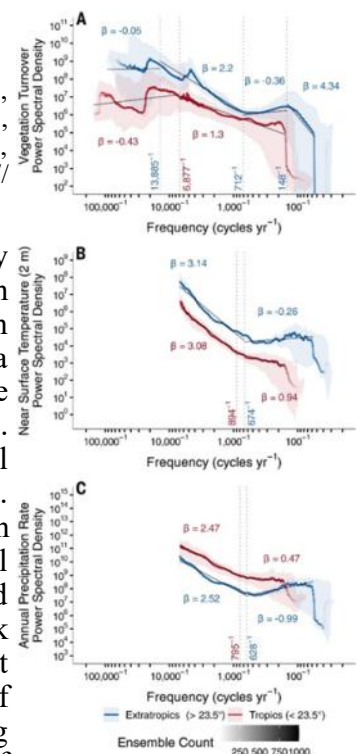
2D geodynamic experiments of flat subduction testing the influence of mantle flow, imposed plate convergence, and slab pull on flat-slab forward propagation.



Coupled, decoupled, and abrupt responses of vegetation to climate across timescales.

Fastovich, D., Meyers, S., Saupe, E. E., Williams, J. W., Dornelas, M., Dowding, E. M., Finnegan, S., Huang, H., Jonkers, L., Kiessling, W., Kocsis, Á. T., Li, Q., Liow, L. H., Na, L., Penny, A. M., Pippenger, K., Renaudie, J., Rillo, M. C., Smith, J., Steinbauer, M., Sugawara, M., Tomasovych, A., Yasuhara, M., & Hull, P. M. (2025). Science 389 (6755), 64-68. <https://doi.org/10.1126/science.adr6700>

While accepted that climate is changing quickly, it is less clear how quickly ecosystems will be able to respond and adapt. Fastovich et al. used fossil pollen records spanning 600,000 years and spectral analysis to identify how vegetation responds to climate change over a range of timescales. They developed a spectral analysis-based approach that provides detailed estimates of the timescales at which vegetation tracks climate change, from 10^1 to 10^5 years. They report dynamic similarity of vegetation and climate even at centennial frequencies (149^{-1} to $18,012^{-1}$ year $^{-1}$, that is, one cycle per 149 to 18,012 years). A breakpoint in vegetation turnover (797^{-1} year $^{-1}$) matches a breakpoint between stochastic and autocorrelated climate processes, suggesting that ecological dynamics are governed by climate across these frequencies. Heightened vegetation turnover at millennial frequencies (4650^{-1} year $^{-1}$) highlights the risk of abrupt responses to climate change, whereas vegetation-climate decoupling at frequencies $>149^{-1}$ year $^{-1}$ may indicate long-lasting consequences of anthropogenic climate change for ecosystem function and biodiversity. Meaning that vegetation responded at timescales from hundreds to tens of thousands of years, but not at timescales shorter than about 150 years, suggesting that concerns about ecosystems lagging rapid climate change are warranted.



The continuum of tropical and extratropical vegetation turnover and climate variability.

PNAS

Reply to Johnson: Holistic evaluation of ecological models in paleobiology.

Saulsbury, Parins-Rukuchi, Wilson, **Reitan**, Liow (2025). PNAS 122 (10) e2415303122. <https://doi.org/10.1073/pnas.2415303122>

Last year's paper *Age-dependent extinction and the neutral theory of biodiversity* by Saulsbury et al. (PNAS, 121, e2307629121) drew some attention and a discussion on that curve-fitting alone cannot validate neutral theory (NT) and would not invalidate the Red Queen (RQ) but complement each other. Thus, elevated extinction among young species emerges from RQ-like dynamics. Likewise, NT increases the understanding of extinction. NT is a unified theory, able to link and explain disparate ecological phenomena across scales and data types.

Reply to Grossman et al.: The case for a time-varying oxygen isotopic composition of seawater and cooler Ordovician oceans.

Thiagarajan, Lepland, Ryb, **Torsvik**, Ainsaar, Hints, Eiler (2025). PNAS 122 (12) e2426540122. <https://doi.org/10.1073/pnas.2426540122>

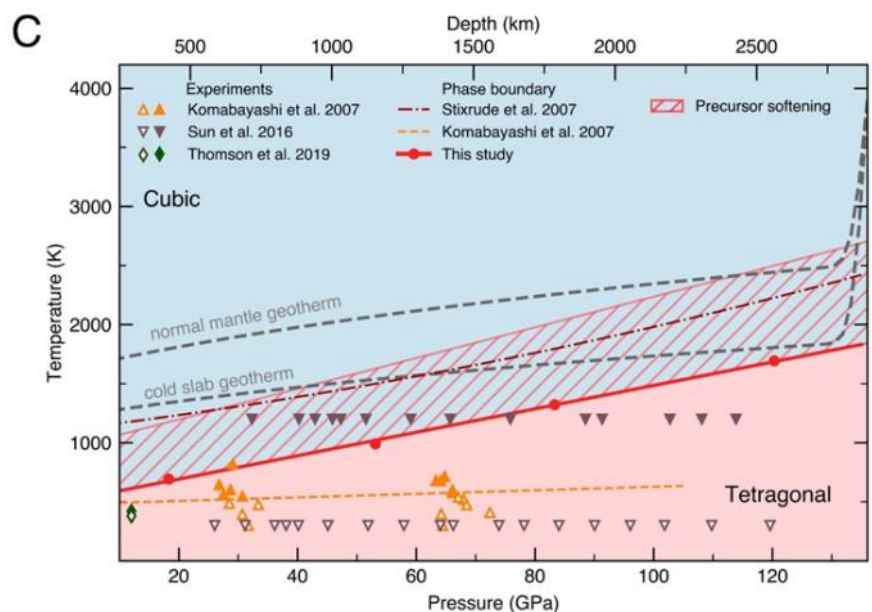
Last year's paper *Reconstruction of Phanerozoic climate using carbonate clumped isotopes and implications for the oxygen isotopic composition of seawater* by Thiagarajan et al. (PNAS 121, e2400434121) drew some attention and a discussion about whether isotopic compositions of ancient marine carbonates reflect past surface temperatures, past ocean compositions, or postdepositional diagenesis. The answer refers to an alternative approach that neither depends on exceptional carbonate preservation nor assumes specific water–rock ratios during alteration.

Strong precursor softening in cubic CaSiO₃ perovskite.

Zhang, C., Yang, J., Sun, T., Zhang, H., & **Brodholt**, J. P. (2025). PNAS 122 (5) e2410910122. <https://doi.org/10.1073/pnas.2410910122>

The Earth's deep interior is inaccessible to humans and much of our knowledge of its composition and temperature is inferred from matching seismic observations with the elastic wave velocities of minerals. Zhang et al. report the elastic wave velocities of CaSiO perovskite (CaPv), a crucial mineral component of the lower mantle. They find that CaPv is seismically undetectable under typical mantle conditions, yet it exhibits pronounced reduction in the shear wave velocities near the tetragonal–cubic phase boundary, suggesting that the low-velocity zones observed near the lowermost mantle may be caused by subducted oceanic crust rich in CaPv with temperature lower than ambient mantle, in contrast to the prevailing view that low velocity structures are associated with elevated temperatures.

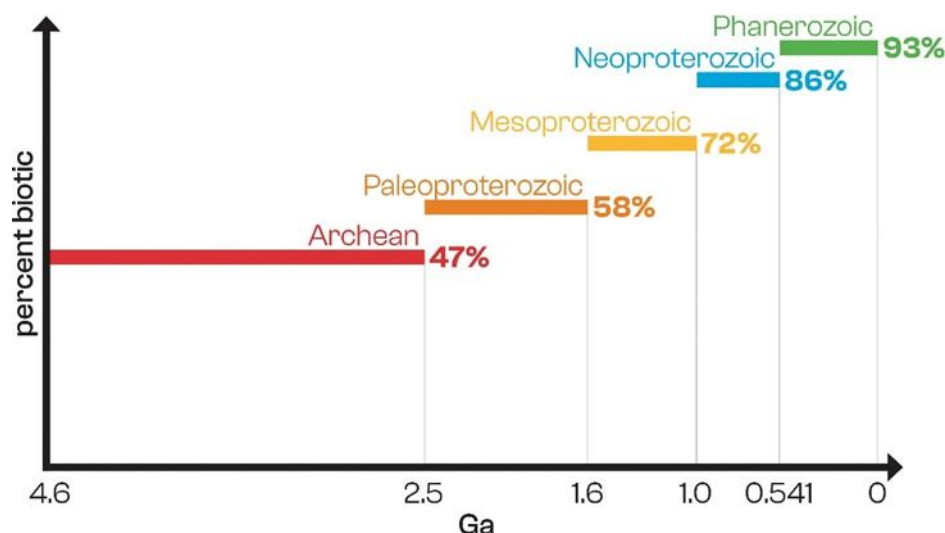
Phase diagram of CaPv.



Organic geochemical evidence for life in Archean rocks identified by pyrolysis–GC–MS and supervised machine learning.

Wong, M.L., A. Prabhu, C.O. Alexander, H.J. Cleaves, G.D. Cody, G. Hystad, M. Bermanec, W. Bleeker, C.K. Boyce, A. Corpolongo, A.D. Czaja, S. Das, R.R. Gaines, D.D. Gregory, J.A. Jaszczak, E.J. Javaux, **J. Jodder**, A.H. Knoll, M. Van Kranendonk, K.M. Maloney, N. Noffke, R. Rainbird, E. Slaughter, E.E. Stüeken, R.E. Summons, F. Westall, J. Wiemann, S. Xiao, & R.M. Hazen, (2025). PNAS 122 (47) e2514534122. <https://doi.org/10.1073/pnas.2514534122>

Teasing out biochemical information from ancient organic-rich sediments, notably the timing of the emergence of photosynthesis relative to the inferred oxygenation of Earth’s atmosphere, remains a challenging opportunity. To tackle this problem, Wong et al. analyzed 406 diverse ancient and modern samples and used supervised machine learning to discriminate samples of biogenic vs. abiogenic origin, as well as photosynthetic vs. nonphoto-synthetic physiology. Comparing organic-rich samples of uncertain affinity to their training data, ca. 3.33-billion-year-old sedimentary rocks group among microbial samples, and rocks as old as 2.52 billion years ally with more recent photosynthetic life. The application of supervised machine learning thus approximately doubles the interval within which fossil organic matter can be shown to retain molecular information of evolutionary relationships and physiology.



The percentage of biogenic (vs. abiogenic) samples increases significantly through time.

From the Director

The Centre for Planetary Habitability has existed for nearly three years now. The journey began in September 2022 when the Research Council of Norway announced the nine new Norwegian Centres of Excellence. PHAB started on March 1st, 2023, the grand opening happened in September 2023, and this document is our second annual report covering the events and achievements of the year 2025.

In July of 2025, I took over as a director of PHAB, one year earlier than planned in the original application, but in absolute time the transition was scheduled for 2025 anyway. A big thanks to Trond for steering PHAB through its constitution and continuing the advice as a Vice-Director!

From an organizational point of view, the role of the director shall comprise leadership on the organisation's scientific strategy, research activities and innovation to maximize scientific impact and discoveries, and yes, we are a Centre of Excellence! Our strategy is the PHAB application. The Centre is in its formative phase, and when I took over, we had hired one of two new professors, we have hired young and talented new staff, and we look forward to the tasks ahead of **recognizing and characterizing the key conditions that make a planet habitable**.

But there is the “pinch of salt”: Colleagues at PHAB won ERC grants, but none could stay. We are supposed to hire another professor, but we currently have a hiring freeze at the Faculty. Furthermore, regulations that shall protect the rights of workforce, limits our ability to employ task-oriented and excellent personnel... Building a Centre of Excellence is not as easy as it may seem.

On the bright side, we currently have a reasonably healthy budget for hiring PhD candidates and postdoctoral researchers. We can also report eleven contributions in the journal families Nature, Science and PNAS in just the one year, and close to 90 publications in total. I would say, not bad for about 40 researchers in one year. We could also celebrate four new doctors during 2025. PHAB colleagues won three additional Research Council of Norway funded projects, GOE-PHAB - to investigate the Earth's atmospheric Great Oxygenation Event and one of Earth's major tipping points, GREP - the Galactic Recipe for Exo-Planets, and GIANTS - on Giant Impact Accretion of Terrestrial Systems. Congratulations!

Thank you, to all PHAB colleagues, for the productivity in science, your academic curiosity and the genuine ambition to study the natural world, by measuring and modelling, what we still try to understand, and which is the scientific strategy of PHAB:

The idea that worlds around other stars could develop and maintain environments hospitable to life — in a way like our planet — has captivated scientists for centuries. Yet, to investigate this question, we must recognize and characterize the key conditions that make a planet habitable. This endeavour is the prime objective for PHAB, and a centre dedicated to research on the habitability of star-planet systems is the first of its kind in Norway.

Planetary habitability is a measure of a planet's potential to provide environments hospitable to the life that we know, and commonly defined by the presence of liquid surface water. However, a planet's orbital parameters, surface and interior temperature, interior composition and dynamics, surface tectonic style, magnetic field, rotation rate and

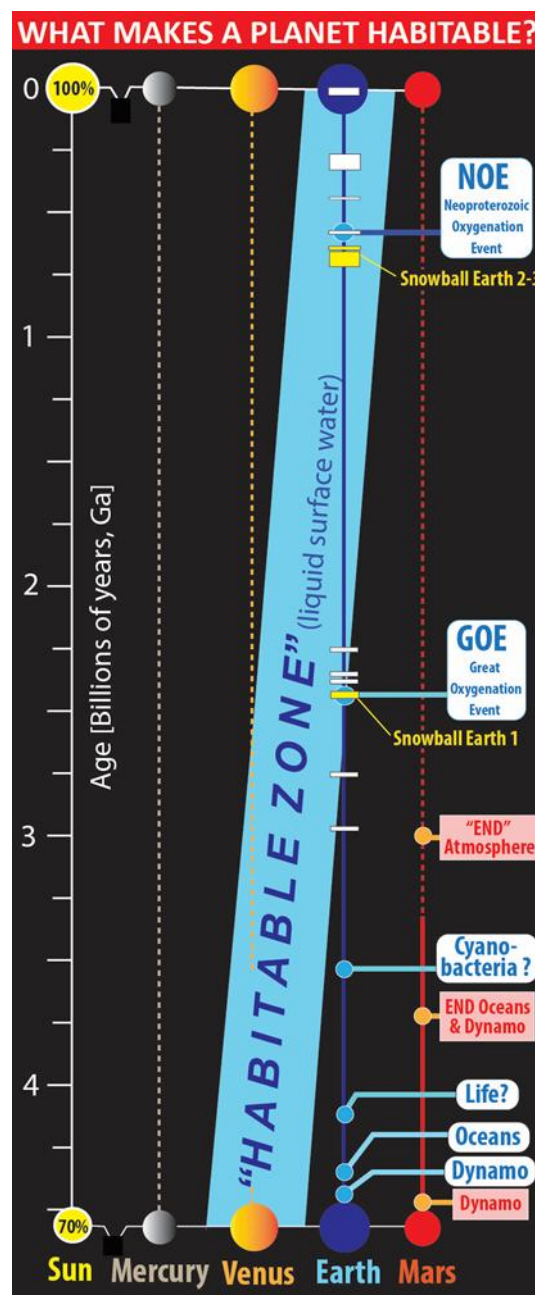
tilt, atmospheric composition and density, water mass fraction, as well as the type, age and elemental composition of its host star (location in the galaxy), are all key to its habitability. Importantly, habitability is time dependent. Our presently habitable planet was not originally in the “Habitable Zone” — and will fall outside it again in the far future.

The Earth-Sun distance and the present inventory of atmospheric greenhouse gases make the current surface temperatures optimal for complex life, but with a much fainter Sun in the deep past (by ~30%), early Earth was not at an ideal distance from the Sun. Instead, a dense greenhouse atmosphere probably saved us from runaway cooling and permanent icehouse conditions. Mars was once wetter and (arguably) warmer, but is now a permanent icehouse, whilst Venus has been a hothouse for an unknown time. These planetary siblings lack surface water, long-lived magnetic fields and plate tectonics, factors we consider to be key elements for long-term habitability. Additionally, the complex multicellular life we know requires an oxygenated atmosphere not identified elsewhere in the Solar System.

Earth’s habitability may have resulted from a chain of singular events. Yet, the most fundamental characteristics of its habitability are debated, and a major challenge is that habitability factors vary because they are time dependent due to changes in the Sun’s energy and our planet’s chemical, thermal and (thereby) physical and tectonic evolution.

An in-depth knowledge of Earth-like habitability, and how our planet sustained conditions for life’s evolution over geological time scales, is critical for identifying habitable planets around other stars. A new understanding of planetary habitability is especially important and timely as we have now embarked on an unprecedented era of exploration of extra-solar planetary systems.

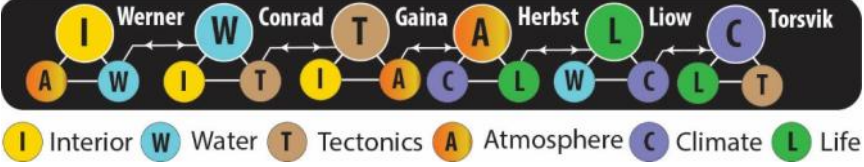
We keep our fingers crossed for the applications, which have been and will be submitted during 2025 and 2026 to the European Research Council, the Research Council of Norway, and looking forward to progress and outcomes of the plenty and diverse projects and research activities already active at PHAB. The 2025 results of PHAB’s efforts are reported here:



The “Habitable Zone”, known icehouses (horizontal white bars) and three Snowball Earth conditions (horizontal yellow bars) when the Earth was almost fully glaciated.

Activity by Theme

PHAB activities comprise three interrelated research themes: (1) PLANETS AND EARLY EARTH, (2) MODERN EARTH and (3) EXO-EARTHS, each headed by two principal investigators (PIs). Research themes are structured in work-packages headed by PIs or staff members. Each PI also fronts a triplet of interconnected research topics: tectonics, interior, atmosphere, climate, water & life.

 Planets/ EARLY EARTH Theme Leaders: Carmen Gaina and Trond Torsvik Addresses planet formation, evolution, and comparative planetology to identify the initial conditions for habitability and how a planet's composition and interior influence its ability to nurture a biosphere. Fundamentally, this requires accurate timelines to constrain critical changes in the environment and climate, and for Earth specifically, the conditions for early life and Earth's evolution as a habitable planet. Work Packages WP1.1—Timelines WP1.2—Planet Formation WP1.3—Atmosphere Evolution WP1.4—Early Oceans WP1.5—Magnetic Fields WP1.6—Tectonic Regimes and Interior WP1.7—Snowball Earths and Tipping Points WP1.8—Conditions for Early life	 MODERN EARTH Theme Leaders: Clint Conrad and Lee Hsiang Liow Addresses the most recent 750 million years, starting from the initial dispersal of the oldest well-established super-continent, Rodinia, and accompanied by dramatic cooling events (Snowball Earths), the onset of modern plate tectonics, unprecedented carbon-cycle fluctuations, rising atmospheric-oxygen levels, and the rapid evolution of multicellular organisms, including animals. Work Packages WP2.1—Plate Tectonics and Paleogeography WP2.2—Volatile Cycles WP2.3—Paleoclimate Proxies WP2.4—Paleoclimate Models WP2.5—Drivers of Biodiversity	 EXO- EARTHS Theme Leaders: Konstantin Herbst and Stephanie Werner Aims to identify planets orbiting other stars that potentially are, or have been, habitable. Currently exoplanets are recognized in a wide range of planetary systems. The physical parameters of the central stars and planets are quite diverse, and of the more than 7000 known planets, as few as 5% are potentially Earth-like in terms of mass and orbital distance. Work Packages WP3.1—Observational Constraints WP3.2—Asteroseismology WP3.3—Exo-Planet Formation WP3.4—Exo-Planet Structure WP3.5—Exo-Planet Evolution WP3.6—Space Weather Impact WP3.7—Fate of Habitable Planets
Principal Investigators (PIs)  Each PI fronts a triplet of interconnected research topics		

Theme 1 (Planets/Early Earth) addresses planet formation, evolution, and comparative planetology to identify the initial conditions for habitability and how a planet's composition and interior influence its ability to nurture a biosphere. The theme is structured into eight work packages, many also relevant for Modern Earth. In addition, several externally funded projects belong to this theme. We also participate in ESA and NASA Space Missions (NASA/ESA Mars Sample Return and ESA ExoMars rover) and the International Continental Drilling Program (ICDP).

Theme Leaders: Carmen Gaina and Trond Torsvik



The transience and fragility of habitability is engraved in our own planetary history. After the Sun formed, followed by the first solids 4.567 billion years ago (Connelly *et al.* 2012), a proto-planetary disc coalesced and evolved from gas and dust to planetesimals and planetary embryos (**WP1.2**). Through violent collisions, these objects grew to form Earth and the other planets within a relatively short time interval. Shortly thereafter, our young planet seems to have collided with another massive proto-planet, leading to a circum-terrestrial disc of ejecta that gave rise to our Moon (Canup & Asphaug 2001).

Characterizing the initial boundary conditions for habitability requires absolute ages (**WP1.1**), but isotopically dated and well-localised rocks are only available from the Earth and Moon. Temporal constraints for other planetary bodies therefore rely on cratering-based age-determination calibrated at the Moon. Considering revised radiometric ages of the Moon (Werner *et al.* 2023) and modern planet formation models (**WP1.2**), cratering-based ages must be re-calibrated. That will reveal the timing of major changes in orbital architecture of our Solar System with implications for understanding volatile delivery by small bodies (asteroids/comets) and the timing of the earliest possible life (**WP1.8**). Environmental conditions and related propensity for life (global water layer vs. land-ocean distribution) are linked to the tectonic regime (e.g. stagnant lid vs. plate tectonics). Thus, the interlinked rock and volatile cycles of the life-forming elements (CHNOPS) were significantly modified when Earth transitioned into a plate tectonic regime, but *when* this occurred is debated (**WP1.6**), ranging from the Hadean (>4 Ga) to 700 Ma and depend on *how* plate tectonics is defined.

Liquid surface water was present on Mars in its early history (**WP1.4**) but any seas, rivers or lakes disappeared, perhaps by ~3.7 Ga. The precise timing and cause of the permanent change (*tipping point*) from a wet and likely warm planet to a permanent icehouse is unclear (**WP1.3/1.7**) and requires improved chronology to distinguish internal or external forcing. Mars also once had a *magnetic field*, but as the smaller planet cooled, it lost its magnetic field and its *atmosphere* (**WP1.3**) and transitioned into a permanent icehouse. Using dynamo (**WP1.5**) and mantle flow/tectonics (**WP1.6**) simulations, cratering-based age-determination (**WP1.1**) and climate models, we explore *why* and *when* the Martian field stopped and *how* this influenced atmospheric loss and global cooling.

Earth has been in a greenhouse state (Fig. 1.1) during most of its life span, interrupted by a dozen icehouse periods and three Snowball Earth events (**WP1.8**). The reasons for such cooling events are disputed but often explained by enhanced rock weathering. Interestingly, the oldest Snowball Earth (~2.4 Ga) is contemporaneous with the Great Oxygenation Event (GOE). If oxygenation occurred first, then rising atmospheric oxygen levels may have

triggered rapid oxidation of atmospheric methane, weakened the greenhouse effect, and forced a catastrophic climate change. Evolutionary innovation by the biosphere (oxygen) may therefore have caused the first Snowball Earth (**WP1.7**). But *when, where* and ultimately *how* the biosphere innovated requires an integration of geological and biological insight.

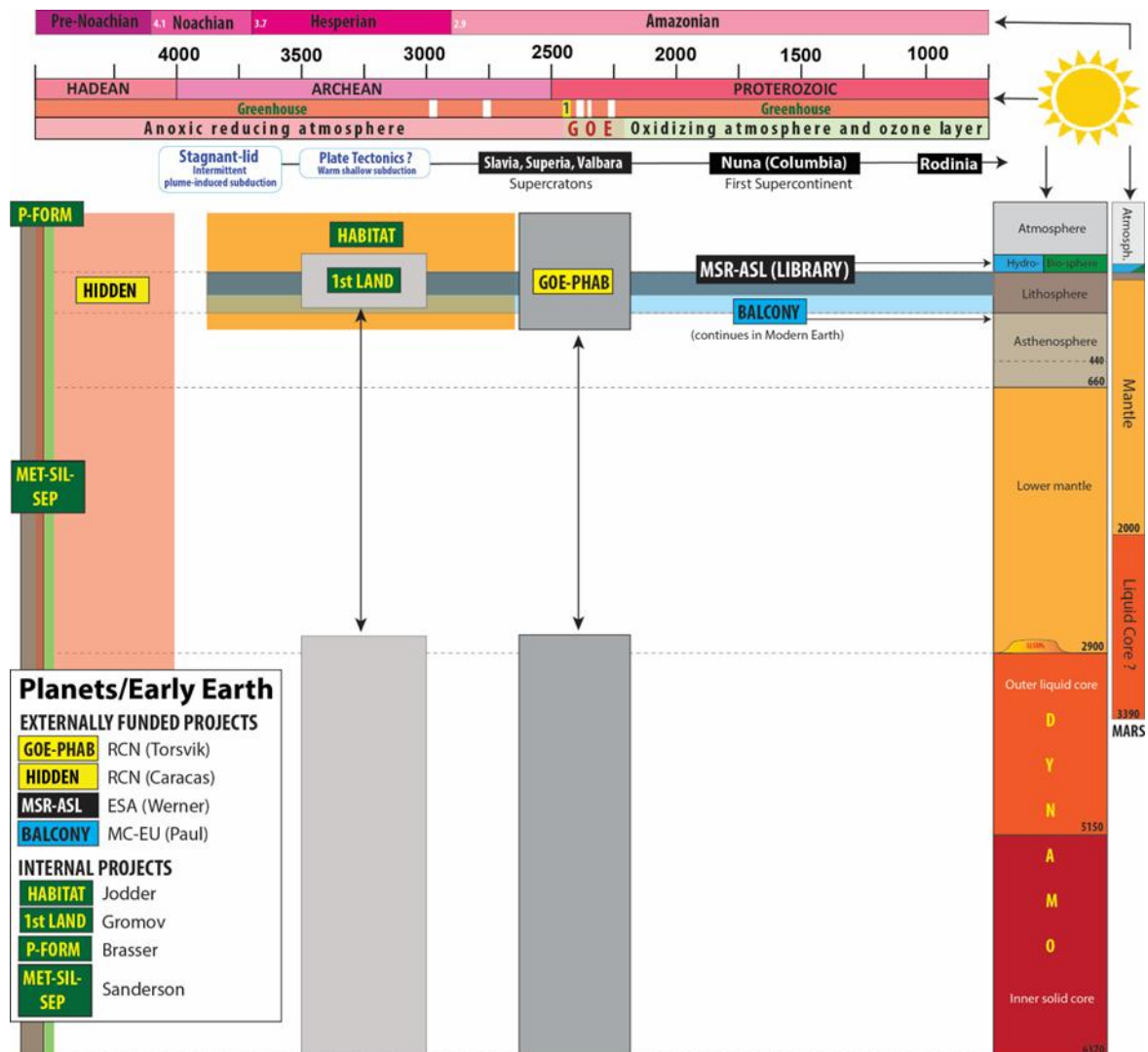


Figure 1.1 Early Earth timescale, greenhouse vs. icehouse (white, yellow=Snowball Earth 1) conditions, atmosphere characterization (GOE, Great Oxidation Event), tectonic regimes and timelines for supercratons (Slavia, Superia, Valbara) and supercontinents (Columbia and Rodinia) during Early Earth. The tectonic regime when the mantle was at its warmest may have been one of plume- (or impact-) induced subduction type or squishy-lid type. The first continents probably formed by partial melting of hydrated metabasalts, and the assembly of crust into supercratons suggest a change to a plate tectonic alike regime with lateral motion and subduction before 2.8 Ga.

Right-hand column shows the Earth's internal structure (LLSVP, Large Low Shear-wave Velocity Province) and active externally and internally funded projects are indicated in both time and depth. Projects LAND and GOE-DEEP includes paleomagnetic studies and thus can shed lights on dynamo processes. Planetary core dynamos initially draw their power from slow core-cooling due to heat loss to the mantle and a gradual crystallisation of a solid inner core provides additional power for the dynamo and increases the atmospheric protective power. Inner core nucleation may have occurred only very late in Earth's history, perhaps at the dawn of the Phanerozoic (~541 Ma).

Planet formation in the solar system (Brasser)

Aim: Understand how the solar system came to be as it is today.

Objectives:

- Building the giant and terrestrial planets of the solar system, paying special attention to their different compositions.
- Establish what was the structure of the gas disc around the young Sun.

Links to PHAB work packages: WP1.1, 1.2, 3.2, 3.3.

How did the planets in the solar system form? Many studies have been performed to understand the formation of terrestrial planets, and many models exist in the literature. The first model that relied on planetesimal accretion to grain traction is dubbed the classical model wherein the giant planets were assumed to have fully formed and reside on their current orbits. Unfortunately, the classical model suffers from the 'small Mars' problem, in which the mass of formed planets near the current orbit of Mars are systematically too great. Proposed solutions for this problem are: limiting the width of the initial planetesimal disc in the annulus model, invoking the migration of the giant planets to truncate the planetesimal disc with the Grand Tack model, lowering the planetesimal surface density beyond Mars with the depleted disc model, steepening the surface density slope of the planetesimal disc, and invoking an early dynamical instability of the giant planets to stir up the inner Solar System. One new model that was invented at PHAB is the 'implantation model', which relies on the concurrent formation of the giant planets with the terrestrial planets to implant material from the outer solar system into the inner solar system. This implanted, cold, volatile- and organic-rich material could have delivered Earth's water and some biomolecules.

We tested this in Brasser (2025a) where we investigated the effect of growing giant planets on the formation of terrestrial planets, splitting the investigation across two publications (one published, one in preparation). It turns out that the mass in planetesimals that are being scattered by Jupiter into the inner solar system (Fig. 1.2) and be consistent with the isotopic composition of the inner planets, is only 1 Earth mass. This is rather low, and follow-up studies that consider the inflated radii of Jupiter and Saturn while these planets are growing is ongoing.

The results from these simulations were used to investigate the rate of impact-bombardment onto the terrestrial planets (Brasser, 2025b; Fig. 1.3), and whether this comports with the lunar chronology of Werner et al. (2023). Investigation is ongoing, but early results indicate that the population of leftover planetesimals must mostly been Mars-crossing, but not Earth-crossing. This results places strong constraints on the orbital distribution of planetesimals from terrestrial planet formation, and therefore on the initial distribution of solids in the terrestrial region – whether spread out, or in a compact ring near 0.8 au.

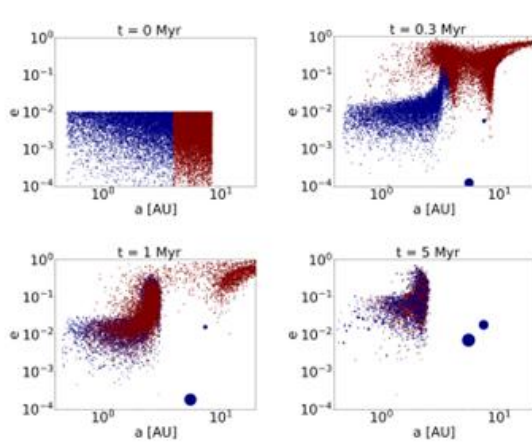


Figure 1.2 Implantation of outer solar system material (burgundy) into the inner solar system while the gas giants are growing. (Brasser 2025a).

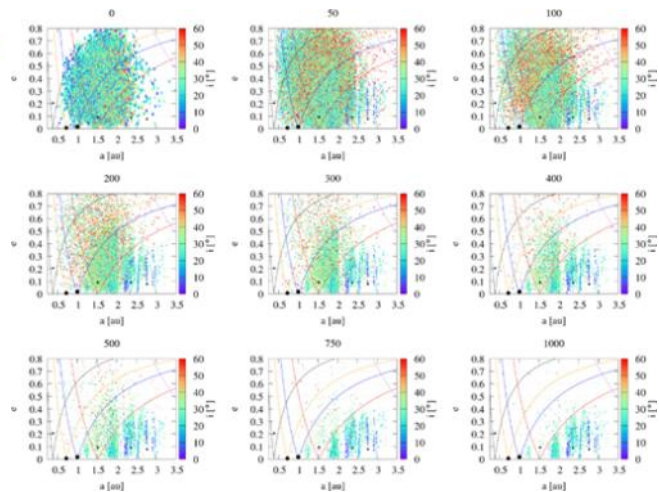


Figure 1.3 Evolution in semi-major axis and eccentricity of planetesimals left over from terrestrial planet formation (Brasser, 2025b). The colours pertain to the inclination.

MET-SIL-SEP (Post. Doctoral project: Sanderson, Conrad)

Aim:

Investigate the dynamics of metal-silicate separation in magma oceans following Fe disproportionation or FeS exsolution and determine the implications for mantle and surface redox evolution and dynamo generation.

Objectives:

- Determine the characteristic timescales for metal droplet segregation through silicate for a range of melt fractions and planetary properties (Earth, Mars, Venus).
- Investigate the importance of time-dependent variables (mantle melt fraction, planetary rotation) on droplet separation and the implications for mantle redox evolution.
- Determine whether droplet settling can affect dynamo generation.

Links to PHAB work packages: WP1.2, 1.5, 1.6

Post-accretionary magma oceans are a defining stage in a rocky planet's history. Processes within these magma oceans set the initial conditions for planetary thermal and chemical evolution. Understanding these initial conditions is vital to reveal the triggers of the divergent evolution of Earth, Mars and Venus and utilise geochemical tracers of these planets' histories.

Metal-silicate separation is a crucial magma ocean process and occurs either through Fe disproportionation or FeS exsolution. Movement of metal produced by these mechanisms from the mantle to the core has three key influences on planetary evolution. First, it will generate a redox gradient within the planetary mantle and alter the surface redox state. Second, metal segregation to the core will lower the mantle concentration of highly siderophile elements (HSEs) prior to late accretion. The degree of HSE replenishment required during late accretion to match present-day mantle abundances constrains the amount of material added in late accretion. Third, the temperature and quantity of metal arriving at the CMB will alter the CMB temperature gradient. This may inhibit or enhance dynamo generation and could contribute to the differing dynamo histories between Earth, Mars and Venus. Both geochemistry and geophysics are required to understand the implications of Fe disproportionation and FeS exsolution on planetary evolution. While the geochemistry of these processes has received much attention, detailed research into the physics of the movement of this material from the mantle to the core is lacking.

How metal moves from the mantle to the core depends on the mantle's melt fraction (Fig. 1,4). In a runny magma ocean, metal droplets could reach the core via Stokes' settling, but this will depend on droplet size and the vigour of mantle convection, which may permanently entrain droplets or transport metal to pressures where it will recombine with silicates. In a partially crystallised magma ocean, metal droplets could reach the core via percolation, but timescales for this will depend on metal-silicate interfacial energies and silicate melt fractions.

Transport timescales and mechanisms will change the degree of metal-silicate equilibration at different mantle depths, and hence the redox gradient and HSE abundances within the mantle. The degree of thermal equilibration as material moves to the CMB will also change the CMB heat flux available to drive a dynamo.

Since the beginning of the project in November 2025, I have focused on a literature review of magma ocean chemistry, droplet dynamics (both metal and silicate crystals) in magma oceans and different modelling approaches to this topic. I have attended two conferences to improve my understanding of magma oceans and discuss my ideas with experts in the field. These conferences also enabled me to establish connections with researchers who have numerical codes that I would like to use.

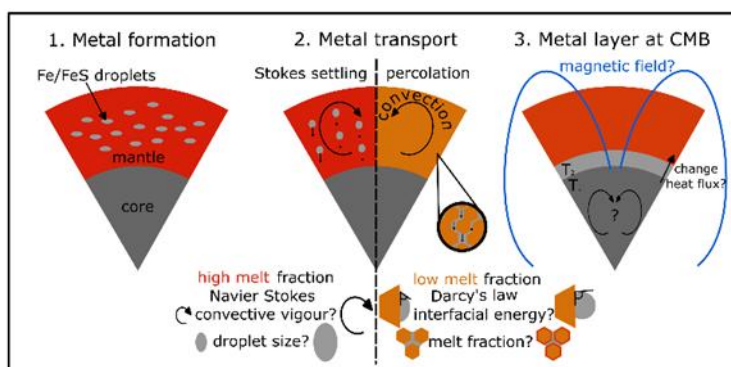


Figure 1.4. Transport mechanisms for metal within the mantle

HIDDEN (RCN FRIPRO project: Caracas)

Aim:

Identifying potential geochemical reservoirs in the deep Earth that were isolated from contact with the surface during geological time. To do so, we calculate the solubility of the noble gases in iron and various silicate melts and crystals to identify their best entrapment and storage place.

Objectives:

- Calculate the partitioning of He between the magma ocean and the molten outer core.
- Estimate the loss of the gases into the early atmosphere.
- Determine the entrapment and potential escape of the noble gases in crystalline aggregates.
- Obtain a consistent time-evolution image of the outflow of noble gases from the deep interior.

Links to PHAB work packages: WP1.3, 2.2, 3.5

We investigate the physical mechanisms controlling volatile retention and loss during the magma-ocean (MO) stage of terrestrial planet formation, with a particular focus on noble gases and carbon. Using first-principles molecular dynamics, we quantify how pressure, temperature, and melt composition govern degassing, diffusion, and partitioning processes that ultimately shaped the early Earth's atmosphere and deep volatile reservoirs. We find that noble-gas degassing from MO (Fig. 1.5a) is strongly controlled by pressure, temperature, and the presence of other volatiles (Davis and Caracas, 2024). Helium does not nucleate bubbles on its own but is efficiently stripped from the melt when carbon is present. CO₂ stabilizes vapor cavities, increases melt porosity, and acts as a carrier gas, enhancing He loss by up to a factor of two under early-Earth surface conditions (Fig. 1.5b). These results imply a thicker, hotter, and more carbon-rich early atmosphere than previously assumed, with significantly larger noble-gas fluxes to the atmosphere and a prolonged magma-ocean cooling time due to enhanced greenhouse insulation.

Concerning the other noble gases (Davis and Caracas, under review), their relative volatility increases with increasing atomic size, Xe being the most volatile, and He the least. Our results indicate that more noble gases may have been stored in the Earth's mantle than previously thought. This is also supported by the diffusivities of the noble gases, which may mitigate the strong partitioning of the larger noble gases into the vapor (Saurety et al., 2024). Ar, Kr, and Xe diffuse less quickly through silicate melts, inhibiting their ability to reach nucleated nanobubbles. Thus, they degas less efficiently than is expected from the solubility numbers alone, indicating an increased retention in the magma ocean. Partitioning simulations further show that He strongly prefers the silicate melt over the liquid core at all magma-ocean conditions (Ozgurel and Caracas, 2023). Thus, over geological time, He and the other noble gases are expelled from the core and accumulate in the MO. At the surface, under the hot, dense early atmosphere, He therefore remained largely trapped in the magma ocean and degassed efficiently only at later stages, providing a viable mechanism for the preservation of primordial helium in deep mantle reservoirs sampled by present-day plume volcanism.

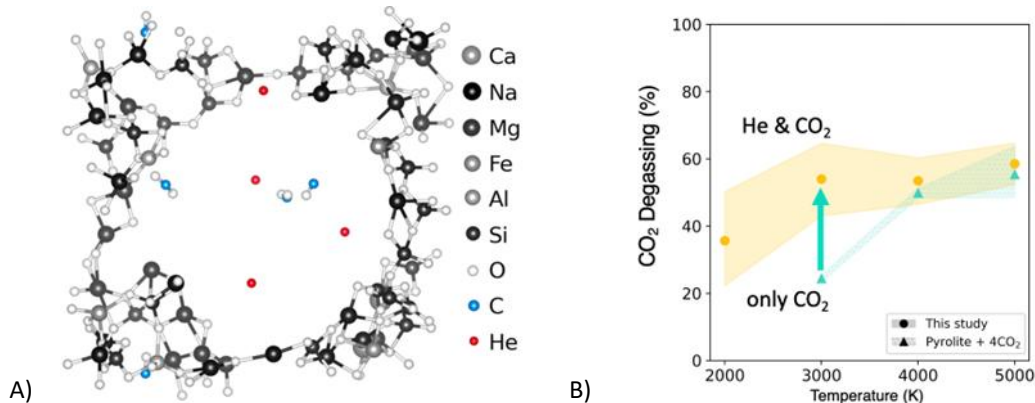


Figure 1.5 (a) Vapor-containing nanobubble coexisting with pyrolite melt at 0.5 kb and 3000 K. (b) The joint presence of incompatible volatiles enhances their degassing.

HABITAT (Post. Doctoral project: Jodder, Torsvik)

Aim:

Explore Earth processes and habitable conditions on early Earth

Objectives:

- The case of the Archaean Ocean: new insights from the Singhbhum and Kaapvaal cratons.
- How diverse was the early microbial ecosystem during the Archaean times?
- Habitable conditions during the Archaean: links to ancient Large Igneous Provinces (LIPs) and early life.

Links to PHAB work packages: WP1.4, 1.6, 1.8

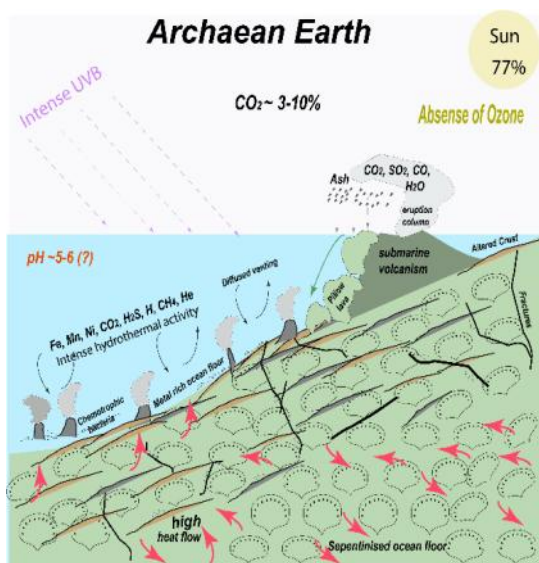


Figure 1.6 Schematic illustration of Archaean Earth conditions. Note widespread sub-marine volcanism and hydrothermal activity with low solar luminosity, high CO_2 levels.

Notably, preliminary data from the 3.4 Ga old Tomka cherts show similarly low $\delta^{18}\text{O}$, adding to this debate (Fig. 1.7). Our triple oxygen isotope analyses reveal these cherts were not in equilibrium with seawater. Their isotopic signature is multifaceted, recording overlapping influences from diagenesis, paleo-heat flow, and temperature. The conventional $\delta^{18}\text{O}/^{16}\text{O}$ method is insufficient; only a holistic triple-oxygen isotope (^{16}O , ^{17}O , ^{18}O) approach can effectively disentangle complex Archaean sedimentary records and advance our understanding of early ocean conditions and biogeochemical cycles. In this context, Earth's earliest biosphere was likely energy-limited, with productivity concentrated in volcanically active basins fueled by hydrothermal chemicals like H_2 and Fe^{2+} (Fig. 1.6, Stüeken, 2025). Such **productive hotspots** are rarely documented from the Archaean record so far. We report exceptionally high total organic carbon content (TOC up to 17.45 wt.%) for the first time in ~3.53 Ga sedimentary rocks from South Africa's Nondweni Greenstone Belt. Coupled light $\delta^{13}\text{C}$ (down to -39.6‰) and moderately positive $\delta^{15}\text{N}$ values suggest a methane-cycling ecosystem dominated by nitrogen fixation, while sulfur isotope anomalies ($\Delta^{33}\text{S}$ up to 2.31‰) indicate a low-oxygen, sulfate-poor atmosphere. These features are interpreted as evidence of Archaean hydrocarbon seepage driven by extensive mafic volcanism, supporting a diverse early microbial biosphere. We propose the term "**Nondwenite**" for this distinct, organic-rich rock type (Jodder et al. 2025).

The physicochemical state of the Archaean Ocean, particularly seawater temperature gradients, defined critical boundaries for early habitable conditions (Fig. 1.6). Traditional paleothermometry relies on $\delta^{18}\text{O}$ values from chemical sediments (i.e. cherts, carbonates, phosphates), yet interpretations of the secular $\delta^{18}\text{O}$ trend are highly divergent—ranging from **cold**, ^{18}O -depleted oceans to **hot** ($\sim 80^\circ\text{C}$), or **modern-like seawater**. We report new oxygen isotope data from well-preserved 3.4 Ga banded cherts of the Tomka formation (Singhbhum Craton, India), exhibiting some of the lowest $\delta^{18}\text{O}$ values in the Archaean record (down to $+7.5\text{‰}$ VSMOW, Fig. 1.7). If interpreted through conventional $\delta^{18}\text{O}$ systematics alone, these values would imply seawater either exceedingly hot or isotopically light beyond current geodynamic and thermodynamic constraints. Archaean cherts consistently show lower $\delta^{18}\text{O}$ and higher $\Delta^{17}\text{O}$ than modern equivalents (Zahnw, unpublished data). The cause of low $\delta^{18}\text{O}$ is debated; it may reflect lower seawater $\delta^{18}\text{O}$ from intense CO_2 -driven alteration (e.g., carbonatization; Herwartz et al., 2021) or higher Archaean heat flow (Tatzel et al., 2022).

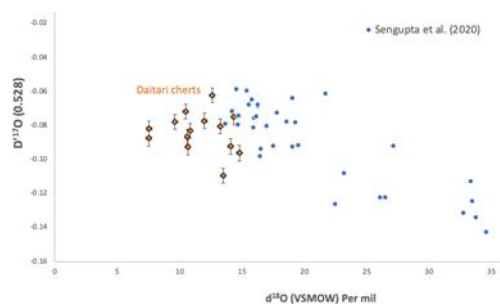


Figure 1.7 3.5 Ga old Tomka cherts

FirstLAND (Ph.D. candidate project: Gromov, Jodder, Conrad, Torsvik, Gaina)

Aim:

To document the growth of first continents on early Earth and their influence on paleoenvironment

Objectives:

- To determine Earth's tectonic conditions ~ 3.5 Ga that led to felsic volcanism.
- To reconstruct Earth's paleogeography around 3.5-3.0 Ga.
- To assess the distribution of most plausible habitable environments during the Archaean.

Links to PHAB work packages: WP1.3-1.6, 1.8

The Archaean (4 to 2.5 billion years old, Ga) record is critical towards understanding pivotal early Earth processes. But challenges persist due to a sparse Archean rock record, which is only 7% from today's crust. Fundamental questions yet to be resolved are: When did the first continents form? How much exposed land was available for early life? How pervasive/deep were the Archaean oceans? Subaerial land today is mainly formed by continental crust, but before the stabilization of the first cratons, at ca. 3 Ga (Kamber, 2015; Hofmann et al., 2022, Reimink & Smye, 2024; Rollinson et al., 2024), volcanic islands on early oceans may have had brief subaerial exposures. However, information related to this is rarely documented. Understanding the onset of felsic magmatism is crucial for understanding the role of early volcanic islands in the formation of the first continental crust.

Our work explores the oldest known preserved felsic volcanic rocks, which erupted around 3.5 Ga in the Kaapvaal (South Africa), Singhbhum (India), and Pilbara (Australia) cratons (Jodder et al., 2023). In 2025 we put together a set of rock samples from the three abovementioned cratons and extracted zircons from them. Oxygen isotopes ($\delta^{18}\text{O}$) from zircon crystals were analyzed as they are effective proxies for distinguishing the melt source between mantle-derived and crustal (e.g. Valley et al., 2005). The measurements were conducted using the Secondary Ion Mass Spectrometry (SIMS) at the GFZ laboratory in Potsdam, Germany. Our preliminary U-Pb-O results fit well in the new global Archean $\delta^{18}\text{O}$ compilation (ca. 13,000 data points), which hints that both the juvenile (purely mantle) melts and seawater-altered basalts remelting were important sources of felsic magmatism in Archean (Fig. 1.8). This suggests global heterogeneity of tectonic regimes, with plausibly stagnant intraplate zones (i.e. juvenile plume related melts) and zones of ocean-floor basalts remelting, possibly caused by crust overturn or sagduction-like processes.

The other crucial objective of our study is to reconstruct the paleolatitude of Singhbhum Craton at 3.5 Ga, which is known only back to ca. 2.8 Ga today (Kumar et al. 2017). We have completed demagnetization experiments on the samples collected from our fieldwork in 2024 in Daitari greenstone belt (Singhbhum Craton). Our planned assignments for the academic year 2026 will be to finalize all remaining measurements (i.e. in-situ $\delta^{18}\text{O}$, trace element geochemistry and Lu-Hf in zircon), interpret paleomagnetic data, and present preliminary results on European Geosciences Union 2026 in Vienna.

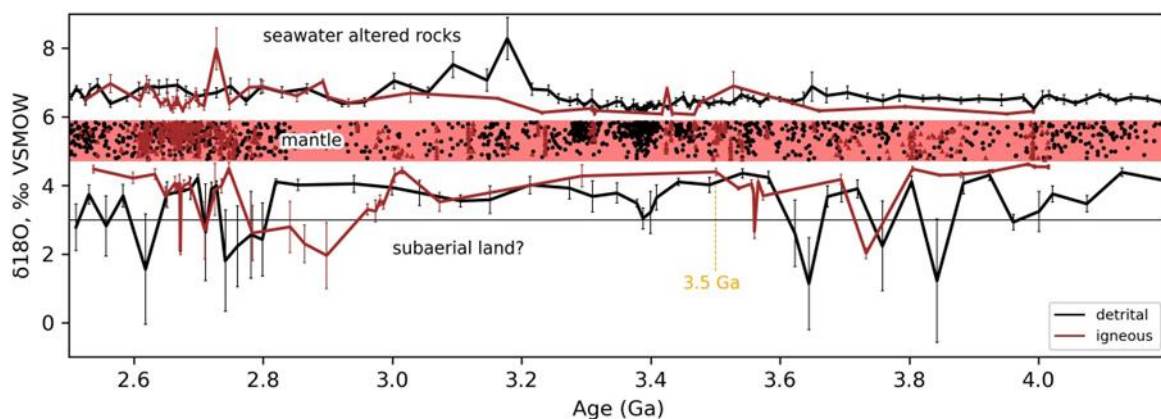


Figure 1.8 8 Gliding mean curves of $\delta^{18}\text{O}$, ‰ VSMOW from detrital and igneous zircons global compilation. Zircons in equilibrium with mantle ($\delta^{18}\text{O}=5.3\pm0.6\text{‰}$; dots within the red band) reflect purely mantle derived rocks. The curves above the mantle band reflect remelting of seawater altered rocks. The curves below the mantle reflect mixing with meteoric water, and values $\delta^{18}\text{O}<3\text{‰}$ potentially imply subaerially weathered rocks remelting. Error bars show Standard Error of the Mean (SEM).

GOE-PHAB (RCN FRIPRO project: Torsvik, Jodder)

Aim:

Understand the environmental changes that enhanced planetary habitability during the early Proterozoic.

Objectives:

- Building a paleogeographic framework regionally (Franceville/Congo Craton) and globally.
- Establishing absolute timelines for the Great Oxidation Event (GOE), Snowball Earth-1 and Large Igneous Provinces.
- Identifying the driver(s) for GOE and Snowball Earth, and ultimately.
- Determining the nature of the unparalleled carbon excursions that occurred in the aftermath of the GOE and Snowball Earth-1.

GOE-PHAB is part of GOE-DEEP (Gabon and Oxygenation of Earth – Drilling Early Earth Project), co-funded by the International Continental Scientific Drilling Program to obtain 11 drill cores from the Franceville Basin in Gabon (NW Africa). Drill targets (80% cored in 2025) span the time interval of key events in the early Proterozoic, and one of our objectives is to develop a global paleogeographic model based on paleomagnetic data from Gabon (part of Congo Craton). No high-quality paleomagnetic poles from the Congo Craton exists to constrain its 2.5-2.0 Ga paleogeography, but it may have been part of a supercraton named Supervaalbara. This Supercraton straddled the equator at ~2.42 Ga (Fig. 1.9a) and low latitude glaciogenic deposits (e.g. in the Kaapvaal craton) are evidence for Snowball Earth conditions.

A prevailing hypothesis for Snowball Earth-1 is that a series of low-latitude LIP events (starting at ~2.51 Ga) led to enhanced weathering that triggered a runaway icehouse process. But Supervaalbara covered only 25 million km² (Fig. 1.9a) and several cratonic LIPs were submarine and thus lowering the silicate weathering efficiency. The emergence of subaerial continents is debated but a substantial increase in their emergence may have occurred during the Late Archean/Early Proterozoic (Fig. 1.9b), increasing the weathering efficiency (CO₂ drawdown) and coinciding with Snowball Earth-1 and GOE. Rocks in warm/wet tropical environments weather the fastest, enhanced by extensive blankets of LIP-lava, but the potential cratonic surface area located within 10° from the equator during Snowball Earth-1 is small and the exposed land fraction may have been very limited. The prevailing Snowball Earth-1 hypothesis assumes that onset of GOE occurred *after* Snowball Earth-1, but GOE onset may have occurred between 2.5 and 2.43 Ga — and thus *before* Snowball Earth-1 (~2.42 Ga). GOE onset may perhaps have been linked with extensive LIP-related weathering and enhanced flux of phosphorus and other essential nutrients that accelerated cyanobacteria photosynthetic activity and oxygen production. **An alternative hypothesis** therefore postulates that rising atmospheric O₂ levels may have triggered rapid oxidation of atmospheric CH₄ (produced by methanogenic archaea), weakening the greenhouse effect, and forcing run-away cooling and catastrophic climate change. Evolutionary innovation by the biosphere may therefore have caused the first Snowball Earth.

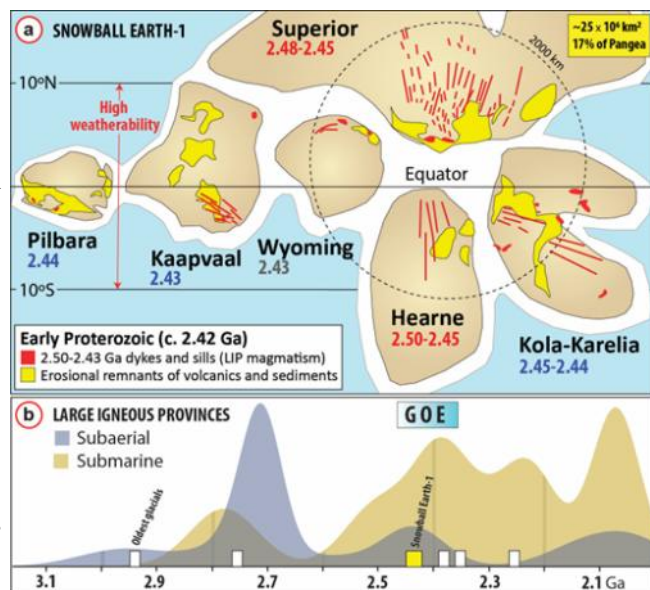


Figure 1.9 (a) ~2.42 Ga reconstruction of the Supervaalbara Supercraton at around Snowball Earth-1 time (Gumsley et al. 2017). Individual cratonic LIP ages with blue/red numbers are characterized as submarine/subaerial. (b) Kernel density estimates for submarine/subaerial continental LIPs (Liebmann et al. 2022). Icehouses (continental glaciations; white boxes) and Snowball Earth-1 are marked (yellow box).

BALCONY (MSCA project: Paul, Conrad)

Aim:

Develop global numerical models to investigate the physical mechanisms that maintain the thickness of cratonic roots over time through continuous disruption and self-healing.

Objectives:

- Examine the role of self-compression in craton thickening.
- Understand the mechanisms that have balanced craton thickness (self-compression, gravitational thickening, and viscous anisotropy) for billions of years and their geological implications.

Links to PHAB work packages: WP1.6, 1.8, 2.2

We investigate the evolution of craton thickness in the past 3000 Myr using 2-D thermomechanical numerical models. Petrological data suggests that cratons were initially thick and compositionally buoyant in Archean. To remain consistent with observation, we start each model with a thick and less dense craton (1% less than mantle) in a hot convecting mantle and let it run for 3000 Myr (Fig. 1.10a). Initially the thick craton is gravitationally flattened due to its lower density (Fig. 1.10b-e). With progressive cooling, thermal density becomes larger than the compositional density, and the craton thickness increases (Fig. 1.10e-g). Mantle flow is diverted along the viscous cratonic edges to self-compress the craton. Though the craton topography varies by a few hundred meters due to periodic compression and extension, the denser continental lithosphere remains stable. Most cratons in our models become thicker than 160 km depth after 1500 Ma. This is a crucial depth for generating kimberlite magma, which requires >160 km depth. Global kimberlite databases suggest that kimberlite eruptions were negligible before 2000 Ma. Eruptions became continuous after ~1500 Ma and accelerated after ~1100 Ma. This pattern is consistent with our models of a slowly growing craton thickness. We find that before 1500 Ma cratons were mostly thinner than the kimberlite window (Fig 1.10b, e). After 1500 Ma, their thickness increased, allowing them to host more kimberlites. Our results conclude that craton thickness also exerts a first order control on the kimberlite eruptions.

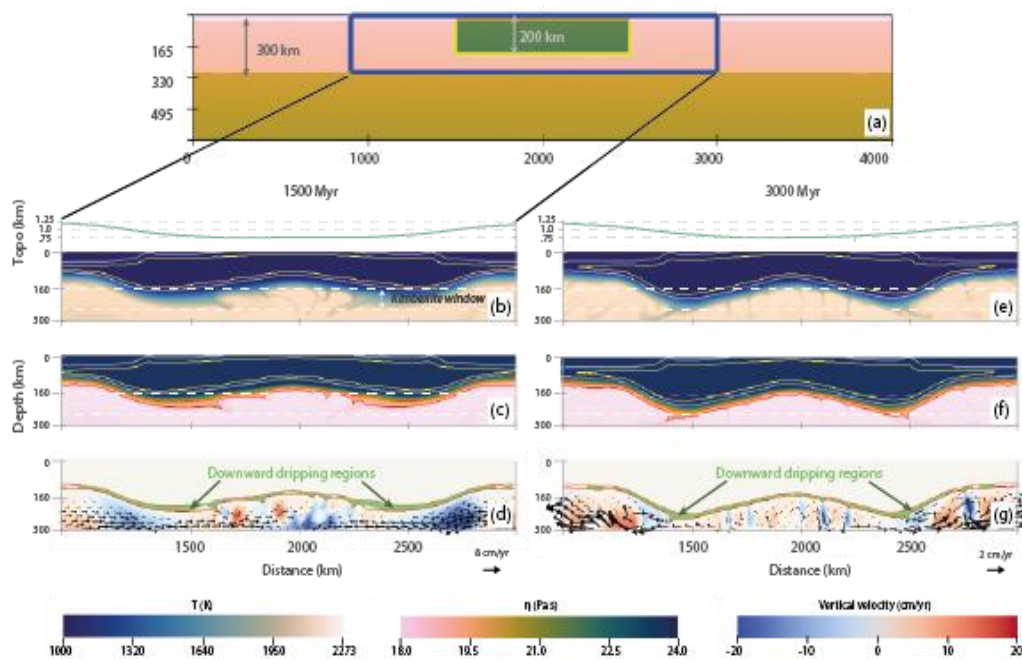


Figure: 1.10. Snapshots from a craton evolution model. (a) Initial model set up, background color: viscosity. (b-d) Snapshot after 1500 Myr, background colors are temperature, viscosity and vertical velocity, (e-g) Snapshot after 3000 Myr (present-day) with same description of background colors. Topography is plotted on top of each panel. Yellow lines indicate compositional boundary of craton, and the two red lines indicate isotherm of 1573 K, and 1873 K. Kimberlite window is marked by white dashed line.

Mars Missions Analogue Sample Library (ESA project: Werner, Krzesińska, Ciocco)

Aim: Establish and curate the *Mars Analogues Library and Collection* at the Natural History Museum of the University of Oslo

Links to PHAB work packages: WP1.8

Currently, NASA's Mars 2020 Perseverance rover is collecting, characterizing and caching into sealed tubes samples along its track through Jezero Crater on Mars. The samples represent both igneous and sedimentary formations or regolith materials that come from environments potentially habitable in Noachian (>3.8 Ga). When returned to Earth in later future, studies of these samples in laboratories will provide unprecedented insight into habitability (and inhabitation) of martian environments.

Simultaneously, another mission, ESA's ExoMars Rosalind Franklin Mission (RFM) rover is in final preparation for launch in 2028. Instrument suite of ExoMars RFM is designed to characterize mineralogy of Noachian rocks in subsurface of Oxia Planum. Vast deposits of phyllosilicates seen from orbit are likely to still preserve biosignatures and traces of ancient life and therefore they will be the primary target of detailed in situ characterization during RFM mission.

Preparation for both missions requires instrument testing on relevant analogue material. The data collected by NASA's Perseverance already allow for identification of terrestrial analogues that resemble the cached samples in one or more of the following properties: physical and textural characteristics, geochemistry, mineralogy, and the organic content. In preparation for best scientific use of returned samples and testing optimal analytical workflow, the *MSR Lead Scientists*, in coordination with the *MSR Campaign Science Group - Phase 1* (MCSG1) and the *NASA-ESA Joint Science Office* has initiated an analogue program to support early testing activities for engineering, curation, planetary protection and science. After evaluating analogue potential of several sites, suitable material was collected. Curation and distribution of these analogue samples was contracted by ESA to University of Oslo to provide systematic care of rocks and enable preliminary characterization. The curation facility is being developed at the Natural History Museum, University of Oslo. Within MM ASL we have been performing characterization of the analogues collected and we assess their mineralogical representativity when it comes to various essential features of rocks collected by Perseverance (such as departure from exact chemical composition of minerals or presence of individual alteration phases; Ciocco et al., 2025 EPSC and MetSoc).

Likewise, tests are required to assess ESA's Rosalind Franklin Mission instruments performance. Series of simulations are run on mineralogically or geochemically representative rocks in broader *Mission Reference Samples Campaign* under coordination of ESA. These analogue rocks must be curated in a systematic way until landing on Mars to enable real-mission tests and verifications.

To select respective analogue material for the above activities and to identify caveats of analytical techniques that require addressing via tests, input from scientific community was gathered by NASA and ESA. Members of MM ASL project were actively contributing to these activities. Agata Krzesińska took part in works of *Mars Sample Return Sample Receiving Facility Measurement Definition Team*, the team of international experts tasked to develop optimal concept of analytical operations to be performed on rocks returned from Mars. Final report of the team was published in 2025 (Carrier et al., 2025) and it provides a list of all potential impacts that analytical techniques may have on martian rocks with recommendations of areas for testing. For their work, the team was awarded **NASA Honor Award**. All MM ASL members regularly participate in works of ExoMars Mission Reference Samples Campaign. Furthermore, we provided 3 out of 13 analogue samples used currently as reference for payload testing activities (Bultel, Krzesinska et al., 2025 EPSC).

To further support preparation for sample return studies and enhance interpretation of data collected by Perseverance in-situ, we investigate the possible overprint of impact cratering and aqueous alteration in rocks. Jezero Crater is an impact crater that after formation hosted a lacustrine system. Impact craters are of crucial interest when it comes to astrobiology. For instance, they might provide shadowing, to allow the formation and survival of water ice on bodies (such as the Moon). Additionally, fractures in impacted basement rocks can act as a shelter from harmful radiation and dust to micrometric species. Most importantly, heat released during impact-forming event can trigger long-lasting hydrothermal systems on planets (such as the Early Earth and Mars), capable to support formation and persistence of organisms.

While all processes are recorded in mineral composition, understanding how fluids affect rocks that have undergone strong shock deformation from remotely sensed data solely, is currently challenging.

To support interpretation of habitability potential of Jezero Crater, we have experimentally reproduced impact conditions and aqueous alteration on analogue basalt material.



Artist representation of what Jezero Crater may have looked like ~3.8 billion years ago.

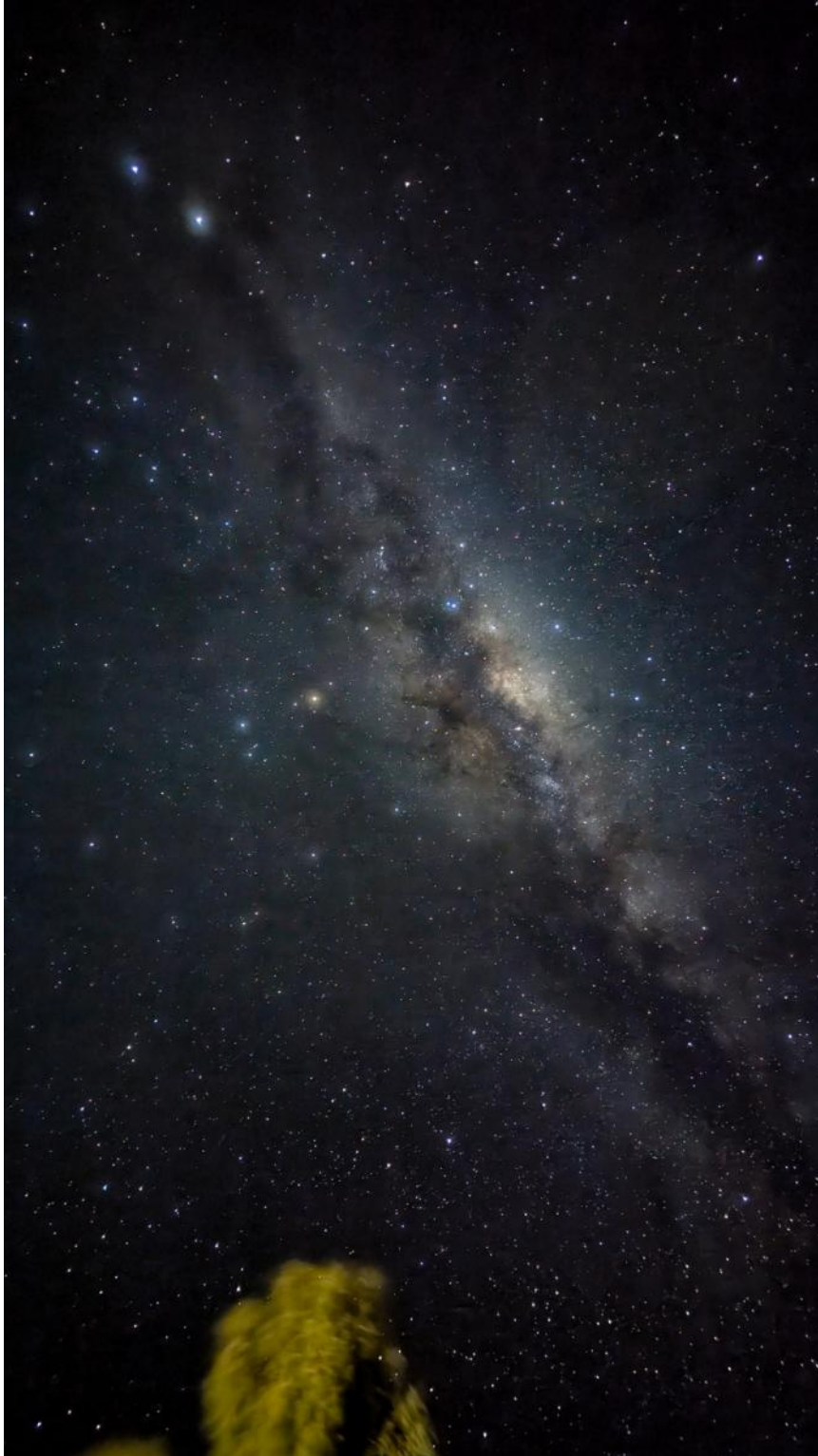
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View of the Milky Way from Yarrabubba crater, Australia, July 2025.

Photo: Marine Ciocco.

Theme 2 (Modern Earth) addresses the most recent 750 million years, starting from the initial dispersal of the oldest well-established supercontinent Rodinia. The theme is structured into five work packages in addition to many externally funded projects.

Theme Leaders: Clinton Conrad and Lee Hsiang Liow



The solid Earth's dynamic surface (lithosphere) is the interface between its interior and the ocean and atmosphere. Paleogeography is therefore a critical component of our Earth System Model (**WP2.1**). Full-plate paleogeographic models, pioneered by PHAB scientists (e.g., Domeier & Torsvik 2014), also enable direct estimation of surface-mantle fluxes to inform time-dependent models for water cycling between Earth's surface and interior (**WP2.2**), and to estimate plate tectonic degassing (CO₂ source). The latter serve as input for long-term climate models (Torsvik et al. 2024). Our global full-plate model must be constructed for the past 750 Myrs but will also be extended to include the regions (dynamic polygons) that defined exposed and flooded land through time. This allows us to parameterize silicate weathering (CO₂ sink) for 3D climate and carbon cycle simulations. Through PHAB, a unified full-plate model will be used to estimate both CO₂ sources and sinks for climate modelling (**WP2.3**). This will allow us to expose the cause(s) for greenhouse vs. icehouse conditions.

Evolutionary pressures are inflicted on species by other organisms and by changing environmental conditions imposed by a dynamic and evolving planet. The Cambrian radiation was one of the most significant evolutionary transitions seen in the fossil record, where all major animal phyla evolved. The evolutionary diversification that followed during the Mid-Ordovician (~470-455 Ma) saw a huge increase in the number of different complex animal forms established during the Cambrian. This was followed by a mass extinction at ~445 Ma, the *first of the big five* and the only known mass extinction occurring during icehouse conditions (Fig. 2.1). The reason for this mass extinction is debated and all others occurred during greenhouse conditions (Torsvik et al. 2021) that have been causally linked to large igneous provinces (Wignall 2001) or impacts (Alvarez et al. 1980).

A deep understanding of *why* and *how* biological diversity has varied over geological timescales requires both rigorous modern statistical analysis and solid data (**WP2.5**). With the statistical toolbox — layeranalyzer — developed and currently also expanded by PHAB scientists (Reitan & Liow 2019), we have started quantifying the effects of multiple abiotic and biotic drivers of biological diversification (Wilson et al. 2024), shedding light on how and when environments become (in)habitable to organisms over the Phanerozoic. Inferences of abiotic drivers are only as good as the data to which models are fit, and we will therefore ensure using not only robust diversification estimates but also improved paleoenvironmental proxies (**WP2.3**), e.g. O₂, CO₂ and temperature (Torsvik et al. 2024; Thiagarajan et al. 2024), which are thought to influence diversification rates in our comprehensive modeling framework. In addition, theoretical ecological frameworks are also being incorporated as necessary null models in our quest to understand long-term evolution as observed from the fossil record (Saulsbury et al. 2024).

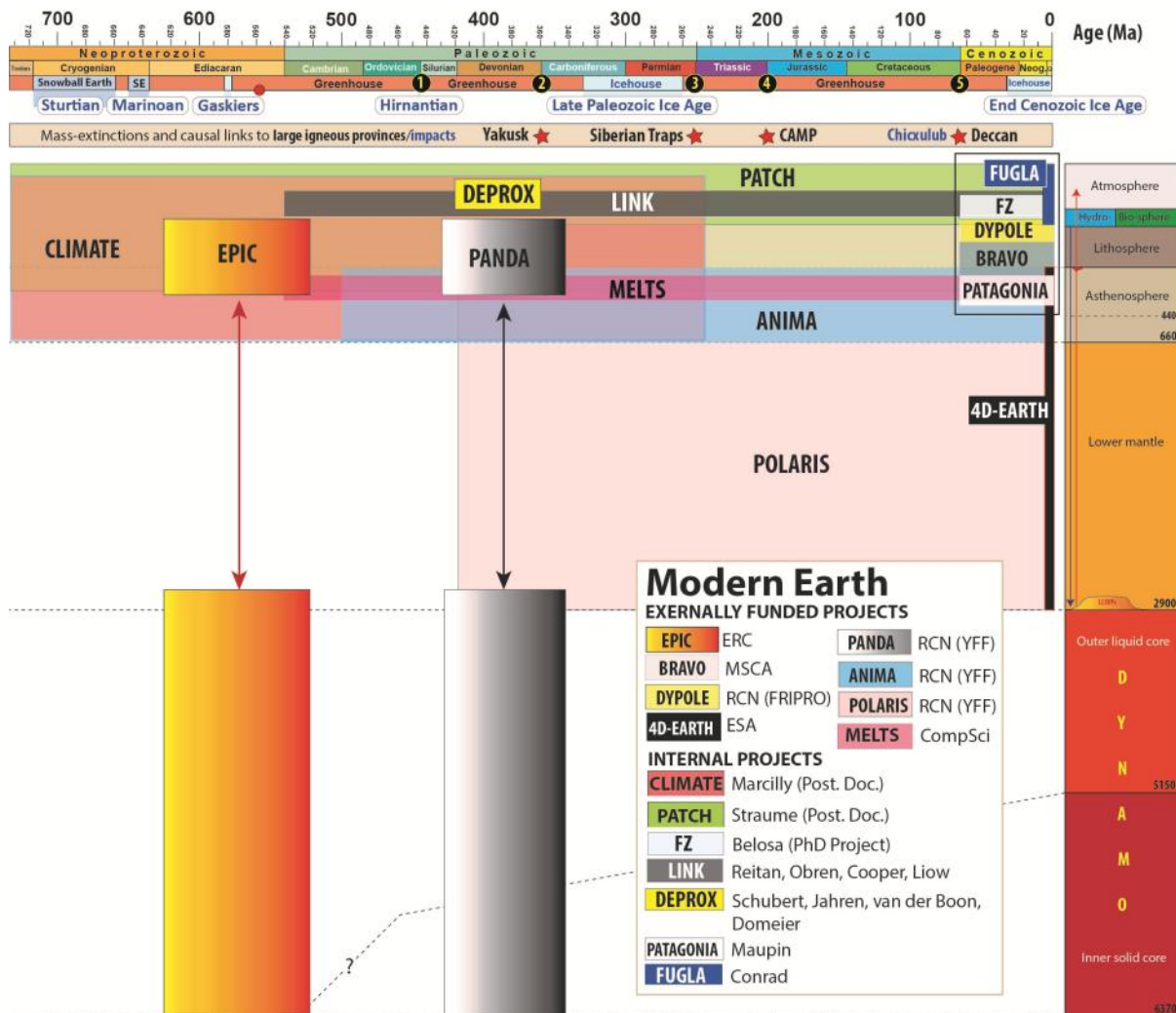


Figure 2.1 Modern Earth timescale, greenhouse vs. icehouse (including Sturtian/Marinoan Snowball Earths), mass extinctions 1-5 (black numbered circles) and potential links to large igneous provinces or impacts. Right-hand column shows the Earth's internal structure and active externally and some internally funded projects are indicated in both time and depth. Projects EPIC and PANDA includes paleomagnetic studies and thus can shed lights on dynamo processes (e.g. dipole nature and strength of the field).

CLIMATE (Post. Doctoral project: Marcilly, Torsvik)

Aim:

Investigate the interplay between paleogeography, carbon cycle dynamics, and climate particularly during the Neoproterozoic Era, focusing on Snowball Earth events and their links to large-scale environmental and biological changes.

Objectives:

- Enhance long-term carbon models by incorporating paleogeographic reconstructions, topography, and weathering dynamics.
- Simulate glaciations, particularly Snowball Earth events, by modeling CO₂ and temperature dynamics using biogeochemical models.
- Categorize land exposure during the Neoproterozoic and estimate global flooding to calculate sea level changes using the hypsometric method.
- Adapt and extend carbon-climate models to explore Mars' climatic evolution.

Links to PHAB work packages: WP1.6, 2.1, 2.4

The Neoproterozoic Era experienced major climatic crises, including two Cryogenian Snowball Earth episodes (~710–640 Ma), likely driven by increased carbon uptake from tropical landmasses, basaltic emplacement, and reduced solid Earth degassing, leading to intense cooling. Understanding these events requires both continental positioning and estimates of exposed land area. Given limited data, the study will develop scenarios to illustrate the potential scale of change.

Paleogeography exerts a fundamental control on Earth's long-term climate by regulating the efficiency of silicate weathering, the primary negative feedback stabilizing atmospheric CO₂ over geological timescales. Accurate reconstructions of past land distribution, topography, and shelf geometry are therefore essential for quantifying weatherability and modelling deep-time climate–carbon cycle interactions. In 2025 we developed a paleoelevation model for the entire Phanerozoic (past 540 million years) but with a focus on constraining the weatherability (Fig. 2.2) and carbon cycle modelling during the Late Paleozoic Ice Age (LPIA). LPIA is the longest-lived Phanerozoic icehouse climate and the only recorded greenhouse–icehouse–greenhouse cycle on a vegetated Earth.

We have started to extend our Phanerozoic paleoelevation to the Neoproterozoic, estimate global flooding (shallow shelves in Fig. 2.2), and extend the Marcilly et al. (2022) sea level curve using the hypsometric method. After adapting our models to the Neoproterozoic, we plan to extend our approach to Mars. Simplifying parameters to match Martian fluxes will enable carbon-climate modeling to explore the planet's dramatic climatic shifts.

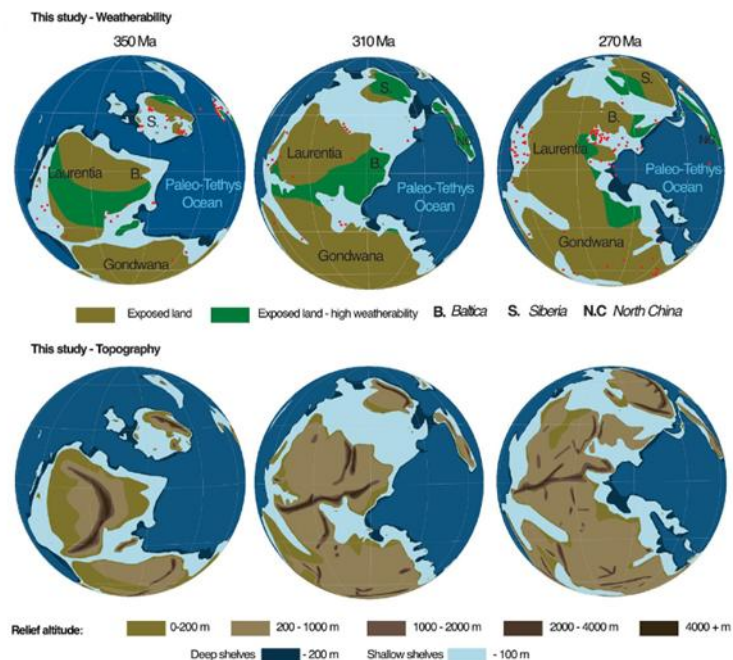


Figure 2.2 *Top panel:* Reconstructions of exposed land, high weatherability zones (in green) and distribution of evaporites (red dots). B, Baltica; NC, North China; S, Siberia. *Lower Panel:* Exposed land with estimated relief. (Marcilly et al. 2025).

EPIC (ERC Consolidator project: Domeier, Antonio, Gallo, Tonti-Filippini, Xue)

Aim:

To understand the nature of enigmatic paleomagnetic changes in the Ediacaran Period (~635-540 Ma), which have precluded attempts to build robust paleogeographic models at this time.

Objectives:

- Collect new paleomagnetic (directional and intensity) data from the Ediacaran to better constrain the strength, stability and morphology of the geomagnetic field in Ediacaran time.
- Acquire new geochronological constraints to enable an understanding of rates of paleomagnetic rates of change.

Links to PHAB work packages: WPs 1.5, 1.7, 2.1, 2.5

Paleogeographic models are fundamental to understanding the history of plate tectonics and their derivative effects on global volatile cycling, paleoclimate, and the biosphere. The Ediacaran Period is particularly significant because it witnessed dramatic changes in climate, the carbon and oxygen cycles, and the biosphere. Despite its importance, our ability to study how these changes unfolded in space—and the potential role of plate tectonics in driving them—is hindered by unresolved anomalies in Ediacaran paleomagnetic records, which are typically used to constrain paleogeography.

At face value, these records suggest continent movements at implausibly rapid rates. To reconcile this, the records have instead been proposed to reflect episodes of True Polar Wander and/or an exceptionally weak and potentially hyperactive geomagnetic field. To test these hypotheses, we are conducting a series of targeted sampling campaigns and analyses, including paleomagnetic, paleointensity, rock magnetic, and geochronologic studies of Ediacaran successions from several paleo-continents. This includes ongoing work in Norway, Sweden, Spain, Canada, the United States, Brazil, Paraguay and Argentina.

Work in 2025 yielded several new important insights. Firstly, we have made significant progress in untangling complex magnetic signals from the both the ca. 616 Ma Egersund dikes (Norway), as well as the ca. 585 Ma Fen Complex (Norway), the results of which we expect to be published in early 2026. These results have important implications for Ediacaran paleogeography (Fig. 2.3). Our work in the Itapucumi Group (Paraguay) has revealed these rocks to have been pervasively remagnetized, but through the development of a new statistical learning approach, we have been able to link remagnetization to a specific diagenetic event, thereby opening a door to the ability to directly date remagnetization events (Gallo et al., 2025).

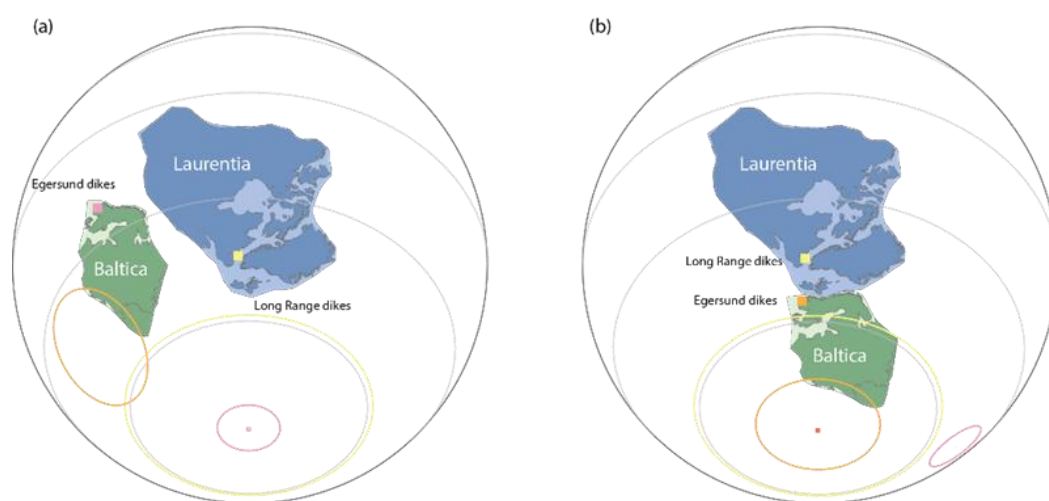


Figure 2.3 Paleogeographic reconstruction of Laurentia and Baltica at ca. 615 Ma according to new (a) vs. previous (b) paleomagnetic data from the Egersund dikes.

PANDA (NFR Young Talent project: van der Boon, Rye)

Aim:

Elucidate behaviour of Earth's magnetic field in the middle Paleozoic (~440-340 million years ago), which currently represents a gap in the paleomagnetic record.

Objectives:

- Study changes in strength of Earth's magnetic field from the Silurian to the Carboniferous.
- Constrain reversal rates during the late Silurian.
- Provide paleopoles for plate tectonic reconstructions in the Silurian to Carboniferous.

Links to PHAB work packages: WP1.2, 1.3, 1.5, 1.6, 1.8, WP2.1, 2.5, WP3.4, 3.6

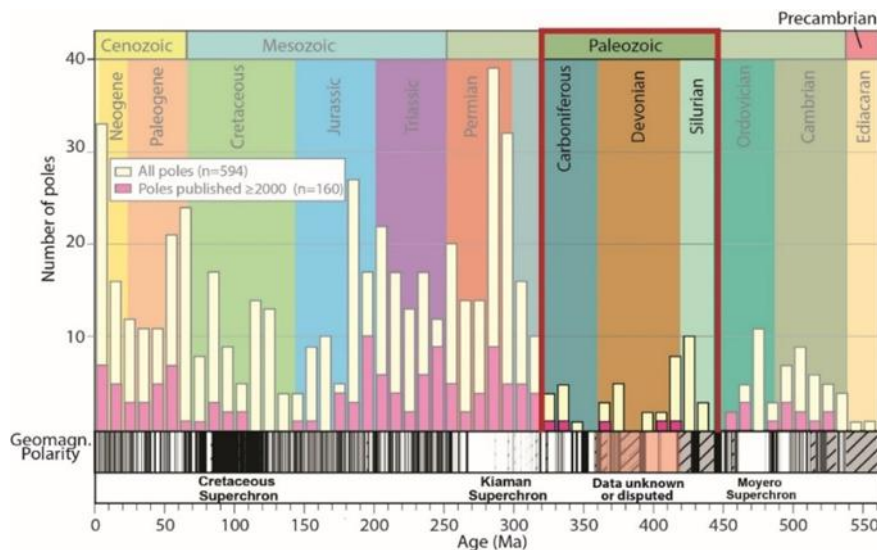


Figure 2.4. Highlighting the paleomagnetic data gap in the Middle Paleozoic, with the number of poles in the global apparent polar wander path of Torsvik et al. (2012), and geomagnetic polarity pattern of the geologic time scale 2020. Black (white) represents times in which the polarity of Earth's magnetic field was normal (reversed), whereas unknown (disputed) is marked in grey (red). The red outlined box highlights the middle Paleozoic.

Earth's magnetic field (EMF) is generated in the liquid outer core, and is thought to be essential for planetary habitability. Paleomagnetism studies EMF as recorded in rocks, and enables us to reconstruct how EMF changed through time, providing constraints on paleogeography and the evolution of the deep Earth. The middle Paleozoic (440-340 million years ago) represents a large gap in paleomagnetic data, from the late Silurian to the early Carboniferous.

PANDA is currently interrogating this gap using an integrated paleomagnetic approach on both sedimentary and volcanic rocks in diverse localities. We show evidence for an extremely weak EMF during the Middle Devonian, but surprisingly, also during the Kiaman superchron, a time that was previously hypothesised to have a strong magnetic field. Key 2025 achievements are the publication of three papers and the submission of one more (in review since July). A research stay by the PI at the Paleomagnetic Laboratory Fort Hoofddijk implemented paleointensity experiments on Silurian–Devonian samples, results of which are currently being processed. Furthermore, outreach and visibility activities included an invited seminar at IPGP (Jan 2025), public talks (UiO Open Day, Blindern VGS), art–science collaborations and exhibition involvement, and conference contributions (GSA regional, GSA Connects).

ANIMA (NFR YRT project: Király, Wang, Conrad)

Aim:

To evaluate the importance of anisotropic viscosity for geodynamic processes.

Objectives:

- Implement anisotropic viscosity and LPO development within a 3D mantle flow model.
- Understand how anisotropic viscosity and olivine LPO interact to affect tectonic plate motions.
- Constrain the importance of anisotropic viscosity for subduction and relate this to seismic anisotropy.
- Determine how frozen anisotropy in the lithosphere affects slab deformation and subduction initiation.

Links to PHAB work packages: WP1.6 & 2.1

Anisotropic Viscosity in Mantle Dynamics (ANIMA) is an NFR-funded Young Research Talent project hosted first by CEED and then by PHAB at the University of Oslo. ANIMA has been investigating rock textures that form in response to mantle deformation, and the anisotropic rheology associated with them. Subduction zones are a particular focus. The project concluded in the middle of 2025, with project participant Yijun Wang receiving her PhD in August. During 2025, ANIMA participants have been working to publish on two themes:

1) Olivine CPO & viscous anisotropy around subduction zones

The mantle near Earth's subduction zones experiences intense deformation, leading to anisotropic rock textures. We used time-series clustering analysis on tracers in subduction models to identify regions with common deformation histories and olivine crystallographic preferred orientation development. Our results show significant variations in textures and anisotropy within the mantle wedge, sub-slab, and subducting plate regions (see Figure T1-1). These findings enhance our understanding of seismic anisotropy in subduction zones. This work was published during 2025 (Wang et al., 2025).

2) Methodology to effectively model CPO induced viscous anisotropy (Király et al., in review)

Anisotropic viscosity of olivine is often overlooked in geodynamic models. To constrain its role in mantle dynamics, we calibrated a method to derive anisotropic viscosity parameters from CPO mean orientation tensors using a comprehensive texture database. This method was integrated and tested within the ASPECT geodynamic code, demonstrating its efficacy for simple shear scenarios.

One major success of ANIMA is that it led to a successful ERC-Starting Grant for PI Király. The new DYNAMICE project (2025-2030) will run out of the Njord Centre, and will look at the importance of anisotropic fabrics both for both olivine and ice. This will enable study of anisotropic viscosity for both mantle dynamics and ice sheets.

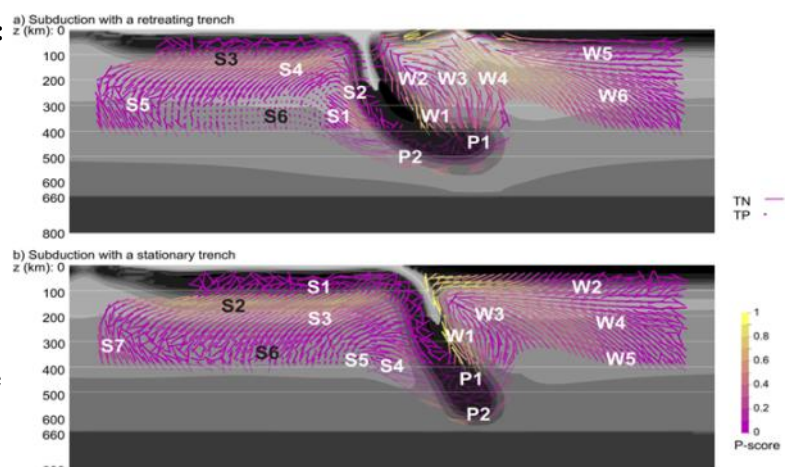


Figure 2.5 Mean olivine a -axis with colors representing the anisotropy amplitude (from 0 to 1). Background colors show mantle viscosity at the end of the models for (a) retreating-trench subduction and (b) is stationary-trench subduction. The orientations are 3D lines such that if the line shows its full length, the orientation is trench-normal, and if the line appears as a point, the orientation is trench-parallel. The (white and black) labels refer to different “clusters” that are defined within the flow model. Note the differences between anisotropy patterns for retreating-trench and stationary-trench models. These differences may be detectable by observations of seismic anisotropy. They should produce different anisotropic rheology, leading to feedbacks between flow and anisotropic fabric that affect the dynamics of these subduction systems.

POLARIS: Evolution of the Arctic in deep time (NFR YRT project: Shephard, Heyn, Conrad)

Summary of the project: The aim of POLARIS was to build an integrated geodynamic model of the Arctic and surrounds with a focus on post-Devonian times (~420 Ma). The project focused on the interplay of tectonics and whole mantle convection in explaining regional magmatism and volcanism, and significant changes in paleogeography. The project was completed at the end of 2025 and employed Grace Shephard (now at the Australian National University) and Björn Heyn. POLARIS resulted in 20 peer-reviewed publications, at least 32 first-authored abstracts and presentations, and at least 20 co-authored abstracts. The publications ranged across the breadth of the project objectives, including tectonics, paleogeography, mantle convection, volcanism as well as other topics including polar education, science in prisons, and scientific visualization. Additional activities included teaching (UiO and UNIS), field trips and expeditions (including Alaska, Svalbard, Barents Sea, Central Australia), overseas research stays (ANU, Münster) teaching and supervision (10 BSc and PhD students at UiO, ANU, IPGP, U.Helsinki, LMU, U.Amsterdam, Williams College), science communication and outreach (blog posts, social media, embassy and primary and high school visits), leadership and technical roles (IASC, UArctic, APECS, Geodynamica, WOMEESSA) and smaller funding/contracts for running courses, workshops, and industry collaborations.

Links to PHAB work packages: WP1.5, 2.1, 2.2, & 2.4

Highlights from 2025:

- North Atlantic rifting study (Shephard et al., 2026; Gondwana Research): The result of over 10 years of work, a plate tectonic modelling study related to the long-lived and multi-stage rifting history of the Northeast Atlantic ocean was finalised. Using the open-source software *GPlates* and a wealth of observational data, the study was the first to create a “deformable” plate reconstruction that included four discrete phases of rifting back to the Permian times. The paper holds implications for other areas of rifting and challenged the traditional “rigid plate” starting approach. This paper built on the earlier co-authored study of Abdelmalak et al. (2022) and involved several PHAB scientists
- HALIP dredge sample study (Williamson, Shephard et al., 2026; Communications Earth & Environment): In 2016 a rare deep sea dredge sample was collected from the Alpha Ridge and was analysed for geochemistry and geochronology. Results have revealed insights into the eruption timing and paleogeographic setting of HALIP.
- Crockerland and polar exploration chapter (Shephard, 2026): As part of the UiO group “Collecting Norden” an invited book chapter was written about the connection between Robert Peary’s Crocker land (a mirage or fabrication) and the geological landmass of Crockerland. It will be soon be released by Brill as part of a Humanities special collection.

In 2025, the POLARIS project also contributed to an additional 6 peer-reviewed publications*. In 2026, a final POLARIS paper will be finalized that proposes link between 250 Myrs of massive volcanism – connecting the Siberian Traps, HALIP, North Atlantic Igneous Province and the Iceland Plume; (Shephard, Heyn and Conrad, in prep). Two co-authored publications are in review including Rich et al. (on Arctic rifting modelling, Tectonophysics) and Senger et al. (an Arctic/HALIP field guide, Geodynamica).

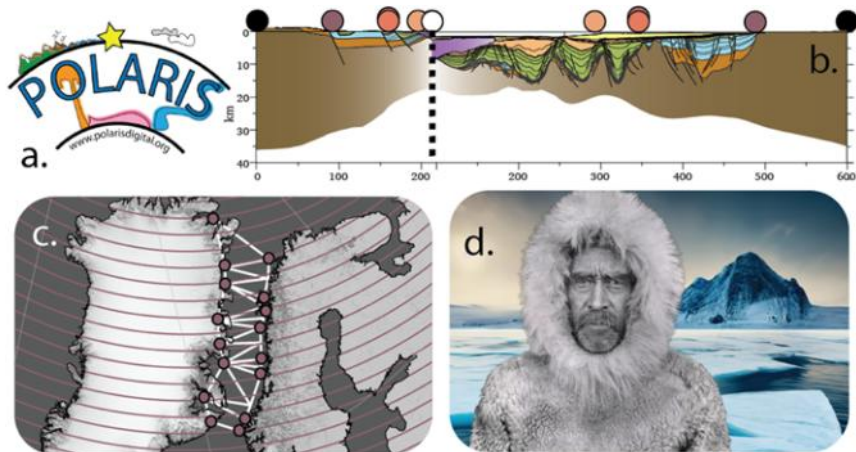


Figure 2.6 a. POLARIS logo, b. and c. Snapshots of the NE Atlantic deforming model (Shephard et al., 2026), d. Crockerland cover image (Shephard, 2026).

BRAVO: BARENTS SEA EVOLUTION (MSCA project: Lasabuda, Shephard)

Aim:

Reconstruct paleogeography of the Barents Shelf in the Cenozoic (the last 66 Myr) and simulate the corresponding sediment source-to-sink.

Objectives:

- Test different paleogeographies and modified ones as input for sedimentary source-to-sink analysis in the Barents Shelf.
- Compare simulation results with seismic data and explore the impact of climate on sediment erosion, transport and deposition.
- Constrain the timing of Barents Seaway opening and its regional to global consequences on the Arctic-Atlantic shallow water connection.

Links to PHAB work packages: WP1.5, 2.1 & 2.4

The PI (Lasabuda) has completed his outgoing phase at The University of Sydney (September 2023–August 2025) and started his returning phase at PHAB, UiO. During 2025, the PI and key collaborators (Assoc. Prof. Tristan Salles and Dr. Sabin Zahirovic at USYD and Dr. Grace Shephard at Australian National University) focused on developing codes of coupling GPlates and Badlands. GPlates software was used to reconstruct paleotopography through time, in which relative velocity values were extracted. This aspect is strongly linked to PHAB WP 2.1 Plate Tectonics and Paleogeography. The project is also linked to PHAB WP 1.5 Tectonic Regimes and Interior, where the Cenozoic tectonic development of the Barents Shelf plays a crucial role in reshaping the paleotopography of the sediment source areas.

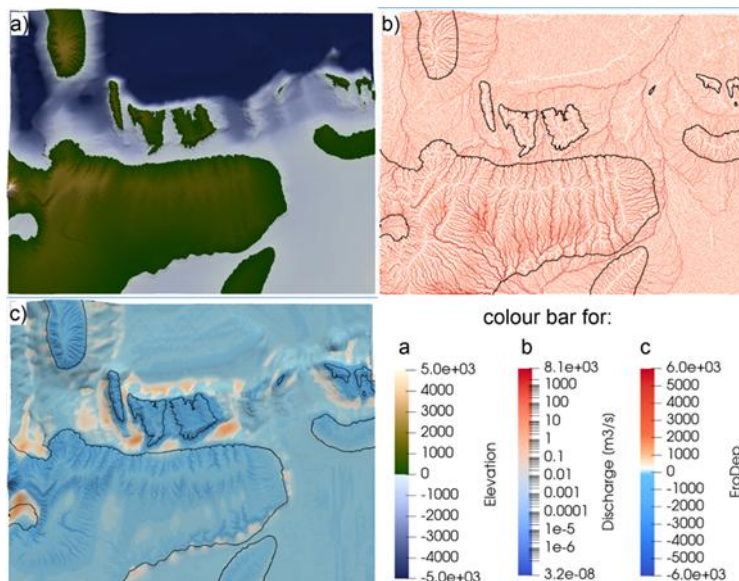


Figure 2.7. Key area for BRAVO in the northern Barents Shelf adjacent to the Eurasia Basin. Here are snapshots of simulations from the coupled Badlands and GPlates models at 55 Ma during the plate tectonic breakup, that led to the seafloor opening of the Gakkel Ridge. a)

Paleogeography from Straume et al. (2020). b) sediment discharge. c) erosion (blue) – sediment deposition (red).

For the sedimentary source-to-sink analysis, BRAVO used Badlands open-source codes to model erosion, sediment transfer and deposition (Fig. 2.7a, b, c). Seismic geomorphological features and stratal stacking patterns found in seismic data are to be compared with the simulation results. For example, mapping a turbidite channel (e.g., Amundsen et al., 2025) will be useful to understand the sedimentary architecture, reflecting the depositional environment. It has been suggested that climate has a key role in eroding and depositing sediments (e.g., Lasabuda et al., 2025), which is linked to PHAB WP 2.4 Paleoclimate Models. We further test how sensitive climate perturbation is to sediment deposition in the High Arctic. Some preliminary results have been presented at conferences (e.g. ICAM-X Bremen in March 2025) and invited talks (e.g. The University of Melbourne in July 2025), and integrated in teaching (GEOS3103: Environment, Sediment and Climate Change – Sedimentary basins and sediment source-to-sink, USYD). Finally, the PI was awarded the 2025 Robert Mitchum Award from the European Association of Geoscientists and Engineers (EAGE).

DYPOLE: Dynamics of polar confined basins - The Eurasia Basin from breakup in greenhouse to present in icehouse conditions (NFR FRIPRO project: Gaina, Minakov, Meza Cala, Shephard)

Aim: To investigate the role of Arctic Ocean basins in triggering climatic changes in the Cenozoic.

Objectives:

- Reveal the causes of the Paleocene continental breakup that led to the opening of the Eurasia Basin and establish the processes that shaped the margins of this basin.
- Establish the causality between inherited continental margin heterogeneities, mantle structure, as well as spatial and temporal changes in seafloor spreading in the Eurasia Basin, with a focus on Eocene - Miocene time intervals.
- Determine possible links between Cenozoic Arctic palaeogeography and regional climatic changes.

Links to PHAB work packages: WP1.6, 2.1 & 2.2

Project participants: Juan **Meza Cala** (PhD candidate), Alexander **Minakov** (Researcher), Jan Inge **Faleide** (Professor Emeritus), Mansour **Abdelmalak** (Researcher), Grace **Shephard** (Researcher), and Carmen **Gaina** (Professor). This is an UiO-UiT-UiB-NORSAR NFR project.

At the end of 2025, the DYPOLE project concluded 4 years of research in the Arctic region. Highlights of this project include 3 Arctic expeditions as part of the GoNorth national programme (<https://gonortharctic.no/>), educating 2 PhD students, and publication of 14 papers, with two of them (*Meza-Cala et al., 2024* and *Gaina et al., 2025*) published in high-impact journals.

The project team made important contributions to understanding possible links between Cenozoic Arctic geodynamics and paleogeography, and regional climatic changes. The role of bathymetry and paleobathymetry in climate variations through time was published in Nature Reviews Earth & Environment (*Gaina et al., 2025*). Paleogeography is a central expertise of PHAB, and it will continue to be expanded to the entire Phanerozoic and possibly beyond by the work of newly recruited postdoctoral fellow, Eivind O. Straume.

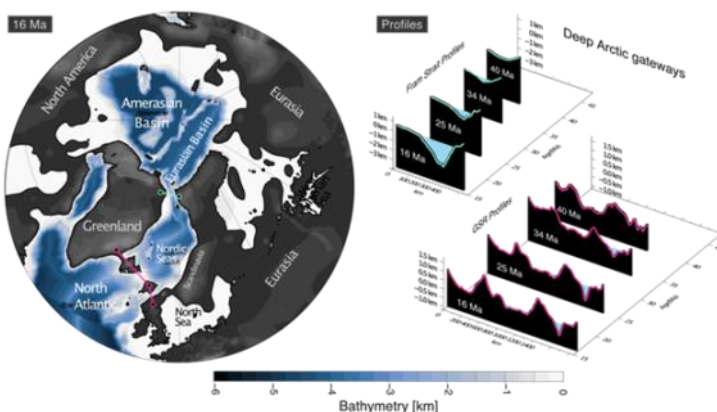


Figure 2.8 Paleobathymetry of the Circum-Arctic region in the Miocene time (left) and the evolution of the oceanic gateways (right). The digital model is developed by Eivind Straume and collaborators. Figure modified from Gaina et al., 2025.

In November-December 2025, the DYPOLE group joined the 2025 GoNorth Arctic expedition. Together with collaborators

from the Greenland and Denmark Geological Survey (GEUS), we collected data in the Boreas Basin (part of Fram strait region) and Sophia Basin (north of Svalbard). This included about 410 km of multichannel seismic data, in addition to continuous gravimetry and bathymetry measurements made along the entire sailing route. During this expedition we have also sampled 1 submerged ridge and 2 seamounts using the NORMAR remote operating vehicle (ROV) Ægir 6000. The DYPOLE project legacy will be used to contribute to follow-up projects (like the newly established national Polhavet2050, <https://uit.no/polhavet2050>), which will continue to build knowledge about the Arctic region.

LINK: Linking evolutionary and earth processes (Internal project: Reitan, Obren, Liow, Cooper)

Aim: To understand how biological diversity waxes and wanes on differential spatial and temporal scales given the backdrop of dynamic earth processes.

Objectives:

- Develop statistical tools to infer past processes using patchy and heterogenous data from the fossil and geological records.
- Robustly infer drivers of evolutionary dynamics on geological time scales using adequate statistical models.
- Understand the relationship between short timescale biological processes and long timescale evolutionary patterns.
- Improve dialogue between geologists and biologists.

Links to PHAB work packages: WP2.1, 2.5 and PHAB as a whole

Participants: Trond Reitan, Nicole Obren, Rebecca Brown Cooper, Lee Hsiang Liow, Yan Feng

In 2025, we furthered our objectives by working with Yan Feng, a visiting PhD candidate from the China University of Geosciences (Wuhan) to study the effect of paleotemperature and carbon dioxide on the size evolution of diverse lineages of Foraminifera through the Phanerozoic, in order to understand

short timescale biological processes and long timescale evolutionary patterns. This work is in preparation (Feng, Reitan, Liow et al.), as is the work with PhD candidate Nicole Obren (main supervisor Reitan). Obren, a first year PhD student at PHAB, is investigating regional versus global Cenozoic dynamics of molluscs in order to understand what drives the waxing and waning of these ubiquitous marine organisms documented in their rich fossil record. Obren is also compiling information for a review on how geoscientists infer causality in the geological record to be able to make recommendations.

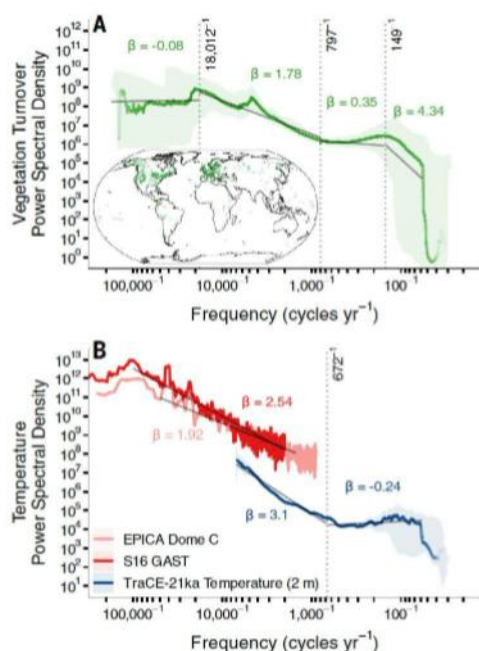


Figure 2.9 Reproduced from Fastovich et al. 2025 Science (Fig. 2)

timescales from hundreds to tens of thousands of years, to climate, but not at timescales shorter than about 150 years (Fastovich et al. 2025), suggesting that habitability must take into consideration response time of the organisms involved. In a different study, we found again that biological context and history matter for responses to changing mineralogical compositions in the oceans (Saulsbury et al. 2025a). We also contributed two major reviews for the 50th anniversary of the journal Paleobiology, pushing for greater integration between biology and geology via paleobiology (Liow & Quental 2025, Hunt et al. 2025). In addition, our paper Saulsbury et al. 2024 tackling extinction in the fossil record attracted so much attention that we triggered a debate that culminated in Saulsbury et al. 2025b.

At the end of 2025, we welcomed a new postdoc Dr Rebecca Brown Cooper (Swiss Mobility Grant) to PHAB with the LINK project. Dr Cooper is an expert in using AI models to estimate diversity and diversification rates in the deep past using patchy fossil data (Cooper et al. 2024, 2025). At PHAB, she will expand on her work of estimating origination and extinction rates in the deep past, not least by incorporating time series models developed by Reitan and Liow to robustly infer drivers of paleontological dynamics to understand habitability.

Other research highlights from LINK in 2025 include discovering that vegetation dynamics responded at

Fracture Zones: The Role of Fracture Zones and Transform Faults in Geodynamic Processes (PhD candidate project: Beloša, Gaina, Callegaro, Mazzini, Trønnes)

Aim: To determine the role of oceanic fracture zones in intraplate volcanism

Objectives:

- To understand the processes that led to the formation of the solitary seamount Vesteris in the Greenland Sea.
- To determine the role of the Jan Mayen Fracture zone in the distribution of magmatic features in the central NE Atlantic.
- To revisit the distribution of global oceanic transform faults and understand their connections with seafloor spreading processes.

Links to PHAB work packages: WP1.6, 2.1 & 2.2

Project participants: Lea Beloša (PhD candidate), Carmen Gaina (Professor), Sara Callegaro (Researcher), Adriano Mazzini (Research Professor), and Reidar Trønnes (Professor Emeritus)

Transform faults and fracture zones (TFZs) are active and paleo-plate boundaries, respectively, which offset mid-ocean ridges up to thousands of kilometres. As TFZs divide lithosphere of different ages, the lithosphere-asthenosphere topography has a step gradient in these regions. This may lead to the formation of mantle ponds and small-scale convection in the fracture zone vicinity and, consequently, to increased volcanic activity on either side of the fracture zone.

The PhD project: “The Role of Fracture Zones in Geodynamic Processes” by Lea Beloša was finished in 2025, and a PhD thesis was successfully defended by the candidate in August 2025. In addition to the papers dedicated to the Quaternary Vesteris seamount (situated north of the western Jan Mayen Fracture Zone, JMFZ, see Beloša et al 2024a, b), Beloša investigated the Cenozoic evolution of the Jan Mayen Fracture Zone and its possible role in facilitating the construction of shallow submarine igneous features.

This work examined the tectonic and magmatic mechanisms of thickening oceanic crust at the Traill Ø Igneous Complex (TIC), Eggvin Bank, Logi Ridge, Southern Seamount, Vøring Spur (VS), and the East Jan Mayen Fracture Zone segment ridges by combining plate tectonic reconstructions and a recent melt-production model (Steinberger) that allowed assessing excess melt and key topographic highs near JMFZ. Plate-tectonic reconstructions reveal a spatial link between the TIC and Vøring Spur, with crustal-thickness anomalies and excess magmatism at 48–50 Ma marking their onset. The Vøring Spur anomaly originated in the initial tectono-magmatic phase (~47.3 Ma), with possible Miocene reactivation. Another three EJMfZ topographic highs formed under Early–Mid Eocene transtension, later uplifted during transpression. These findings add to our understanding of NE Atlantic geological history and highlight fracture-zone–plume interactions in generating anomalous crustal features.

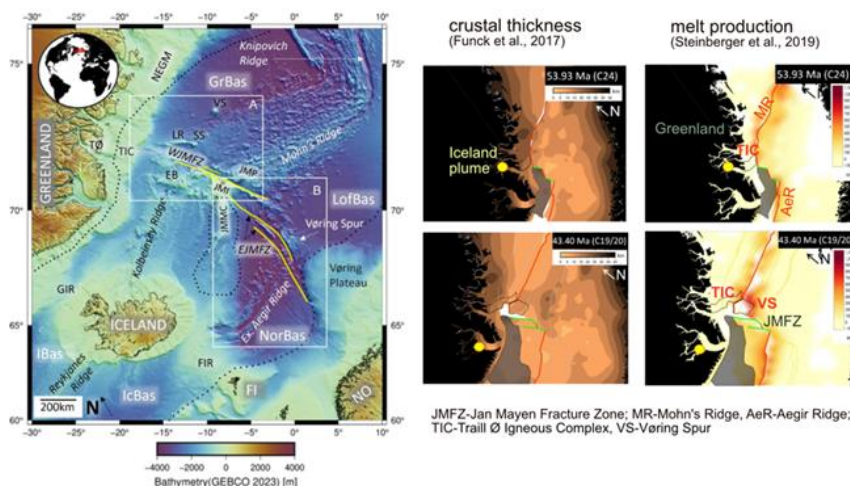


Figure 2.10 The Jan Mayen Fracture Zone (JMFZ) region in the NE Atlantic (left) and Cenozoic plate tectonic reconstructions (right). Excess magmatism due to the proximity of the Iceland plume may have contributed to the formation of igneous features situated on both Greenland/North America plate and Eurasia plate. Figure modified from Beloša (2025).

4D Dynamic Earth (ESA project: Conrad, Ramirez, Domeier)

Aim: Understand the sensitivity of ground and satellite observations to the dynamics of Earth's deep interior.

Objectives:

- Utilize combinations of observations and modelling from seismology, gravity, magnetics, GPS, InSAR, petrology, and topography to gain new understanding of the deep earth.
- Assess the sensitivity of different Earth observations to the dynamics of Earth's deep interior.
- Determine which new satellite observations are necessary to make progress understanding the internal dynamics of the Earth.
- Inform the European Space Agency (ESA) regarding future observations, satellite missions, and modelling efforts to improve ESA's Deep Earth program.

Links to PHAB work packages: WP1.5, 1.6, 2.1 & 2.2

The [4D Dynamic Earth](#) project, funded by the European Space Agency (ESA), concluded during 2025. This project undertook a variety sensitivity studies to understand the applicability of current ground and satellite datasets available for understanding the dynamical behavior of the solid Earth. PHAB was one of [ten European universities and research institutions](#) contributing to this project.

PHAB's contribution was led by PHAB scientists **Clint Conrad** and **Florence Ramirez**. Working to understand Earth's gravity and dynamic topography, they have discovered that the observed gravity anomalies on Earth are sensitive to long-wavelength variations in Earth's viscosity. This could potentially complicate the relationship between Earth's density anomalies (e.g., as observed by seismic tomography) and Earth's surface gravity and geoid (e.g., as observed by satellites). On the other hand, this sensitivity offers an exciting opportunity to use observations of Earth's gravity to place new constraints on lateral viscosity variations within Earth's interior.

As part of this project, we have also published several studies relating to the 4D dynamics of Earth's interior. In particular, we have published constraints on the time-dependent water content of Earth's lower mantle (Mohn et al., 2025) and mantle transition zone (Wang et al., 2025a). In particular, we discovered that the tectonic history of water injection into the mantle by subduction predicts a wet area of the mantle that preferentially lies beneath Earth's intraplate volcanism (see Figure 2.11).

Finally, we have shown that the depth-rotation of seismic anisotropy places an important new constraint on mantle dynamics (Wang et al., 2025b). In particular, we have found that tomographic models that include anisotropy show the fastest depth-rotation in the asthenospheric beneath the Atlantic basin. This is because asthenospheric anisotropy in the Atlantic is controlled by pressure-driven and shear flows that are mis-aligned, which is not the case in the Pacific or Indian basins.

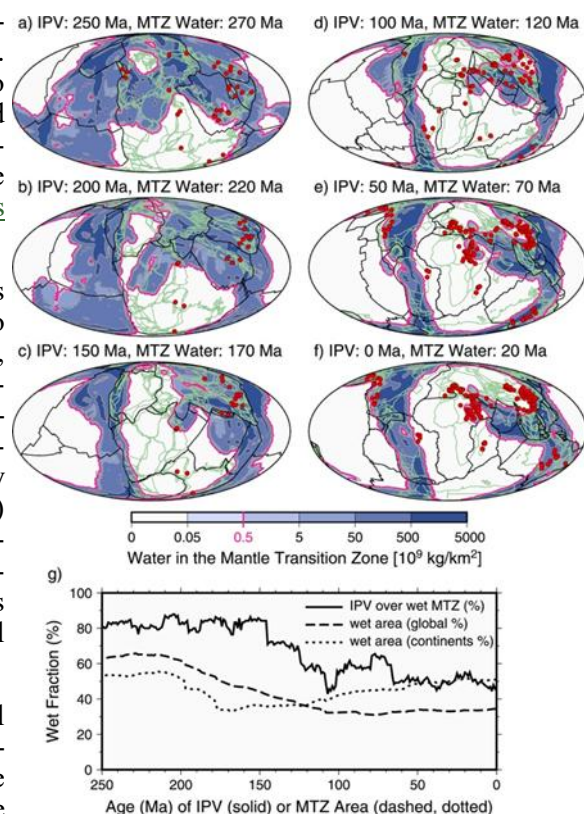


Figure 2.11 Comparison of the “wet” regions of the mantle transition zone (blue areas) to the locations of intraplate volcanism (red dots) since 250 Ma (panels a-f), and the fractional area of continents, oceans, and intraplate volcanism (panel g) as a function of time. Note that intraplate volcanism preferentially occurs above the wet areas of the mantle transition zone.

DEPROX: Devonian Paleo Proxies: Schubert, van der Boon, Domeier)

Aim: Understand changes in atmospheric chemistry that coincided with colonization of forests during the early Phanerozoic.

Objectives:

- Test effects of concurrent climate change (e.g., droughts) on reconstructions of CO₂ (completed: Jahren and Schubert, 2024, Communications Earth and Environment).
- Quantify CO₂ change across the Devonian (in progress).
- Use terrestrial sediments from Svalbard to inform periods of biologic crises on land (in review).
- Reconcile disparate CO₂ data with global temperature curves.

Links to PHAB work packages: WP2.3 & 2.4

Estimates of CO₂ for the Devonian are notably coarse and yield diverging estimates for CO₂ during the colonization of life on land (Figure 2.12a). Geochemical models link the rise of forested ecosystems with deeply rooted trees to a long-term decline in CO₂, but the sparse CO₂ proxies for this time provide incomplete and incongruent records of CO₂ change. Laboratory experiments, field collections, and literature compilations are being used to reconcile these differences and provide a nearly continuous record of CO₂ for comparison with global temperature curves.

We completed Objective 1 in 2024 (Jahren and Schubert, 2024) and are now applying this work towards Objectives 2 and 3. In 2025, we produced a preliminary CO₂ record for the Devonian (Figure 2.12, Objective 2) based on more than 300 stable carbon isotope measurements from the Appalachian Basin, USA. A manuscript of this work is in progress (Thomas Algeo, Brian Schubert, Hope Jahren, Jennifer McElwain, Harry Rowe, Peter Sauer, Stephen Scheckler, and Zhenzhu Wan).

We also completed a manuscript with new data collected from Mimerdalen, Svalbard (Objective 3) that reports a new terrestrial carbon isotope excursion that likely spans the Taghanic crisis within the Middle Devonian (Annie van der Boon, Brian Schubert, William Hagopian, Mathew Domeier, and Hope Jahren, *in review*). We use these data to produce a high-resolution CO₂ record, which reveals a very short (< 10⁵ years) doubling of CO₂ during the Taghanic crisis. This CO₂ spike is consistent with a ¹³C depleted source, such as methane, as a trigger for Middle Devonian biotic crises and high climate variability. These short timescales of rapid CO₂ change cannot be resolved by existing proxies.

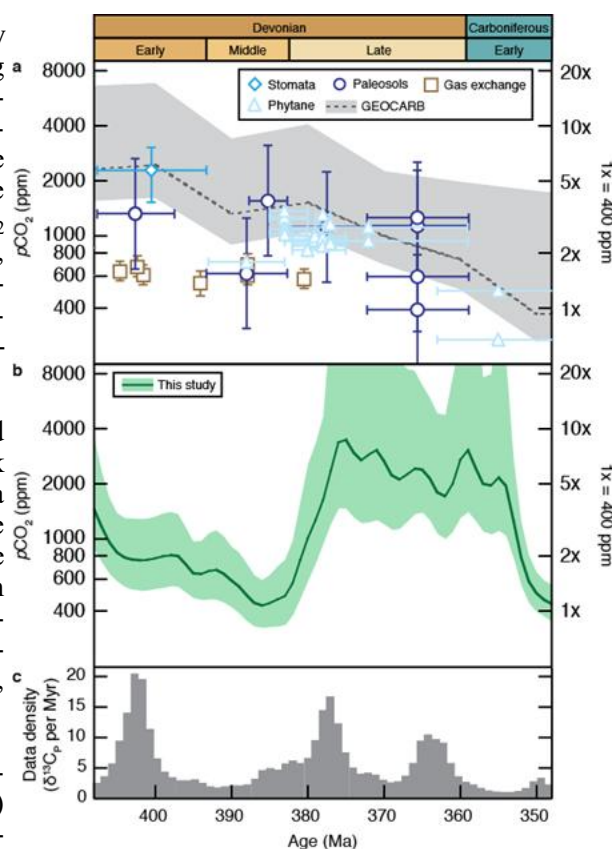


Figure 2.12 Atmospheric carbon dioxide concentrations during the Devonian. (a) Published proxy and model CO₂ estimates. (b) Preliminary CO₂ record for the Devonian based on the carbon isotope composition of terrestrial C₃ plants ($\delta^{13}\text{C}_p$). (c) Data density (number of $\delta^{13}\text{C}_p$ measurements per million years).

MELTS: Kimberlite melts (CompSci project: Anzulovic, Gaina, Caracas)

Aim: Develop chemical models of kimberlite melt with varying volatile contents to determine how melt chemistry and different carbon and hydrogen contents affect physical properties related to kimberlite volcanism.

Objectives:

- Examine chemical speciation of a kimberlite melt, with a focus on the effect that volatiles (CO_2 and H_2O) have on speciation and density.
- Determine the degree of polymerization in kimberlites and constrain pressure conditions of CO_2 degassing.
- Compare kimberlite melt density with cratonic density and assess their buoyancy potential.
- Determine the minimum quantity of carbon required for kimberlites to successfully traverse the crust and reach the surface.

Links to PHAB work packages: WP2.1, 2.2 & 1.6

Kimberlite melts are primary carriers of mantle-derived carbon and hydrogen, playing an important role in Earth's deep carbon cycle and diamond transport. Their low densities, viscosities, and vapor exsolution enable fast ascent rates (WP1.5—Tectonic Regimes and Interior/WP2.1—Plate Tectonics and Paleogeography). Ascending from the upper mantle, kimberlite melts incorporate xenoliths and xenocrysts and exsolve volatiles. These processes alter their initial composition, increasing the discrepancy between the proto-kimberlite magma and the magma that reaches the surface. To explain kimberlite volcanism, we examine atomic diffusivities and densities of kimberlite melts with varying volatile contents. We show that water makes the melts more diffusive, which should also lower their viscosity. All our kimberlite melts are positively buoyant below the lower continental crust (the MOHO discontinuity). They require ~8.2 wt% CO_2 to cross and rise through the MOHO. Above the MOHO, the most volatile-rich kimberlite melts can carry up to ~44% xenolithic fragments of depleted peridotite type (Anzulovic et al., 2025).

Our simulations provide a quantitative basis for the distinct structural roles of the major cations. Silicon acts as a rigid network former, with the SiO_4 tetrahedron being exceptionally stable (average lifetime ~0.6 ps), while network-modifying cations (Mg, Ca, Fe) form highly transient coordination environments (lifetimes <0.1 ps), quantifying their role in promoting the melt's characteristic mobility. The dominant speciation change with pressure is the conversion of molecular CO_2 to carbonate ions (CO_3^{2-}), a transition largely completed below 3 GPa. The carbonate ion is the most stable polyanionic complex in the entire system, with a lifetime exceeding 1.2 ps—more than double that of SiO_4 . This stability is more strongly controlled by the melt's redox state than by its total carbon or water content. Hydrous kimberlite melts have the capacity to start degassing at significant mantle depths (>90 km). This early and sustained degassing generates a buoyant, carbon-bearing vapor phase that provides a continuous driving force for the rapid ascent of kimberlite magmas (Anzulovic et al., 2025).

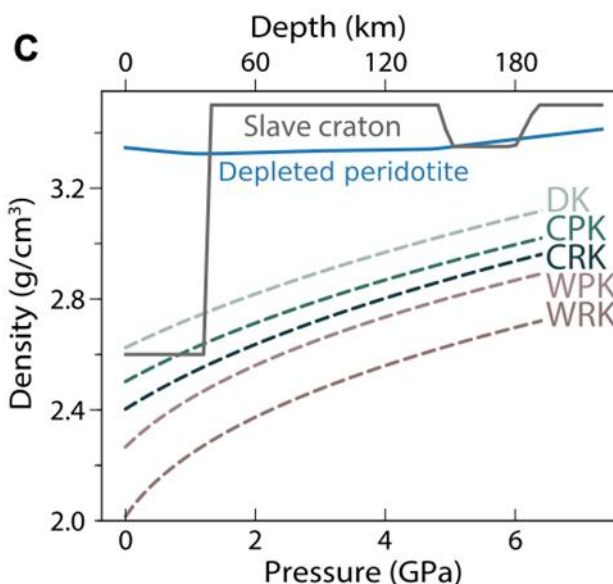


Figure 2.13 The densities are compared to PREM (Dziewonski and Anderson, 1981) and the Slave craton (Canada; Snyder, 2008). DK - dry kimberlite; CPK - carbon-poor kimberlite; CRK - carbon-rich kimberlite; WPK - water-poor carbon-rich kimberlite; WRK - water-rich carbon-rich kimberlite. The densities of the DK and the CPK are higher than that of kimberlite from the Slave craton, causing them to stagnate in the last 38 km of the lithosphere.

PATAGONIA: Seismic regional tomography with application to Patagonia (PHAB internal project: Maupin)

Aim: Optimize usage of seismic data in regional body-wave tomography and map the seismic structure of the upper mantle in Patagonia, where subduction of the Chile mid-oceanic ridge leads to a slab window between the Nazca and Antarctic subducting plates.

Objectives:

- Compare standard methodology for body-wave regional tomography with an improved one using relative kernels.
- Utilize recordings of teleseismic earthquakes at several seismic regional Patagonian networks to measure traveltime residuals for P and SH waves.
- Perform tomographic inversion of these data to obtain 3D models of P- and SH-wave seismic velocity in the upper mantle beneath Patagonia.
- Interpret the models in terms of slab and slab edge corner flows in association with observed seismicity, volcanism and recent magmatism.
- Establish possible relationship between mantle viscosity structure and the anomalously rapid uplift associated with ice melt in the North and South Patagonian icefields

Links to PHAB work packages: WP2.1 & 2.2

This project is done in cooperation with the [Department of Earth, Environmental and Planetary Sciences of Washington University in Saint Louis](#). It contributes to the scientific goals of two main projects: “Seismic Experiment in Patagonia and Antarctica (SEPA) and Glacial Uplift after Neoglaciation in the Andean Cordillera (GUANACO). The present-day tectonic setting of the region encompassing Patagonia, the Drake Passage and the Antarctic Peninsula is not well understood, but very rapid uplift is observed in connection with variation of the ice masses. A relation to upper mantle structure and complex flows related to an intricate system of subducting slabs is suspected, but this region is poorly mapped from a seismological point of view due to lack of seismological stations in these remote areas. The goal of these projects has been to deploy seismological stations and exploit the data to gain knowledge on the seismological structure, and better understand the geodynamics of the region and the relation between deep structure and surface processes like uplift and magmatism.

PHAB’s contribution is being undertaken by PHAB scientist **Valérie Maupin** in main collaboration with Washington University scientists Walid Ben Mansour and Doug Wiens. A tomographic approach developed by Maupin permits to improve the resolution of the tomographic models as proven with resolution tests (Fig. 2.14). The final model shows a well-imaged Nazca slab, and possibly remnants of older subduction slabs further South. Low velocities, interpreted as regions of upwelling and corner flow are also well imaged in association with the location of the slab gap and in the vicinity of the rapidly uplifting icefields, suggesting a relation between low velocity, low viscosity and rapid uplift.

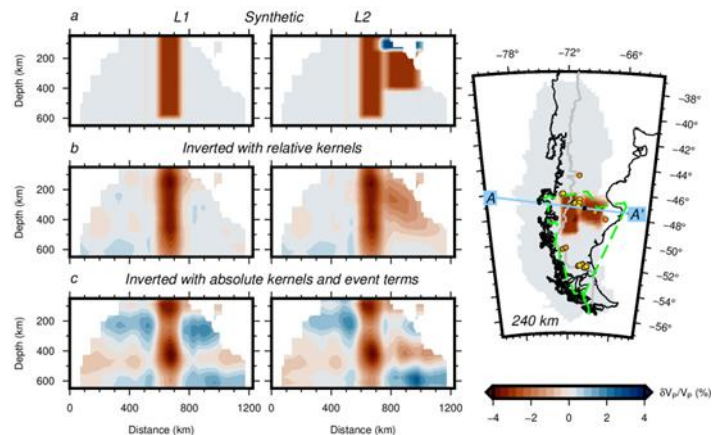


Figure 2.14 Resolution tests of two models L1 and L2 of the Patagonian slab window using two different inversion methods. Vertical sections show in a) the synthetic models and in b) and c) the models resulting from inversion of the synthetic data. The models in b) are inverted with relative kernels while those in c) result from a standard methodology with absolute kernels and event terms, demonstrating the superiority of the relative kernels. The map shows the location of the profiles and the contour of the proposed slab window by a green dotted line, the two icefields by yellow lines, the active volcanoes by triangles and magmatism from 10My to recent by dots, the darkest ones being oldest.

FUGLA: Forebulges Underlying Geographic Level Adjustments (Icelandic rannís Arctic Research Studies pilot study: Conrad)

Aim: Understand patterns of ground uplift and sea level change occurring near deglaciating regions.

Objectives:

- Develop numerical models of forebulge deformation near a retreating ice cap.
- Constrain these models using geodetic observations of ground motion and geologic observations of sea level change.
- Understand how sub-lithospheric heterogeneity affects glacial isostatic adjustment processes.

Links to PHAB work packages: WP1.7, 2.1 & 2.2

FUGLA is a small project supported by the Icelandic Research Council (rannís) to do preparatory work for a larger future proposal. The eventual goal is to study land deformation patterns around a retreating ice sheet (Figure 2.15). Loading of the earth's crust by ice sheet/cap growth can produce a "forebulge" of uplifted earth around the periphery of an ice mass. As this bulge grows or shrinks with the mass of ice, relative sea level is affected. There are indications

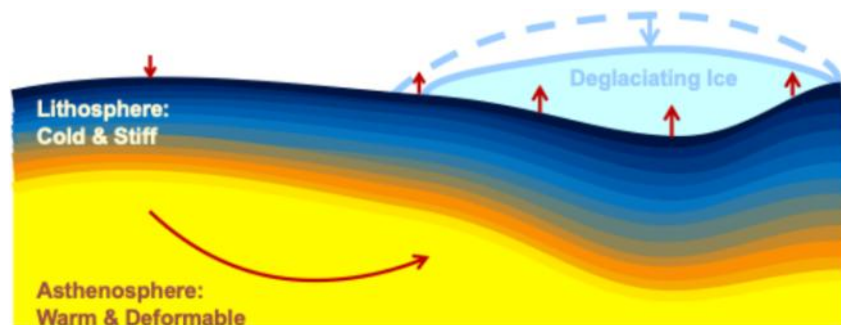


Figure 2.15 Schematic diagram showing the lithosphere's response to deglaciation. Melting ice removes a mass load from the Earth's surface, and the lithosphere responds by rebounding upward. Part of this response is an elastic response that happens instantly but another part is a viscous response that occurs on a timescale that depends on asthenospheric viscosity. For reduced viscosities of $\sim 10^{18}$ Pa s, this viscous response can occur on the same timescale as modern deglaciation (i.e., years to decades). Thus, both types of deformation are important for understanding Earth deformation in response to ice loads.

that such a forebulge may affect relative sea level in several regions of the Earth, but the dynamics of the forebulge are poorly understood. In Iceland, the peripheral bulge may be very important for understanding recent and Holocene sea level change.

The growth or shrinkage of a forebulge may depend on several factors. The ice history is clearly important, but the thermal structures of the lithosphere and asthenosphere, which affects the viscosity of these regions, is also important because the viscosity structure controls the Earth's elastic and viscous response to the load. Preliminary work to model these figures has involved the development of analytical (layered) regional models, as well as more sophisticated numerical models with lateral viscosity variations, which can be reconstructed using geophysical observations (e.g., Ramirez et al., 2024). We have applied sophisticated numerical models to southeastern Greenland, where remnant heat from the Iceland plume is thought to weaken the asthenosphere and thin the lithosphere (Weerdesteijn and Conrad, 2024). These models indeed show a collapsing peripheral bulge along the Iceland Plume Track. Whether such peripheral bulges affect other regions of Greenland's coastline depends on solid earth structure beneath Greenland (Ebbing et al., 2025), as well as Greenland's tectonic and volcanic history (e.g., Heyn et al., 2024). We are planning to use Holocene indicators of sea level change in Greenland, Iceland, Scandinavia, and Svalbard to constrain patterns of land uplift in response to past glaciation and deglaciation events. In particular, we plan to look at periods of ice loss (early- to mid- Holocene as well as recent) and ice gain (neoglacial to Little Ice Age events). The patterns and rates of land response, recorded by relative sea level change, should be related to upper mantle viscosity structures. Patterns of variation may help us to relate past sea level change to past deglaciation, which will help us to test (e.g., Törnqvist et al., 2025) and improve models of future sea level change.

PATCH: Paleogeography with Topography for Climate and Habitability (Post. Doctoral project: Straume, Torsvik, Domeier, Gaina)

Aim: Quantify the role of paleogeography in shaping the long-term evolution of Earth's climate and habitability.

Objectives:

- Develop a new state-of-the-art Digital Elevation Model (DEM) covering 'Modern Earth' time in focus (the last 750 million years) continuously at 1 Myr temporal resolution, building on PHAB's full-plate model.
- Investigate the role of paleogeography on Earth's environmental evolution and habitability by incorporate the DEMs in paleoenvironmental/Earth evolution models.
- Implement the reconstructed paleogeography into fully coupled climate simulations and assessing their impact on climate and habitability for key intervals in Earth history such as the Sturtian 'Snowball Earth' (~717–661 Ma) and the Cambrian radiation of multicellular life (~540 Ma).

Links to PHAB work packages: WP2.1, 2.2, 2.3, 2.4 & 2.5

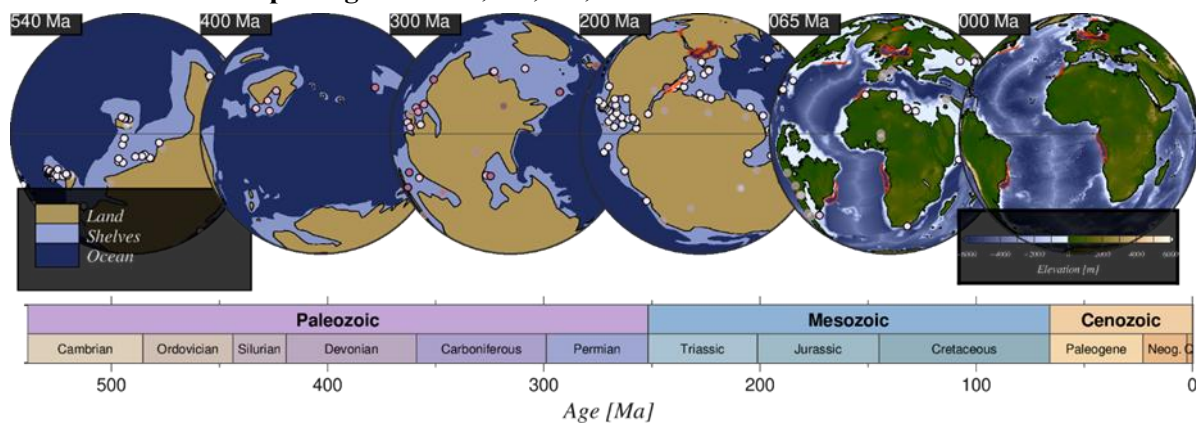


Figure 2.16. Phanerozoic paleogeography. A key objective of this project is to update the flooding maps (> 65 Ma in this figure by Marcilly et al. (2022)) by adding more realistic elevation and ocean bathymetry, creating a continuous DEM like the current model for the Cenozoic (< 65 Ma in this figure, by Straume et al. (2024)).

Paleogeography is a fundamental boundary condition for reconstructing Earth's climatic evolution and habitability. On geological timescales, it governs the latitudinal distribution of environments, controlling incoming and reflected solar radiation and the development of climatic zones. The configuration of continents and oceans also regulates oceanic and atmospheric circulation and influences the evolution and dispersal of marine and terrestrial life.

We are developing a new model (building on PHAB's plate model, Phanerozoic flooding maps, and new datasets) to generate state-of-the-art paleogeographic DEMs. The approach integrates dynamic topography from mantle circulation (100–0 Ma), oceanic lithospheric ages, sediment thickness, evolving continental margins, parameterized subduction zones, and spatiotemporal interpolation between datasets from different time intervals. Similar methodologies have previously only been applied to the Cenozoic (Straume et al., 2020; Straume et al., 2024).

The paleogeographic reconstructions will be implemented in paleoenvironmental models such as COPSE and SCION to quantify how paleogeography influences atmosphere–ocean chemistry, biogeochemical cycling, and biological evolution. However, while these models capture long-term Earth system feedback, their lack of fully resolved 3D oceans and atmospheres limits their representation of oceanic and atmospheric dynamics. We are addressing this by running targeted single-time-slice simulations for key periods using NorESM-F (e.g., the Sturtian Snowball Earth and the Cambrian radiation).

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*Glacial ice that washed out of the Jökulsárlón Glacier Lagoon in southern Iceland, and on to a nearby beach.
Photo: Clint Conrad, March 2025.*



Paleomagnetic sampling of the Nyborg Formation (oriented core drilling along bedding), Varanger Peninsula, northern Norway, August 2025. Photo: Leandro Gallo.



Digital outcrop model of the Nyborg Formation, highlighting the section targeted for paleomagnetic sampling, Varanger Peninsula, northern Norway, August 2025. Photo: Leandro Gallo.

Theme 3 (Exo-Earths) aims to identify planets orbiting other stars that potentially are, or have been, habitable. The theme is structured into seven work packages, and we participate in two ESA telescope missions (PLATO, Ariel).

Theme Leaders: Konstantin Herbst and Stephanie C. Werner



The identification of habitable planets, similar to our own, relies on emerging technologies and future missions. We are involved in several exoplanet missions, including the Habitable World Observatory (HWO) and both upcoming ESA missions (i.e., PLATO and Ariel) that will both be launched and collecting data during the Centre's lifetime. While the PLATO mission (Rauer et al. 2014, 2025) will shift our current science focus to detecting Earth-sized planets in habitable zones around Sun-like stars (**WP3.1**) and to determining the ages of these planetary systems (**WP3.2**), the Ariel space telescope (Tinetti et al. 2018) will gather high-resolution information about exoplanetary atmospheres (**WP3.1**). To fully utilise the data from these missions for comparative planetology, we must develop appropriate models of planetary evolution (**Themes 1-2**). A key observable is the average (uncompressed) density of the discovered exoplanets, which can only be accurately interpreted by understanding the composition of the star, the age of the stellar system, the location of planet formation within the protoplanetary disc, and potential planetary migration patterns (**WP3.3**). While atmospheres contribute minimally to the average density of terrestrial planets, they provide insights into the planet's chemical evolution, including their differentiation and degassing history (**WP1.3**). PHAB will characterise exo-Earths based on their interior structure, composition, and atmosphere.

The first exoplanet discovery (Mayor & Queloz 1995) sparked new ideas regarding dynamical formation models of planets within protoplanetary discs; however, simulations of planet and planetary system formation still lag behind. We will employ planet formation models developed in **WP1.2**, adjusting the initial conditions (**WP3.3**) based on different stellar environments.

Most factors influencing habitability are time-dependent and affected by changes in stellar conditions (**WP3.6**) as well as the planets' own evolutionary trajectories (**WP3.5**). We will systematically explore the parameter space of factors deemed crucial for habitability (**WP3.4**). Eventually, all planets lose their habitability. In approximately two billion years, as the Sun's energy increases by 20%, Earth may enter a moist greenhouse phase, leading to the runaway evaporation of its oceans. This could result in the cessation of plate tectonics and the entire carbon-water cycle. Thereafter, the dynamo effect will stop, and the outer atmosphere will quickly lose its volatile gases (**WP3.7**). However, over even longer timescales, rising surface temperatures could trigger a runaway greenhouse effect, which could heat the surface to the melting point and extinguish all life on Earth. Observing Earth from a distance at this point would resemble a Venus-like planet, raising questions about whether Earth was ever habitable. **But does Venus really predict the Earth's future, and is the “follow-the-water” approach the right one when searching for habitable Earth-like exoplanets?**

In 2025, the Exo-Earths theme was able to extend its expertise significantly by welcoming Assoc. Prof. Konstantin Herbst (in January), Researcher Vincent Kofman (in April), Postdoctoral Fellow Dag Evensberget (in October) and Hannah Sanderson (in November). In the attempt of bringing our research to the next level, the Exo-Earths team submitted and won the NFR FRIPRO GREP (Galactic Recipe for Exo-Planets, PI Werner, Co-PI Herbst) and is awaiting the outcome of two ERC proposals: CLoTH (Clouds on the Horizon) submitted by Kofman as an ERC Starting Grant and SWEEP (Space Weather Effects on Exo-Planets) submitted by Herbst as an ERC Synergy Grant (Role: corresponding PI).

PLATO (Participation in the ESA mission consortium)

PHAB Participants: Werner, Herbst, Hatalova, Mamonova, Maupin, Kofman, Trønnes

Aim: Planet detection and characterization of bulk parameters

Links to PHAB work packages: WP3.1, 3.2, 3.6

As part of the PLATO mission consortium, the PHABs exoplanet group actively engaged in various scientific activities, primarily through online meetings and scientific collaborations.

PHAB's exoplanet group is actively engaged in two working groups: the Stellar Variability Working Group (SVWG) and the Modelling Atmosphere-Interior-Stellar Effects (MAISE). Additionally, the group is involved in three work packages: Composition and Interior Evolution of Terrestrial Planets (WP115 600), Atmospheres of PLATO Terrestrial Planets (WP116 400), and Climate/Atmosphere of PLATO Habitable Zone Planets (WP116 530).

These working groups and work packages are at the forefront of exoplanetary research, significantly contributing to the mission's objectives of determining stellar variability, providing unprecedentedly accurate planetary parameters (including planetary mass and radius), constraining the interior composition of both terrestrial and gaseous planets, and characterising terrestrial planets located in the habitable zone of solar-like stars.

SVWG is dedicated to identifying the most effective methods for detecting planets and accurately determining their mass and radius amidst stellar variability. Our discussions aim to address critical questions regarding the necessary observations and diagnostics for monitoring stellar variability, particularly for stars that host Earth analogues. To facilitate this, we organised data challenges to evaluate how different stellar signals affect planet detection and characterisation in the context of PLATO.

MAISE focuses on combining PLATO expertise on modelling processes affecting the atmospheric evolution of rocky exoplanets, including the main feedback between the atmosphere (climate and photochemistry), the interior (outgassing and deposition) and the central star (stellar activity). Our discussions focus on the impact of stellar variability and radiation on exoplanetary atmospheres, climate/chemistry, and potential biosignatures, aiming to discern patterns that could indicate the presence of life or provide insights into planetary evolution. We further collaborate on refining climate-chemistry modelling of future PLATO observations of rocky exoplanets and the development of robust spectral analysis techniques. The PHAB team is engaged in all MAISE meetings; the first studies will be published in 2026.

WP115 600 is to explore the diversity of small planet (interior) structures that could explain observed planet mass radius observations. Although highly underdetermined, the range of interior structure is chemically constrained when the composition of the star and chemical condensation sequence in the protoplanetary disc are considered. Preliminary results for compact K-dwarf systems suggest that under similar-to-solar-system-formation assumptions, planets without iron cores up to a proportion that is similar to Earth's are natural outcomes to be further explored.

WP116 400 and *WP116 530* focus on the evolution of the atmosphere of rocky exoplanets, including the main feedback between the atmosphere (climate and photochemistry), the interior (outgassing and deposition) and the host star (composition, instellation, stellar wind, space weather), with a focus on the availability of volatiles as a result of planet formation models using PLATO data supported by model studies and theoretically generated data. We further discuss questions on how formation models can be tested with emerging PLATO data. Thus, we collaborate on refining models that will be essential for interpreting future PLATO observations, aiming to discern patterns that could indicate the presence of life or provide insights into planetary evolution.

As we move closer to the launch of the PLATO mission (scheduled for the first quarter of 2027), our work in these groups will play a crucial role in maximising the scientific output of this groundbreaking mission. A next step forward was achieved when Werner, Herbst, and Kofman were nominated and approved by the PLATO Board as members of the newly established PLATO Science Core Team (PSCT), evaluating newly proposed Working Groups and shaping early PLATO science goals.

Ariel (Participation ESA mission consortium)

PHAB Participants: Werner, Herbst, Hatalova, Mamonova, Kofman

Aim: Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres.

Links to PHAB work packages: WP3.5, 3.6, 3.7

As a member of the Ariel space telescope consortium, the PHAB exoplanet group actively engaged in various scientific activities, primarily through online meetings and scientific collaborations. Our involvement spans three crucial working groups (WGs): Atmospheric Chemistry, Planet Formation, and Planet Interiors. These groups are at the forefront of exoplanet research, contributing to the mission's goal of characterising the atmospheres of a diverse sample of exoplanets.

The Atmospheric Chemistry WG focuses on the future unravelling of the complex chemical compositions of exoplanet atmospheres using the Ariel facilities and premodelling retrieval for the project's potential targets. Our discussions often revolve around potential biosignatures, the effects of stellar radiation on atmospheric constituents, and the development of robust spectral analysis techniques. We collaborate on refining models that will be essential for interpreting Ariel's future observations, aiming to discern patterns that could indicate the presence of life or provide insights into planetary evolution.

In the Planet Formation WG, we explore how Ariel's observations can illuminate the processes of planetary system formation and evolution. Our meetings frequently involve debates on the role of migration, the impact of host star properties on planet formation, and the signatures of formation mechanisms that might be detectable in atmospheric compositions. We're particularly interested in how Ariel's large-scale survey approach can reveal trends across different planetary systems, potentially revolutionising our understanding of planet formation theories.

The Planet Interiors WG studies the connections between a planet's internal structure and its atmospheric characteristics and the manifestation of these processes in the potential features in the observed spectrum. Our discussions evolve around developing new models to link core composition, mantle dynamics, and atmospheric properties.

Participating in these working groups has been an enriching experience, allowing us to contribute to cutting-edge exoplanet science and collaborate with experts from around the world. As we move closer to Ariel's launch (postponed to 2031), our work in these groups will play a crucial role in maximising the scientific return of this groundbreaking mission. PHAB's recent results have been presented at the Ariel consortium meeting (08-11/04/2025) in Leiden.

We're excited about Ariel's progress (see Fig. 3.1) and its potential to provide constraints on interior models through precise measurements of planetary radii, masses, and atmospheric compositions. These insights will help to better understand the diversity of exoplanets and their potential for habitability.

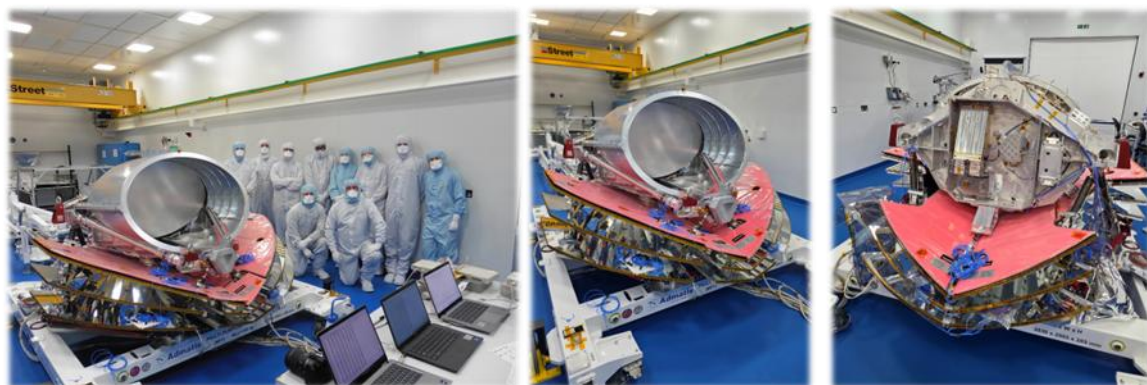


Figure 3.1. Latest Ariel milestone on the pSM build: Successful integration of the telescope assembly onto the bipods. Figure credit: Georgia Bishop.

GREP: Galactic Recipe for Exo-Planets (Werner, Herbst) - granted in September 2025

Aim: Address a significant gap in the field of exoplanet formation by developing a unique planet formation model suite that incorporates the intricate interactions between stellar age, composition, disc chemistry, and evolutionary processes.

Objectives:

- Derive populations of exoplanets and structures of exoplanetary systems, incorporating results from the PLATO LOPS2 field. This will encompass the variety of galactic stellar compositions and a range of system ages.
- Develop a self-consistent, dynamic N-body simulation suite that models exoplanet formation, including gas-accretion, pebble accretion, and migration.
- Investigate the evolution of the protoplanetary disc during the formation of planetesimals and pebbles. This will include examining elemental abundances (including volatiles) to estimate the compositions of planetesimals and pebbles, and ultimately exoplanets.
- Predict and replicate the architecture of exoplanetary systems, along with the composition, structure, and density of exoplanets as influenced by their stellar heritage. This will be validated against observations from PLATO, using the updated planet formation model suite.

Links to PHAB work packages: WP1.2, 1.3, 1.5, 1.7, 2.2, 3.1-3.3

So far, none of the detected exoplanetary systems resembles our solar system, and only a few hundred exoplanets can be broadly classified as temperate and rocky. This indicates a lack of typical inner solar system planets like Mercury, Venus, Earth, and Mars (Fig. 3.2). Despite the numerous numerical models that have been proposed and progressively refined in response to observational constraints over the past decade(s), our understanding of the observed diversity of exoplanets remains incomplete.

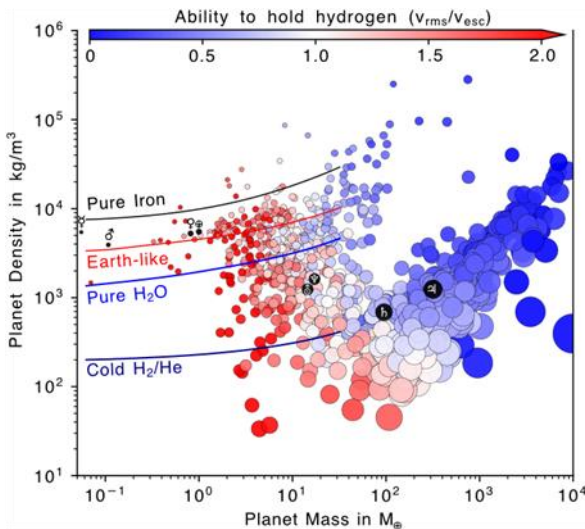


Figure 3.2 Mass-density diagram of confirmed exoplanets in multi-planet systems. Figure from Werner et al. (in prep.)

of the PLATO mission by improving mass/density-radius relationships and aiding in the interpretation of the extensive exoplanet data anticipated from PLATO. GREP builds on the work of Hatalova et al. (2023, 2025) and Yzer et al. (2025).

The project will start in April 2026, but the first set of planet formation simulations have already been run on Sigma2 infrastructure and are currently being analysed.

Besides Werner, Herbst, Hatalova, Brasser and Brodholt, the team will include the two external collaborators Prof. Helling (IWF, Graz) and Prof. Bitsch (University College Cork), a postdoctoral fellow, and a PhD candidate.

EXOATMO (Ph.D. candidate project: Mamonova, Werner, Herbst)

Aim: Primordial atmospheres of newly formed exo-Earths orbiting young M and K dwarfs can reveal their evolutionary pathways to habitability through 1D chemical kinetics modelling, taking into account the intense stellar activity in the form of stellar flaring.

Objectives:

- We suggested a new stellar activity model, the Young M Dwarf Flare (YMDF), which is based on physical processes corresponding to flaring in M dwarfs.
- The model reproduces temporally and spectrally resolved radiation in young M stars in wavelength ranges where the observations are lacking.
- The model helps determine the evolutionary pathways of the water-vapour- or hydrogen-dominated atmospheres in planets in the vicinity of young M and K stars.

Links to PHAB work packages: WP3.1, 3.4, 3.6, 3.7

M dwarfs have become focal points in the search for habitable exoplanets due to their close habitable zones and the prevalence of Earth-sized planets in their orbits. However, these stars present significant challenges owing to their high levels of activity, particularly frequent flares.

We have published two papers on the development and implementation of the Young M Dwarf Flare model (YMDF): The first paper, “Flare frequency in M dwarfs belonging to young moving groups” (Mamonova et al., 2025a), characterised young M dwarf activity from TESS observations of moving groups. The second paper, “Young M-dwarf flare activity model: Towards better exoplanetary atmospheric characterisation” (Mamonova et al., 2025b), presented the Young M-Dwarf Flare (YMDF) model, integrating the RADYN stellar atmosphere models (Kowalski et al., 2024) with flare frequency distributions to predict spectral evolution from coronal electron beams.

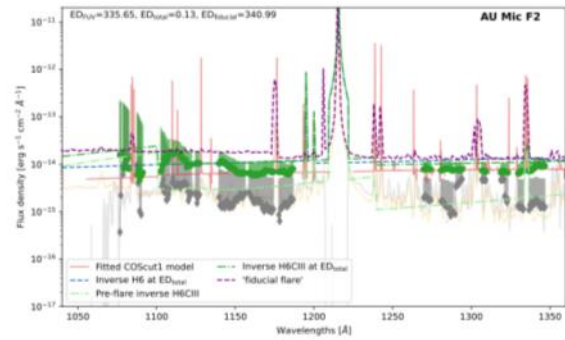


Figure 3.3. Synthetic YMDF spectrum is fitted to the observation at the peak of the flare detected in Au Mic by the Hubble Space Telescope and Cosmic Origin Spectrograph.

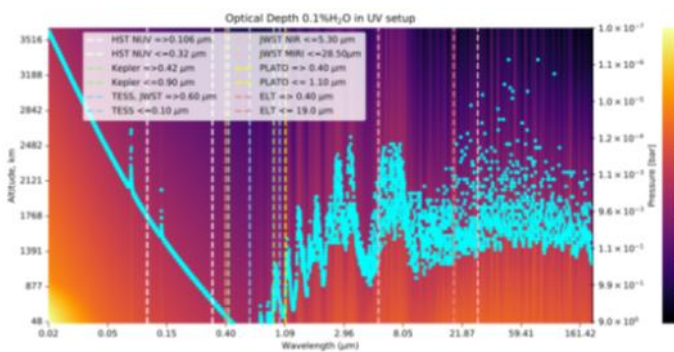


Figure 3.4. Optical depth profile in the modelled atmosphere of an Exo-Earth with 0.1% water vapour orbiting a young active M dwarf.

A third paper on the “Stellar flare-driven evolution of primordial exo-Earth atmospheres: Insights from a Young M Dwarf Flare model” has been submitted and is currently under review. Here we simulated exo-Earth atmospheres with 0.1-100% water vapour under realistically modelled stellar activity, for the first time tracking chemical evolution over one year and quantifying abiotic oxygen production in water-vapour-dominated atmospheres (Figs. 3.3, 3.4).

stability of water in these primordial envelopes under stellar forcing and enables detailed modelling of photochemical and escape processes in young exoplanets. Representing 75% of solar neighborhood stars, M dwarfs require such coupled stellar-planetary models to identify habitable worlds amidst activity-dominated spectra. Our research advances understanding of the fate of primordial atmospheres and refines criteria for potentially habitable exoplanets around active stars.

This framework predicts the evolution as well as depletion of minor species and the

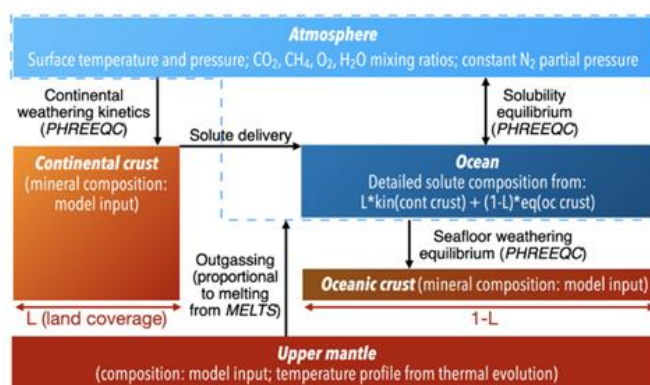
Exoplanetary atmospheres: Sensitivity to planetary processes (Researcher project: Kofman)

Aim: Understand the link between atmospheres and the large-scale planetary processes such as plate tectonics, weathering, and biochemistry. Constrain the extent to which these processes are visible in observations of exoplanets.

Objectives:

- Further develop the framework to simulate the observations of exoplanetary atmospheres.
- Determine the sensitivity of current and future telescopes to detecting signals from planetary processes such as plate tectonics (CO_2 , CH_4 , H_2), weathering (CO_2 , H_2O) and biochemistry (O_2 , CH_4).

Links to PHAB work packages: WP1.3, 2.2, 3.1, 3.4, 3.5



This project is structured of two parts. The first one consists of combining three models and simulating the effects of planets' interior processes, modelled with ExoCycleGeo, on atmospheric chemistry and mixing using photochem, and finally to the Planetary Spectrum Generator to simulate the observations and constrain the detectability of the different atmospheric species (Fig. 3.5). Each of the different models is briefly discussed below.

Figure 3.5. Schematic of ExoCycleGeo's operation.

ExoCycleGeo (Neveu et al., 2023) is developed by Marc Neveu (collaborator on this project) and enables the study of the different planetary processes, such as weathering, outgassing, and differences in mantle composition, on the composition of the atmosphere over time. The model builds on an existing well-established geochemistry code, PHREEQC, which is continuously run over the course of the code's runtime to study the evolution of the planet and its atmosphere.

Photochem (Wogan et al. 2023) is an open-source code developed for Python by Nicholas Wogan and will be used to study the photochemical and climate evolution of the planets simulated in ExoCycleGeo. The code will be coupled to outputs of ExoCycleGeo and subsequently serve as input to the next time step.

Finally, the output of the combined numerical suite will be coupled to the Planetary Spectrum Generator (Villanueva et al., 2022), which can be used to simulate the detectability of atmospheric species. Linking the outputs/inputs of the three codes will allow the study of weathering, carbon cycling, and planetary composition.

For the second part of this work, the methodology to calculate spectra of atmospheres of exoplanets will be further developed. In particular, the consideration of clouds, critical for the strength of the detectability of gases, is being investigated. This is in line with the submitted ERC proposal (Kofman, ERC StG – 2025- Clouds on the Horizon).

Stellar Winds and Atmospheric Escape in an Energetic Particle Environment (Post. Doctoral project: Evensberger)

Aim: This project investigates how stellar winds, magnetic fields, XUV radiation, and energetic particles jointly regulate atmospheric escape and its observable signatures in exoplanetary systems.

Objectives:

Characterize stellar wind pressure, expected magnetic topology, and XUV flux as a function of stellar mass, rotation, age, and magnetic geometry. Assess how stellar magnetic variability, flaring, and coronal mass ejections modify planetary magnetospheres and escape conditions. Predict observable signatures of atmospheric escape under realistic stellar wind and space weather conditions. Evaluate the contribution of stellar energetic particles and cosmic rays to escape rates and atmospheric chemistry.

Links to PHAB work packages: WP 1.3, 1.5, 3.1, 3.6, 3.7

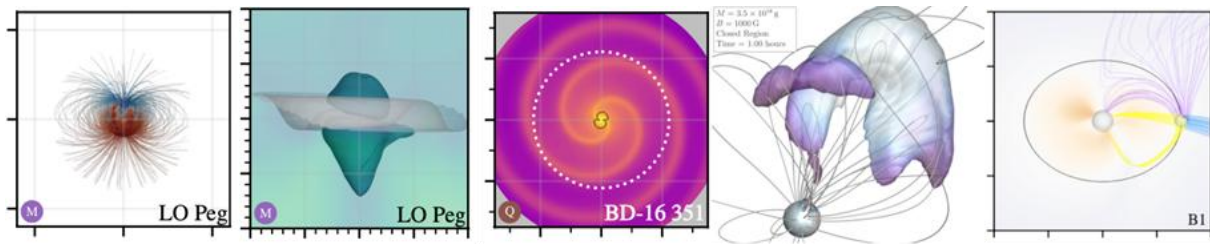


Figure 3.6. Illustrating stellar wind structures, transient events, and star-planet magnetic coupling relevant for atmospheric escape. From left to right: 1–2: Steady-state coronal magnetic field, Alfvén surface, current sheet, and wind speed for the rapid rotator LO Peg. 3: Spirals formed from overdense corotating interaction regions for BD-16 351, an inclined rapid rotator. Figures from (Evensberger et al. 2021, 2022, 2023) 4: An escaping coronal mass ejection shock front modeled with a global magnetohydrodynamic stellar wind code (Strickert, Evensberger et al. 2024). 5: Alfvén characteristics connecting the star–planet system, terminating and originating from the planetary magnetosphere (Evensberger et al. 2025).

Atmospheric escape models must now be able to predict observable signatures in the era of JWST and upcoming missions (Gardner et al. 2006). The stellar wind plays a central role in shaping planetary magnetospheres and regulating energy input into upper atmospheres. Using surface magnetic field maps derived from Zeeman-Doppler imaging (Morin et al. 2010), we use BATSRUS for three-dimensional stellar wind models (Powell et al. 1999). The models reveal a wide diversity of large-scale magnetic configurations and wind conditions among solar-type and lower-mass stars (Evensberger et al. 2021, 2022, 2023). This leads to variations in wind pressure, current systems, and magnetospheric size, implying large system-to-system differences in atmospheric escape efficiency.

X-ray and extreme ultraviolet radiation from the host star heats and ionises the upper atmosphere, leading to expansion and enhanced escape (Lammer et al. 2003). For rapidly rotating and magnetically active stars, frequent flaring and coronal mass ejections further energise the stellar wind and can transiently compress planetary magnetospheres, altering escape conditions (Lammer et al. 2007; Strickert, Evensberger et al. 2024). These effects are expected to be particularly important for planets orbiting M-dwarf stars, where habitable-zone planets are exposed to strong XUV fluxes and intense magnetic activity.

Energetic particles, including stellar energetic particles and galactic cosmic rays, provide an added source of ionisation and can produce observational signatures that overlap with those attributed to atmospheric escape (Helling and Rimmer 2019). Energetic particle transport is strongly modulated by the stellar wind structure and the shape of the astrosphere (Parker 1965). By combining global stellar wind models with particle transport calculations, we aim to develop an integrated framework to quantify the role of energetic particles in driving and modulating atmospheric escape and in shaping its observable tracers (Wang et al. 2006).

Our ongoing work focuses on extending stellar wind models across stellar mass and age and coupling them to radiative magnetohydrodynamic models of planetary upper atmospheres (Carolan et al. 2021). Future developments will incorporate energetic particle transport through the combined astrosphere-magnetosphere system and will be used to predict observable escape signatures for comparison with JWST data and future missions such as Ariel.

Dating planetary systems by dating their central star (Internal project: Maupin, Herbst)

Aim: Determine the age of planetary systems to assess their potential for habitability. This is done in practice by dating the central star.

Objectives:

- Perform an analysis of how the evolution of stars produces observables which can be used to date them.
- Determine how evolution in the structure of stars can be tracked in asteroseismological data.
- Analyse what determines the rotation rate of stars and how this is related to their age.
- Find candidate stars for a comparison of their rotation rate as determined by gyrochronology and splitting of their asteroseismological modes.
- Use binary or multiple star systems to improve methodology to correlate asteroseismological data with stellar age.
- Date planetary systems relevant for habitability.

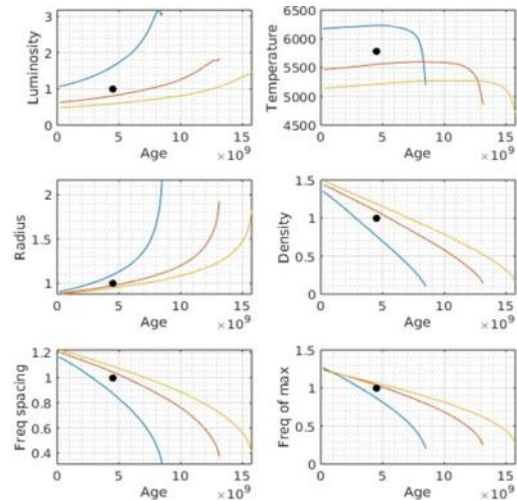


Figure 3.7. Temporal evolution of stellar parameters with the same mass as the Sun. All parameters except for temperature are with respect to those of the Sun, shown as a black dot. The curves are for three metallicities: 0.6% in blue, 2% in red, and 4% in yellow. The two lower plots are the asteroseismological parameters. Data from the Univ. of Geneva, Mowlavi et al. (2012).

Links to PHAB work packages: WP2.1, 2.2, 3.1, 3.2

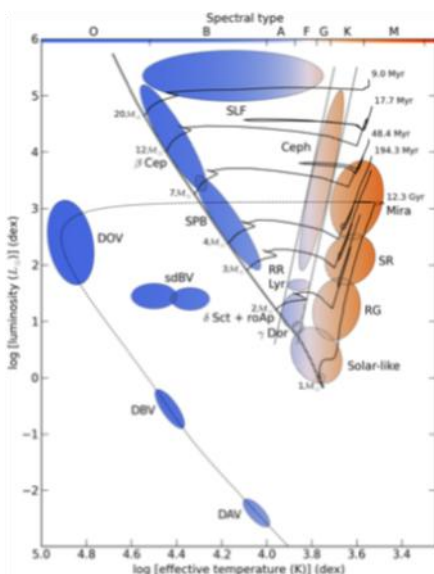


Figure 3.8. - Hertzsprung-Russell diagram showing different stellar classes in terms of the excitation mechanisms, along with the typical periods and amplitudes of the oscillations. The hatching line style used in each of the ellipses marks the dominant type of oscillation mode in each class: // for gravity modes and \ for pressure modes. Figure from Pápics (2013).

It is commonly accepted that for life to develop on a planet, the planet must reside in the host star's habitable zone long enough for life to develop. The age of the planetary systems and how they develop with time is therefore an important parameter to be considered when assessing the potential for habitability of an exoplanet. As planets form alongside the formation of stars, particularly from planetary discs, it is fair to assume that dating a star will give an insight into the age of its planetary systems. Dating stars, however, is no simple task. The two main characteristics of a star as determined by astronomers are its luminosity and its surface temperature. Although there are advanced models of the evolution of stars based on their initial mass, their evolution in terms of luminosity and their masses is not linear: Periods of rapid evolution in the early stages are followed by long periods on the main sequence (see Fig. 3.8), where these parameters do not change significantly. The interior of the stars, however, is changing during these periods, which makes their characterisation much more challenging.

In general, asteroseismology is the analysis of the eigenvibrations of stars and can be used to probe their interiors and therefore give insights into their evolution stages. The most accessible parameters in the asteroseismological spectra inform on the mass and radius of the stars, but not on their internal structure, which requires spectra with a good signal-to-noise ratio and a refined analysis. By obtaining a Fourier transform of the stellar light curves that have been observed with Kepler/K2, TESS, and GAIA, the stellar amplitude spectra can be derived and inform about self-excited p modes, tidally excited g modes, and gravity modes (see Fig. 3.9). Rotation rates of stars have also been proposed to be related to their age.

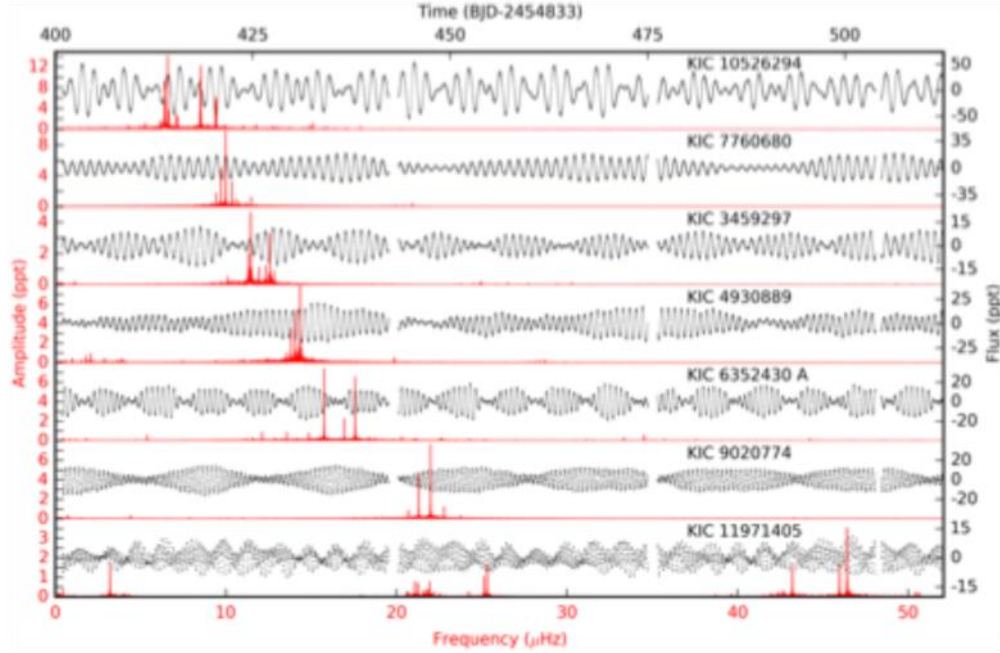


Figure 3.9. From Pápics et al. (2017) - Excerpts of 110 d duration (of the total ~1500 d) extracted from the Kepler long-cadence (~30 min per point) light curves (in black) of seven slowly pulsating B stars. These stars exhibit nonradial gravity modes with individual mode periods of the order of 1 d. The light curves reveal a gallery of diverse beating patterns among the modes and a gradual shift in maximum amplitude from low to high frequency as their rotation frequency changes from low in the top panel to high in the bottom panel.

In collaboration with a PhD/postdoc fellow, Maupin and Herbst will start building up PHAB's expertise in asteroseismology. The first goal is to assert which methodology and data are the most appropriate to date different types of stars, independently from the fact that they support a planetary system or not. The second objective will be to apply the acquired knowledge to stars with exoplanets relevant for habitability studies.

Space weather and its Impact on Exoplanetary Habitability (Internal project: Herbst)

Links to PHAB work packages: WP1.3, 3.1, 3.3, 3.6, 3.7

Space weather events such as flares, coronal mass ejections (CMEs), and energetic particle events are spectacular manifestations of solar/stellar magnetic energy release. Flares appear as a sudden temporal increase in electromagnetic radiation (across the entire spectrum) up to several orders of magnitude, in rare cases briefly exceeding the luminosity of the star in quiescence. A CME is characterised by the eruption of relatively dense, magnetised material to the outer corona and the constantly out-flowing stellar wind (Benz 2017). Both flares and CMEs can act as sources of stellar energetic particles (StEPs), typically protons and electrons, accelerated to very high energies (keV-GeV) via magnetic reconnection (flares) or at the shockfront of CMEs. Solar observations indicate that solar EPs emerging from flare sites are less energetic compared to their CME-shock-driven counterparts (e.g., Reames 2021) and that up to 90% of high-energy flares ($> 10^{31}$ erg) are accompanied by CMEs (Yashiro & Gopalswamy 2009). Thereby the kinetic energy and the mass of CMEs are correlated with the X-ray fluence of the corresponding flare (Lamy et al. 2019), and up to 20% of the kinetic energy can be channeled into the acceleration of energetic particles (Emslie et al. 2012).

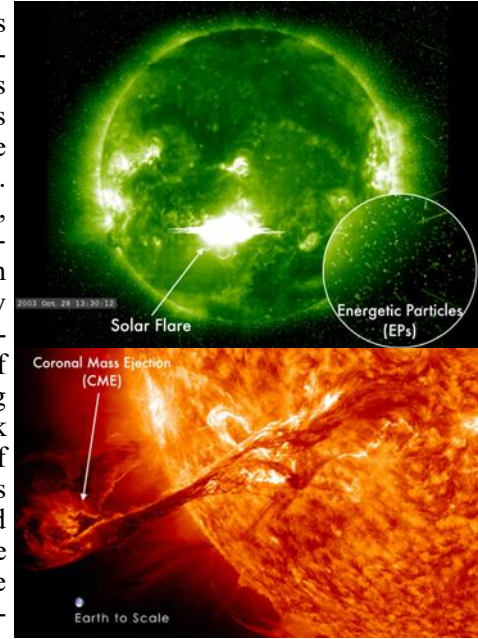


Figure 3.10. Image of a solar flare with a close-up showing flare-accelerated energetic particles (left) and a CME captured in extreme ultraviolet wavelengths (right). Figures: NASA.

Observations and modeling efforts have shown that solar space weather has a direct impact on all planets within our solar system, particularly those close to the Sun (e.g., Earth and Mars). The most energetic solar events pose threats to life on Earth, with recent examples including the March 6, 1989, X15 and X4 class flares ($\sim 10^{33}$ erg) that triggered a CME

causing the collapse of Quebec's electricity grid and the 1859 Carrington Event that ignited telegraph lines and spread aurorae as far south as Hawaii, Cuba, and even Colombia (Carrington 1859). An extraordinary event around AD 774/775, which was discovered in $^{14}\text{C}/^{12}\text{C}$ data from Japanese cedar tree rings (Miyake et al. 2012), was also caused by solar energetic particles powered by an extreme CME that would have destroyed a considerable fraction of the ozone layer of the atmosphere over timescales on the order of years (Melott & Thomas 2012).

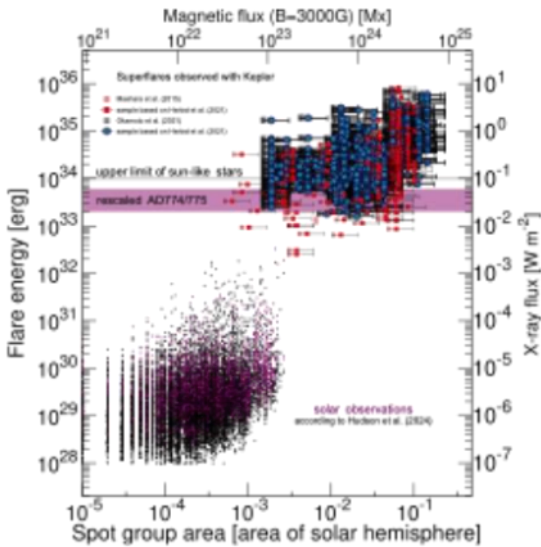


Figure 3.11. Flare energy as a function of spot group area for solar flares (black dots) and superflares of G-type stars from the Kepler sample by Okamoto et al. (2021). Purple dots show the updated solar observations (Hudson et al. 2024), stellar sample updated according to Herbst et al. (2021). Figure from Herbst et al. (2025).

Meanwhile, cool main-sequence stars can display much larger flare energies and frequencies (by several orders of magnitude) compared to the Sun (see Fig. 3.11); however, note that Herbst et al. (2025) showed that $> 90\%$ of the Sun-like stars in the sample are spot-dominated rather than faculae-dominated like the current Sun. Nevertheless, at face value, the enhanced flare activity of stars, combined with the behaviour of magnetic transients on the Sun, suggests equally extreme associated stellar CMEs and EP events (e.g., Herbst et al. 2019). As such, they have been proposed to play a fundamental role in shaping the evolution of activity, mass loss, and rotation (Drake et al. 2013), as well as the exoplanetary conditions around cool main-sequence stars (e.g., Engelbrecht et al. 2024). As observational constraints are missing, often known solar correlations are used and extrapolated to match the stellar flare intensities. But the lack of stellar CME detections currently challenges wheth-

er the solar flare-CME-energetic particle paradigm holds for other stars and if extending the solar correlations to the stellar regime leads to implausibly high expectations for stellar energy and mass loss via CMEs and energetic particles.

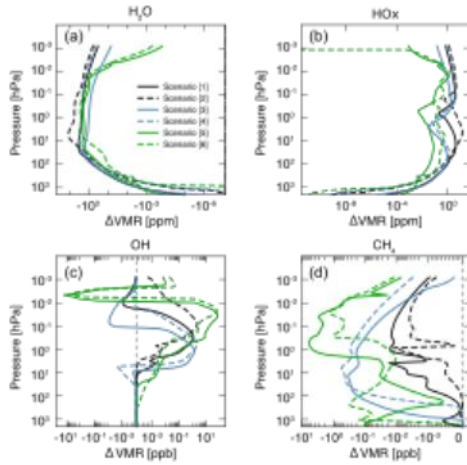


Figure 3.12. Absolute differences between model runs with and without the influence of a Carrington-like stellar particle event (Herbst et al. 2024).

example of the impact of a Carrington-like event on rocky exoplanets with different atmospheric compositions (i.e., dry-dead in black, wet-dead in blue, and wet-alive in green; Herbst et al., 2024). As shown, in all cases large event-induced amounts of NO_2 , a re-duction of the atmospheric transit depth in all water bands and strengthened/weakened methane/ozone features occur. Particularly the latter indicates that StEPs can obscure and/or mimic atmospheric signs of life, with drastic consequences for the interpretation of exoplanetary habitability.

Solar-terrestrial studies have shown that the solar space weather strongly impacts planetary atmospheres by, i.e., inducing the production of secondary particle cascades that lead to changes in atmospheric electric properties, climate and chemistry changes, and enhancements of, e.g., radiation exposure. In the exoplanetary context, particularly the impact of cosmic rays may play a crucial role for atmospheric climate and chemistry changes, and hence the habitability of exoplanets (Herbst et al. 2019). While galactic cosmic rays (GCRs) vary on longer timescales related to possible stellar cycles, stellar energetic particles (StEPs) display short-term variability which can lead to the most dramatic changes in atmospheric chemistry (Fig. 3.12) and climate in the atmospheres of Earth-like planets in the HZ of M dwarfs (Herbst et al. 2019, 2024; Chen et al. 2021) and strongly impact the radiation exposure at exoplanetary surfaces (e.g., Engelbrecht et al. 2024). Particularly the atmospheric chemistry changes have further consequences for atmospheric characterisation with instruments such as HST, CHEOPS, and JWST (e.g., Herbst et al. 2019, 2024). Figure 3.13 shows an

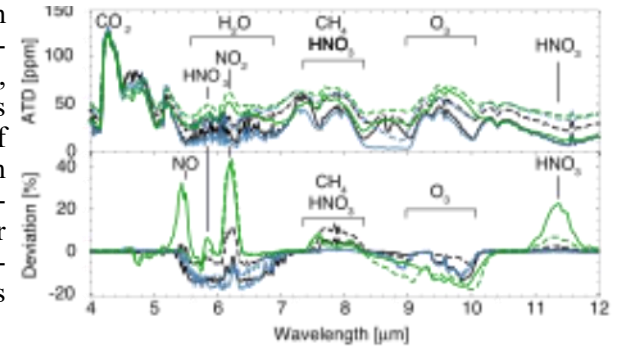


Figure 3.13. Absolute differences between runs with and without a Carrington-like event under different conditions: dry-dead in black, wet-dead in blue, wet-alive in green, 0.1 bar CO_2 (solid lines) and 1 bar CO_2 (dashed lines). Figure from Herbst et al. (2024).

Herbst is the corresponding PI of the ERC Synergy Grant proposal SWEEP (Space Weather Effects on Exo-Planets) that has been submitted to the ERC Synergy Grant 2026 call. Despite its outcome, within the upcoming years, this group will, for the first time, reconstruct the so far unobservable particle environments around nearby cool stars by combining new and archival observations with state-of-the-art 3D physics models. Instead of relying on extrapolations from the Sun, we will directly link stellar magnetic maps, interstellar surroundings, realistic magnetohydrodynamic (MHD)-based particle-transport models, and atmospheric chemistry and climate models to predict the fingerprints of high-energy particles as they interact and transform exoplanetary atmospheres. Therefore, we will leverage gas and ice giants as natural “space-weather detectors”, as their observable atmospheres serve as in-situ sensors that reveal the (previously) unobservable stellar high-energy particle impacts—offering unique insights into the habitability of Earth-like exoplanets.

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*Elena Mamonova (top) and Vincent Kofman (bottom) presenting at the PHAB Board Meeting 22.5.25.
Photos: Trine Sannesmoen.*

The Else-Ragnhild Neumann award 2025

Since 2018, the Else-Ragnhild Neumann Award for Women in Geosciences was given by CEED. In 2023, PHAB decided to take over the award that is awarded to a woman who through her PhD or postdoctoral work has made a significant contribution to research in Geosciences.

*The committee members for 2023 and 2024 were Professor **Carmen Gaina** (PHAB, UiO), Director **Brit Lisa Skjelkvåle** (Natural History Museum, UiO) and Professor **Stephanie C. Werner** (Director of PHAB, UiO).*

Requirements for nomination

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

About the award

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

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

***Her most recent article is:** Neumann, E. R., Callegaro, S., Jacobsen, S. B., Hyung, E., Svensen, H. H. & Larsen, B. T. (2025) Geodynamic evolution of the first basaltic volcanism (B1) in the Oslo Rift (Southeast Norway), *Lithos*. V. 512-513.*

The Else Ragnhild Neumann Award had one recipient in 2025.

The recipient of the Else-Ragnhild Neumann Award for Women in Geosciences for 2025 is Dr. Gabrielle Emma Kleber, from the Arctic University of Norway, UiT.

The winner was nominated by **Matthias Forwick**, head of department at the institute of Geosciences UiT, and **Terri Souster**, iC3 Project Manager, UiT.

The committee views Gabrielle Kleber as an extraordinarily talented and dedicated scientist and person. Dr. Kleber is currently a Postdoctoral Fellow at UiT and she obtained her PhD in 2023 at Cambridge University, after a Master at NTNU and BSc at Michigan University. After graduating with a PhD she has already secured external funding in the form of two NFR projects.

She has published 6 papers, 4 of them as 1st author, with one in Nature Geoscience. She seems to be an inquisitive scientist, heavily involved in field campaigns, but also in teaching and outreach. The committee was impressed by her previous experience as a trained engineer and activity in the Circumnavigators Club Foundation. The nomination letter is very compelling and the committee is very impressed.

In order to receive and celebrate the award, Dr. Kleber was invited to give a lecture at the Centre for Planetary Habitability on the 5th of February 2025. The talk was entitled “Ice, shale and methane: field studies of methane release from glacial catchments on Svalbard”.

**ELSE-RAGNHILD
NEUMANN
AWARD**
FOR WOMEN IN GEOSCIENCES



*left: Else-Ragnhild Neumann Award Logo designed by **Fabio Crameri**.*

Selected publications:

Kleber, G. E., Hodson, A. J., Magerl, L., Mannerfelt, E. S., Bradbury, H. J., Zhu, Y., ... & Turchyn, A. V. (2023). Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic. *Nature Geoscience*, 16(7), 597-604.

Kleber, G. E., Magerl, L., Turchyn, A. V., Redeker, K., Thiele, S., Liira, M., ... & Hodson, A. (2024). Shallow and deep groundwater moderate methane dynamics in a high Arctic glacial catchment. *Frontiers in Earth Science*, 12, 1340399.

Kleber, G. E., Magerl, L., Turchyn, A. V., Schloemer, S., Trimmer, M., Zhu, Y., & Hodson, A. (2025). Proglacial methane emissions driven by meltwater and groundwater flushing in a high-Arctic glacial catchment. *Biogeosciences*, 22(3), 659-674.

Hodson, A., **Kleber, G. E.,** Platt, S. M., Kalenitchenko, D. S. D., Hengsens, G., Irvine-Fynn, T., ... & Römer, M. (2025). Methane in Svalbard (SvalGaSess). *The State of Environmental Science in Svalbard—an annual report*.



Photo: Private



The Else-Ragnhild Neumann Award seminar, 05.02.26, at the Science Library. From left: prize winner Gabrielle Kleber with the Else-Ragnhild Neumann diploma, and Stephanie Werner, Director of the PHAB Centre at UiO. Photo: Gunn Kristin Tjøflot.

Outreach Highlights

Outreach and communication to the public remain priorities in the Centre. Engaging the public, disseminating our research, and being available to answer questions from curious journals justifies our existence as a centre for excellence funded by public money.

Public Lectures and Talks

Members of PHAB have been speaking publicly both in Norwegian and English throughout the year. At the University of Oslo's open day PHAB was well represented. Van der Boon and Werner both presented research to the public, discussing the Earth's magnetic field and its relevance and discussing planetary habitability. The open day attracts people from the city and beyond, and provides an opportunity to reach both prospective students and interested audience to talk about our science.



Annique van der Boon on UiO open day.

Photo: Trine Sannesmoen.

Popular science magazines

With the NASA and ESA sponsored Martian mineral analogue library, PHAB fulfills an important role in the infrastructure support future Martian sample return efforts. Agata Krzesinska and Marine Ciocco co-wrote an article in the Norwegian magazine 'Astronomi' describing the efforts and how to understand the minerology of Mars from the Earth. As a part of the special Mars feature of the magazine, their efforts were featured on the front page of the journal. Another article dedicated to Martian rocks found on the Earth, Martian-meteorites was published in the same article by Agata Krzesinska.

Reidar Trønnes wrote an article in the same journal describing the formation of Earth and moon system, the formation of the moon, and how we can improve our understanding of our own solar system from exoplanets.



Cover February edition of Astronomi.

Online magazines

Clint Conrad's work studying the uplifting of south-eastern Greenland was highlighted in a phys.org article. The centre also contributed to several articles on national forskning.no and the university's Titan online news pages. Exoplanets were of considerable interest, and Vincent Kofman was interviewed to discuss a controversial study claiming molecules relevant for life were detected.

Outreach events at schools

Annie van der Boon visited the Blindern videregående skole to talk about the Earth's magnetic field and whether it is relevant for planetary habitability.

Internal Events at the University of Oslo

Jaganmoy Jodder and Trond Torsvik both gave talks at different internal events at the University of Oslo. Jaganmoy introduced himself and his research questions at an event for new staff. Trond spoke at the "Faglig pedagogisk dag" that took place on 30.10.25.

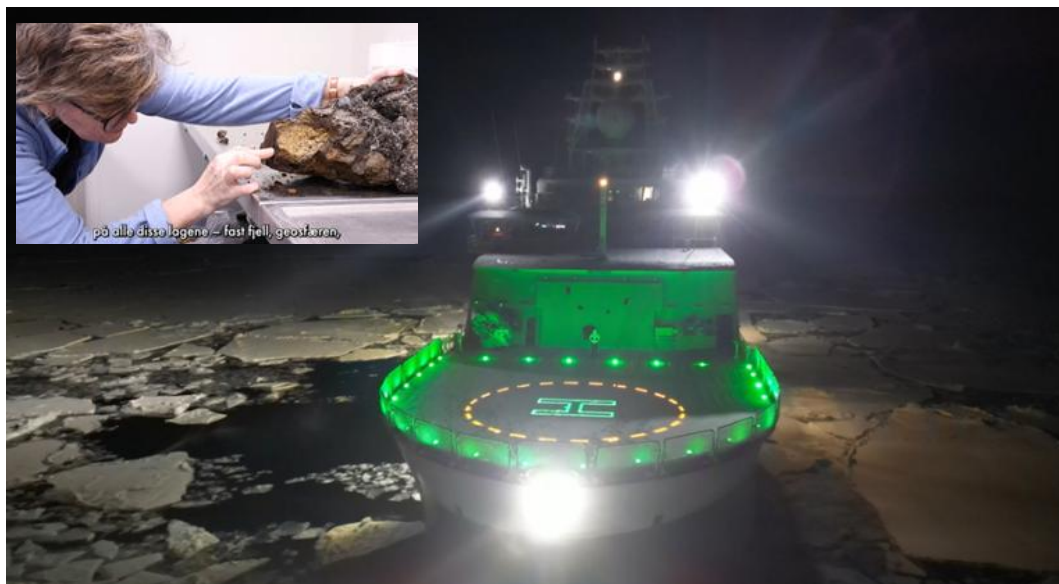
Jaganmoy Jodder at the event for new staff at the MN Faculty, 12.03.25.

Photo: Trine Sannesmoen.



Media

Carmen Giana and Alexander Minakov were featured in a short film documenting the scientific exploration cruise 'GoNorth', exploring Norwegian and Greenland sea.



SOUP (Story Of a Unique Planet) workshop

The Centre for Planetary Habitability (PHAB) at the University of Oslo hosted its inaugural early-career researcher workshop, "Story of a Unique Planet" (SOUP), from 21st to 24th of June 2025. Organized by postdoctoral fellow Jaganmoy Jodder, the workshop brought together 26 participants with the primary goal of fostering a holistic understanding of current concepts and developments in early Earth processes. A key focus was to examine how recent literature aligns with our evolving understanding of planetary habitability.

Following initial discussions at PHAB, the participants relocated to the biological station in Drøbak for the main workshop. The first day featured presentations from distinguished speakers, sparking debates on early Earth processes. The objective was to synthesize established and emerging ideas into a coherent framework to better understand planet formation, ancient geo-biosphere interactions, and the evolution of early life. Key discussion topics included Moon formation, early Earth differentiation, the bulk silicate Earth and magma ocean, the evolution of cratons, early surface processes, biogeochemical cycling, and the future of planetary habitability.

A central outcome of the workshop was to advance several collaborative manuscripts:

- **Earth Science Reviews:** Discussions on the differentiation of the bulk silicate Earth will form the basis of a manuscript summarizing recent advances in modeling and isotope geochemistry.
- **Earth and Planetary Science Letters:** Ideas on the complexity and evolution of cratons, building on an existing manuscript, were refined and will be incorporated into a version to be submitted to this journal.
- **Astrobiology:** Insights from expert discussions on the emergence of early life and the future of habitability will contribute to a planned manuscript for this publication.

International/national participants- Carsten Munker (Uni. of Zu Koln, Cologne), Kris Szilas (NHM, Copenhagen), Axel Hofmann (Uni. of Johannesburg, South Africa), Eva Stüeken (Uni. of St Andrews, UK), Sebastian Viehmann, Johanna Kraye, (Leibniz University, Hannover), Desiree Roerdink (Uni. of Bergen), Kris Szilas (NHM, Copenhagen), Magnus Harding (NHM, Copenhagen), Magnus Harding (NHM, Copenhagen), Austin Jarl Boyd (NHM, Copenhagen), David Murphy (QUT, Australia), Fabian Zahnow (Uni. of Göttingen, Germany), Erik Asphaug (University of Arizona, USA), Francesco Greco (Germany).

Internal PHAB/UiO- Stephanie Werner, Carmen Gaina, Petr Gromov, Jyotirmoy Paul, Trond Torsvik, Konstantin Herbst, Lars Eivind Augland, Fernando Corfu, Ana Azulovic, Vincent Kofman, Justin Tonti-Filippini, Mathew Michael Domeier, Alex Eiler, Jaganmoy Jodder.



SOUP participants at the workshop, Drøbak.

Beyond its specific scientific goals, the SOUP workshop served as a crucial platform for building interdisciplinary bridges within PHAB and fostering new international collaborations.

These initial discussions led to tangible, ongoing collaborative projects:

- **Craton Formation and Crustal Evolution:** Detailed sessions led by **Kristofer Szilas, Axel Hoffmann, Lars Eivind Augland, David Murphy, Jyotirmoy Paul, Petr Gromov, and Fernando Corfu, Jaganmoy Jodder** focused on ancient cratons and zircon records. These debates generated new ideas about how pieces of ancient crust were preserved and their relationship to the tectonic regimes that assembled the primordial continents.
- **Planetary Formation & Interior Dynamics:** Presentations on impact modelling, short-lived radiogenic isotopes, and crater counting by **Erik Asphaug, Stephanie Werner, and Carsten Münker** challenged established narratives like the Late Heavy Bombardment. These discussions clarified existing controversies and energized the community around renewed research objectives concerning giant impact models, early mantle heterogeneity, and interior dynamics.
- **Atmospheric Evolution:** A spirited debate led by **Justin Tonti-Filippini** on the pressure and composition of the early atmosphere has resulted in a direct collaboration between Justin and **Jaganmoy Jodder** on upcoming research projects tracking atmospheric evolution through time.
- **Early Life & Biogeochemistry:** Research presented by **Ana Azulovic, Eva E. Stüeken, and Desiree Roerdink** converged on the frontiers of early microbial life. Their work, combined with studies on banded iron formations and triple oxygen isotopes in Archean cherts by **Sebastian Viehmann, Johanna Krayer, and Fabian Zahnnow**, is providing new insights into ocean redox chemistry, the emergence of early landmasses, and precise estimates of ancient seawater temperatures.
- **Habitability and Biosignatures:** A wide-ranging session on early life and habitability featured contributions from **Trond H Torsvik, Justin Jarl Boyd, Magnus Harding, Francesco Greco, and Jaganmoy Jodder**. Topics included ancient CO₂ models, the rise of silicate weathering, and the preservation of biosignatures. The discussions sharpened the group's understanding of the conditions conducive to life and the methods for detecting it, both on early Earth and beyond.
- **Exoplanets:** By facilitating dialogue between Modern Earth, Early Earth, and Exoplanet research themes, the workshop helped break down silos. Talks by **Vincent Kofman and Konstantin Herbst** (Exoplanets) sparked cross-theme discussions that established a framework for future collaborations and innovative research directions at PHAB.



SOUP participants at SOUP workshop dinner.

A PhD candidate's visit at the Friedrich-Alexander University

Nicole Obren is a 1st-year Phd candidate at PHAB (Centre for Planetary Habitability) at the University of Oslo (UiO).

I am 1st year PhD student at PHAB working on time series inference frameworks, assessing the difference between dynamic processes underlying Earth's biological and geological history. As a marine Paleobiologist I was delighted to be offered a place in the 3-week Analytical Paleobiology summer workshop run by PaleoSynthesis, based at the Friedrich-Alexander University of Erlangen–Nuremberg (FAU). The workshop covered everything analytically paleo, including community diversity analyses, paleogeographic reconstructions, spatial subsampling and niche modeling, phylogenetics, morphometrics, time series analyses, and AI-based analytical techniques in diversity reconstruction.

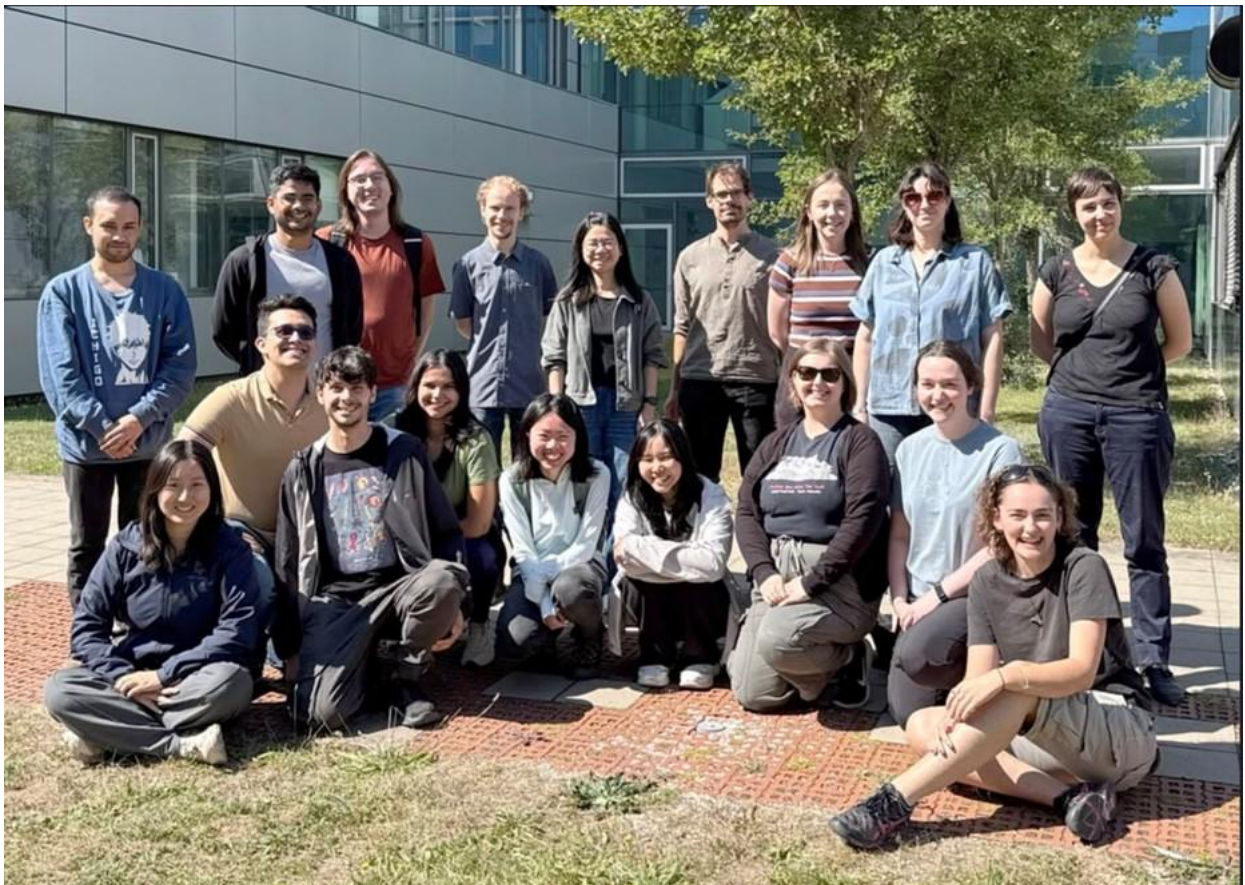


Each section of the course was taught by guest lecturers who represent some of the best in their respective fields, such as Prof. Wolfgang Kießling, Dr. Adam Kocsis, Prof. Rachel Warnock, Dr. Daniele Silvestro and Prof. Lee Hsiang Liow. These lecturers also included some welcome familiar faces, such as my secondary supervisor (Prof. Lee Hsiang Liow), and former CEED Post Doc Dr. Elizabeth Dowding. The workshop included lectures and computational workshops on the topic specific specialised software such as R, Python, ArcGIS, GitBash, Git Hub, Tracer, BEAST, etc.

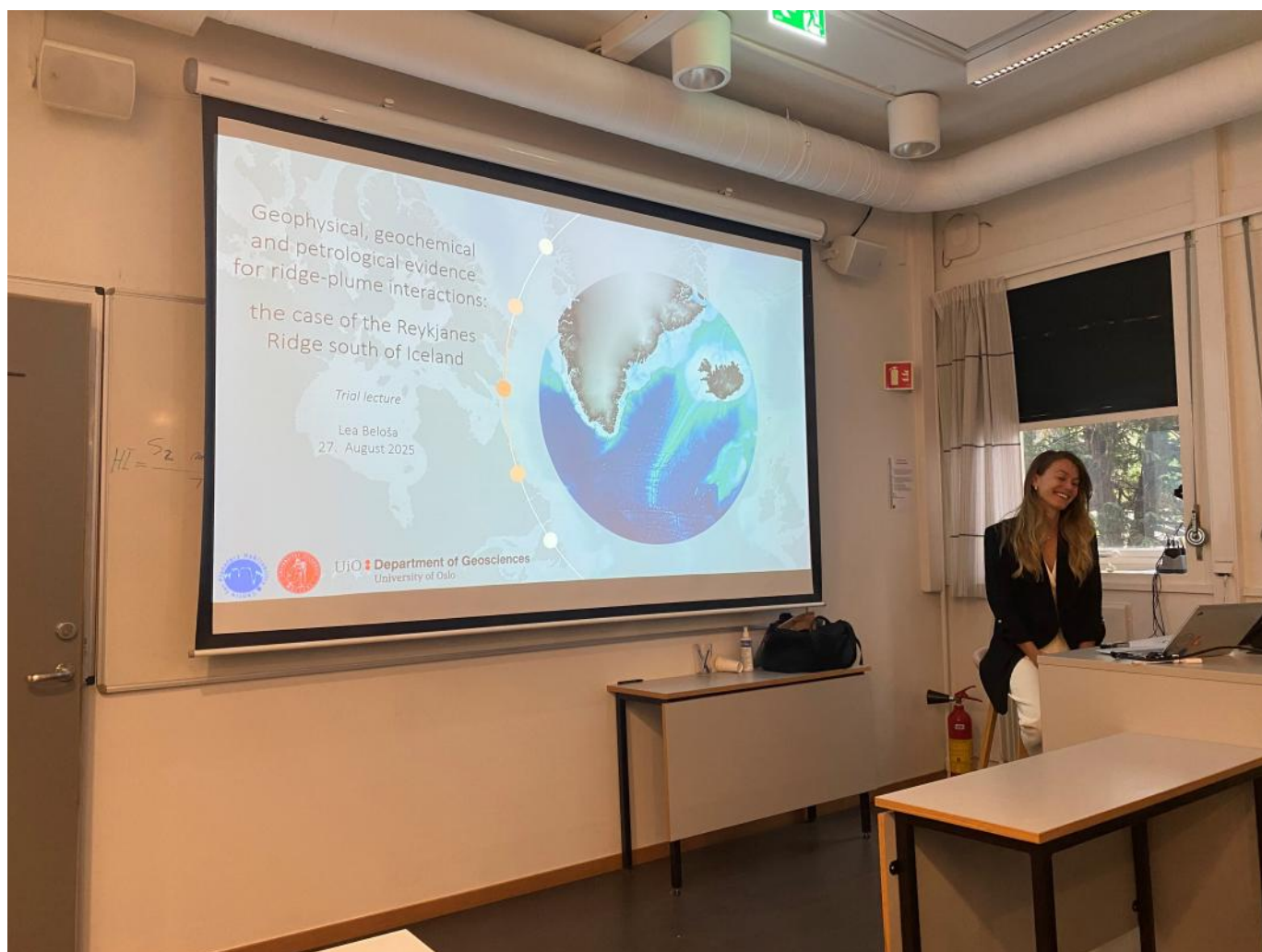
The workshop created an extremely productive space for discussion-based problem solving of in-class topics, and we were always encouraged to discuss our own projects to see if these collaborative discussions could aid in improving our own work. On the few days spare, we were able to explore Erlangen and train to Nuremberg, where we had a great time exploring the history rich city and enjoying the beautiful German summer.



Over the 3-week course, I worked with an incredible group of up-and-coming paleontologists from all around the world studying a diverse array of topics. I was grateful to have the opportunity to get to know such a brilliant minded group of scientists and am very much looking forward to reading all about their contributions to the field in the coming years. I want to express my gratitude to the Paleosynthesis lecturers, organisers and coordinator Dr Barbara Seuß for making this course happen, FAU for hosting, and PHAB and UiO for funding this amazing opportunity. As a first year PhD student, this was my first international workshop meeting the many amazing researchers and fellow peers currently representing my field. The experience has boosted my drive for research and reinforced my confidence in the collaborative scientific community that exists globally.



Appendices



*The trial lecture of Lea Beloša, August 2025.
Photo: Trine Sannesmoen*

Master student projects with one or more supervisors at PHAB

Bold: finished in 25

Name	Topic	PHAB-supervisor(s)
Tvingsholm, Søren B.	Lower mantle controls on plume generation and dynamics	C. Conrad, B. H. Heyn

PhD candidate projects (bold: finished in 25 and for PHAB supervisors)

Name	Topic	Supervisors	Funding
Anzulovic, Ana	Modelling impact of melts on mantle diffusion and viscosity with geodynamic implications.	R. Caracas, C. Gaina	CompSci (EU Horizon)
Beloša, Lea	Intraplate Volcanism, Tectonic Evolution, and Geodynamic Insights in the Northeast Atlantic. *R. Trønnes, A. Mazzini, S. Callegaro	C. Gaina, *for other supervisors	UiO
Gromov, Petr	Quest for Paleoarchean habitats: The growth of first continents on early Earth	C. Gaina, J. Jodder, C. Conrad, T. H. Torsvik	UiO
Mamonova, Elena	A Thorny Path to a Habitable World. Studying primordial exoplanet atmospheres with the Young M Dwarf Flare model	S. Werner, S. Wedemeyer	UiO
Meza Cala, Juan	Tectonic evolution of the SW Eurasia Basin. *C.Gaina, A. Minakov, G. Shephard	J.I. Faleide, *for other supervisors	RCN
Obren, Nicole	Inferring correlative and causal processes in past diversity: Cenozoic of New Zealand as a case study.	T. Reitan, L. H. Liow	RCN
Ryen, Sofie H.	The anomalous behaviour of Earth's magnetic field in the middle Palaeozoic – investigating a 100 million year mystery.	A. van der Boon, M. Domeier, T. Torsvik	RCN
Wang, Yijun	Texture evolution in subduction models, influenced by anisotropic viscosity	Á. Király, C. Conrad	RCN
Xue, Yi	Paleointensity and paleomagnetic investigations of the Ediacaran geomagnetic field.	M. M. Domeier, L. C. Gallo	ERC

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.

International cooperation

Country	Activity	PHAB members involved
Argentina	Collaboration	L. C. Gallo, V. Maupin
Australia	Collaboration, research stay	G. Shephard, C. P. Conrad, A. Lasabuda, J. Jodder
Belgium	Collaboration	S. Werner
Canada	Collaboration	G. Shephard, J. Luu
China	Collaboration, visiting student	T. Reitan, R. Brasser, M. Domeier, S. Werner, R. Caracas
Colombia	Collaboration	K. Herbst
Denmark	Collaboration	C. P. Conrad, J. Jodder, A. Minakov
France	Visitis, collaboration, visiting student	M. Ciocco, R. Caracas, C. P. Conrad
Gabon	Collaboration, fieldwork	M. Mesli, T. H. Torsvik
Germany	Collaboration, lab facilities, exhibition, workshop	A. van der Boon, R. Caracas, C. P. Conrad, S. Werner, A. Minakov, K. Herbst, J. Jodder, C. Gaina, R. Brasser, N. Obren, L. H. Liow
Greece	Collaboration	K. Herbst
Hungary	Collaboration	R. Brasser
Iceland	Collaboration, research stay	C. P. Conrad, J. Tonti-Filippini
India	Collaboration, fieldwork	J. Jodder, S. Werner, P. Gromov, L. H. Liow
Iran	Collaboration	A. van der Boon
Japan	Collaboration	J. Jodder
Nicaragua	Field work	M. Ciocco
Netherlands	Collaboration, research stay	A. van der Boon, C. P. Conrad, J. Tonti-Filippini
Portugal	Collaboration	C. Gaina
South Africa	Collaboration	J. Jodder, K. Herbst
South Korea	Collaboration, visiting student	C. P. Conrad
Sweden	Collaboration	C. P. Conrad, A. Minakov, J. Tonti-Filippini
Switzerland	Collaboration, visits, lab facilities	C. M. Marcilly, T. H. Torsvik, J. Jodder
UK	Collaboration, lab facilities	J. Jodder, A. van der Boon, K. Herbst, Y. Xue
USA	Visiting guests, collaboration	C. P. Conrad, A. Kiraly, Y. Wang, A. van der Boon, J. Jodder, E. Mamonova, J. Tonti-Filippini, V. Maupin, L. H. Liow, J. Luu

Conferences organized by PHAB

Date	Title and organizers (bold: organizers from PHAB)
22.5.25	Summer Symposium and Board Meeting (T.H. Torsvik, T. Sannesmoen)
3.3.25	Workshop on Complexity of Deep Polar Oceans (A. Minakov , A. Mazzini)
21- 23.6.25	SOUP workshop (J. Jodder)
3- 5.12.25	Celebration of new Centre Director (L. Gallo, P. Gromov, E. Mamonova, S. C. Werner, T. Sannesmoen)
29.9.25, 30.11- 14.12.25	SING DEEP, Singhbhum Deep drilling Project workshop (J. Jodder)



The aurora over Reykjavik, where PHAB scientist Clint Conrad did a research sabbatical at University of Iceland during the 2024-2025 academic year.

Photo: Clint Conrad in January 2025.

Workshops, lab work, research stay outside UiO		
25/06 - 28/06/25; 17/09- 15/10/25	Research stays, Centre for Astrophysics and Planetary Science, Canterbury	M. Ciocco
Sep 23- Nov 25	RCN Research stay, Australian National University	G. E. Shep- hard
7/09 - 10/09/25	Geomod workshop, Lisbon	J. Paul
Dec 23- Aug 25	Research stay (MSCA Fellow), University of Sydney	A. Lasabuda
22-26/9/25	Geobiodiversity Workshop, Nanjing Institute of Paleontology, China	Speaker: L. H. Liow
Aug 24- Aug 25	Research Sabbatical, University of Iceland	C. P. Conrad
18/08 - 05/09/2025	Summer school, Friedrich-Alexander University of Erlangen– Nuremberg	N. Obren
10/11- 15/11-25	Visit, Hjerkin (Norway)	N. Obren
24-27/2/25	Lab work, Utrecht University, Netherlands	J. Tonti- Filippini
30/11- 14/12/25	Research visit, IIT Bhubaneswar, India	J. Jodder



*Puffins near the Skálanes
Nature and Heritage Centre,
eastern Iceland, July 2025.*

Photo: J. Tonti-Filippini

Fieldwork in Europe		
6-20/7/25	Pilot study for paleobarometry - Arctic Research and Studies grant Sampling in eastern Iceland, Seydisfjörður	J. Tonti-Filippini
Fieldwork in Norway <i>*more participants</i>		
16-24/8/25	Paleomagnetism of Nyborg Formation, Varanger	M. Domeier, A. van der Boon, L. Gallo
24/3; 7/4-11/4/25	Paleomagnetism of the Ringerike sandstone, Ringerike *M. Domeier, Y. Xue, J. Tonti-Filippini	S. H. Ryen,*
8-9/5/25	Paleomagnetism of the Fen complex (EPIC project)	J. Tonti-Filippini
27/11-18/12-25	Marine research-scientific cruise, Dynamics of confined polar basins-DYPOLE NFR project and GoNorth national project	C. Gaina, A. Minakov
Fieldwork outside Europe		
01/02-10/02/25	Sampling, Young impact crater, Pantasma, Nicaragua	M. Ciocco
19/07-23/07-25	Post-conference field trip, Impact crater investigation introduction, Yarrabubba, Australia	M. Ciocco
30/11-14/12/25	SINGHBHUM Deep Early Earth Drilling Project, Odisha, India	J. Jodder

Paleomagnetic sampling above Seyðisfjörður, eastern Iceland, July 2025.

Photo: J. Tonti-Filippini.



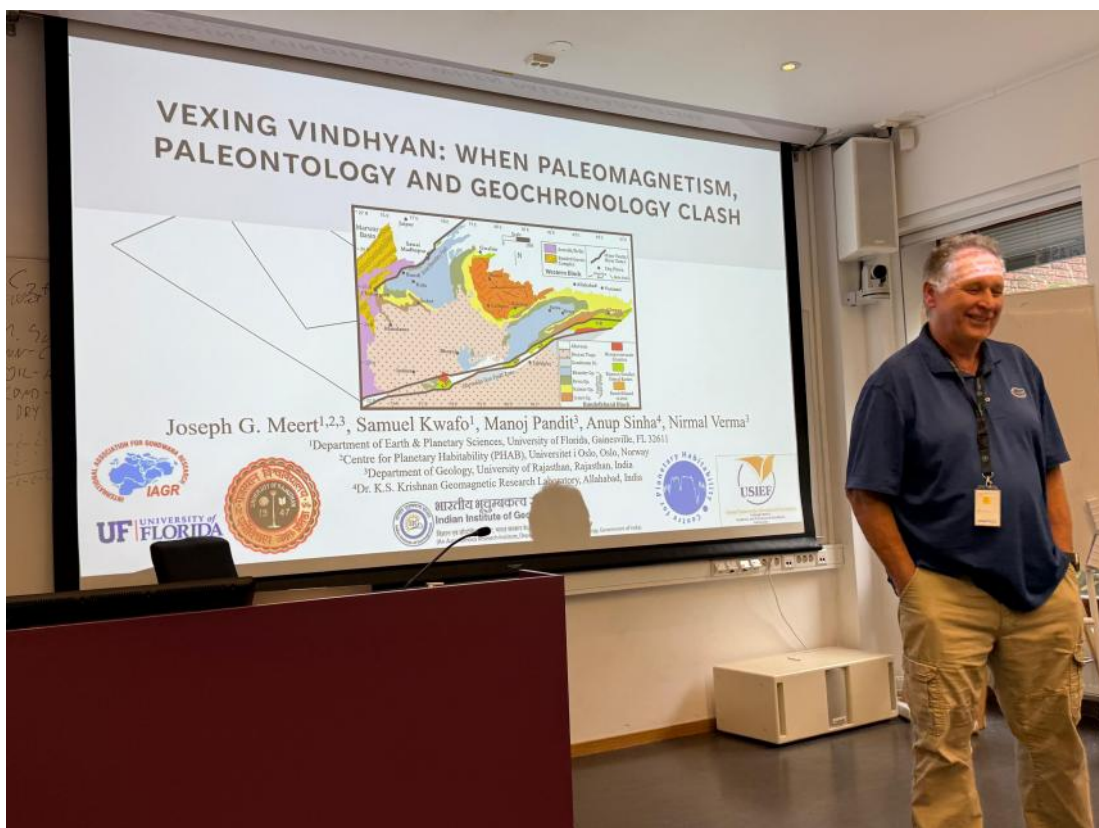
KEPLER Lecture Series

Through the Kepler Lecture Series, we at the Centre for Planetary Habitability (PHAB) invite internationally renowned scholars to the University of Oslo (UiO) to explore and discuss what makes a planet "habitable," here on Earth and elsewhere in the Universe. These seminars are open to everyone with an interest in Earth, the solar system and beyond.

The speakers present a 45-minute seminar that highlights their ideas and work in the sub-discipline of scholarship that addresses Habitability. They come from diverse disciplines, including astronomy, philosophy, planetary science, climate science, and more. Faculty and students affiliated to PHAB are encouraged to attend, the seminars are open to anyone in the community who has an interest.

The seminars are curated and hosted by the scientific team at the Centre for Planetary Habitability (PHAB) and some of the talks can be streamed on [YouTube](#).

1. Time capsules of early Earth environments , Jan. 30, 2025 by Desiree L. Roerdink, Associate Professor, Analytical Geochemistry, University of Bergen
2. Exploring the habitability of the Earth through the deep past, into the deep future, and assessing exo-Earths, Feb. 6, 2025 by Benjamin J. W. Mills, Professor of Earth System Evolution, School of Earth and Environment, University of Leeds, UK
3. Structure and evolution of the crust on Mars through impact craters. June 19, 2025 by Professor Katarina Miljkovic OAM, Curtin University, School of Earth and Planetary Sciences, Space Science and Technology Centre
4. Zircon record of early Archaean crust formation in Africa, Aug. 21, 2025 by Robert Bolhar, Professor, School of Geoscience, University of the Witwatersrand, Johannesburg, South Africa
5. Lava Worlds: From Early Earth to Exoplanets Sep. 11, 2025 by Eric Gaidos, Professor, Department of Earth Sciences, University of Hawaii at Manoa
6. Habitability Insights from Earth Analogue Environments: Explorations of the deep water and carbon cycle, Sep. 25, 2025 by Barbara Sherwood Lollar, Professor, Department of Earth Sciences, University of Toronto
7. Pre-Cenozoic cyclostratigraphy and paleoclimate response to astronomical forcing, Oct. 16, 2025, by David De Vleeschouwer, Professor, Institute of Geology and Paleontology, University of Münster
8. Vexing Vindhyan: When Paleomagnetism, Paleontology and Geochronology Clash, Oct. 23, 2025 by Joseph Meert, Professor, Department of Earth and Planetary Sciences, University of Florida, Gainesville, FL



Top: Desiree Roerdink and Carmen Gaina. Photo: Trine Sannesmoen.

Bottom: Joseph Meert. Photo: Jaganmoy Jodder.

PHAB Scientific Seminar Series

The Scientific Seminar Series is PHAB's weekly seminar series where PHAB-staff and guests present their research. The seminar series is organized by postdoc Justin Tonti-Filippini and researcher Vincent Kofman.

1. CLAIM (Confined Landform Analysis using Incidence Matrix) for Detecting and Analyzing Surface Anomalies: Theory and Applications, Jan. 10, 2025 by Sergei Medvedev, Medvedev Consulting; UiO; VBER.
2. Not-so-red dawn of red dwarf: Flare model to study exoplanet atmospheres, Jan. 17, 2025 by Elena Mamonova, PHAB, UiO.
3. On chemical bonds and chemical species in silicate magmas, Jan. 24, 2025 by Razvan Caracas, PHAB, UiO.
4. Investigating anomalous behaviour of Earth's magnetic field in the middle Paleozoic, Feb. 14, 2025 by Annique van der Boon, PHAB, UiO.
5. Chronological constraints on Solar System formation and evolution, with emphasis on the Earth-Moon system, Feb. 21, 2025 by Reidar G. Trønnes, PHAB, UiO.
6. Exploring the 100 million-year mystery: Further insights into Earth's magnetic field in the middle Palaeozoic, Feb. 28, 2025 by Sofie H. Ryen, PHAB, UiO.
7. Planets/Early Earth @ PHAB: A progress report, Mar. 7, 2025 by Carmen Gaina and Trond H. Torsvik, PHAB, UiO.
8. Confusing yet thriving: New thoughts around early habitability, Mar. 14, 2025 by Jaganmoy Jodder, PHAB, UiO.
9. An earth-scientist's view of human population dynamics, with application to the search for extraterrestrial intelligence (SETI), Mar. 21, 2025 by Stephen G. Warren, Department of Atmospheric & Climate Science, and Astrobiology Program, University of Washington, Seattle, USA.
10. ANIMA the journey: how we failed, reconsidered, and found new approaches to model anisotropic viscosity in geodynamics models, Mar. 28, 2025 by Ágnes Király, PHAB, UiO.
11. The Psyche Mission, Apr. 4, 2025 by Erik Asphaug, KEPLER visitor at PHAB, UiO.
12. Destruction of the North China Craton and its potential links with Cretaceous climate, Apr. 11, 2025 by Jyotirmoy Paul, PHAB, UiO.
13. Boreal lakes: analogous of the ancient ocean? Apr. 23, 2025 by Alexander Eiler, Professor, Center for Biogeochemistry in the Anthropocene
14. Uncovering the Cosmic Threat: Exploring the Space Weather Impact on (Exo)Planetary Habitability, Apr. 25, 2025 by Konstantin Herbst, PHAB, UiO.
15. Pantasma, Nicaragua, May 9, 2025 by Marine Ciocco, PHAB, UiO.
16. Mineral surfaces under confinement, May 15, 2025 by Joanna Dziadkowiec, NJORD, UiO, Recipient of the Else-Ragnhild Neumann Award 2024.
17. The Himalayas' Hidden Breath: Hot Springs and Degassed Deep CO₂, May 30, 2025 by Indra Sekhar Sen, Associate Professor, Indian Institute of Technology Kanpur.
18. The Ediacaran - unlocking the secrets behind early animal evolution, June 6, 2025 by Emily Mitchell, Assistant Professor, Department of Zoology Curator of Non-insect Inver-

tebrates, University Museum of Zoology, Cambridge Fellow and Director of Studies, Newnham College.

19. Relevance of paleomagnetic data in paleogeographic reconstructions: From Greater Iberia rotation and fragmentation to Calabria and Peloritan terranes drift, June 13, 2025 by Gaia Siravo, Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.
20. Energy for Life: From the Land of Fire and Ice to Europa, and Beyond, Sep. 19, 2025 by Eric Gaidos, Professor, Department of Earth Sciences, University of Hawaii at Manoa.
21. Water Worlds? Water Worlds! Oct. 3, 2025 by Li Zeng, guest at PHAB, UiO.
22. Special Seminar: Space Weather, Oct. 14, 2025, organized by PHAB and ITS, UiO.
23. Revealing the structure of Venus' interiors using planetary rumbles, Oct. 17, 2025 by Marouchka Froment, Postdoctoral Researcher, NORSAR, Kjeller, Norway.
24. The role of CO₂ and paleogeography on the global heat budget in deep time climate models, Nov. 21, 2025 by Eivind O. Straume, PHAB, UiO.
25. Modelling the Space Weather of Exoplanets, Nov. 28, 2025 by Dag Evensberget, PHAB, UiO.



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82. Yzer, M., **Brasser, R.**, & Kate, I. L. T. (2025). Forming Earth-like and low-mass rocky exoplanets through pebble and planetesimal accretion. *Astronomy & Astrophysics*. <https://doi.org/10.1051/0004-6361/202453258>
83. Zhang, C., Yang, J., Sun, T., Zhang, H., & **Brodholt, J. P.** (2025). Strong precursor softening in cubic CaSiO₃ perovskite. *Proceedings of the National Academy of Sciences*. <https://doi.org/10.1073/pnas.2410910122>
84. Zhang, Y., Lu, L., **Maupin, V.**, Qin, T., & Ding, Z. (2025). Mapping 3D Sedimentary Structures with Joint Inversion of H/V Spectral Ratios and Multimode Dispersion Curves Derived from Ambient Noise—Application to the Xiong'an New Area, China. *Bulletin of the Seismological Society of America*. <https://doi.org/10.1785/0120240174>

Outreach activities

1. GoNorth 2025 [Video]. <https://api.nva.unit.no/publication/019bdf6ec42d-c7513fdc-69ab-4ff6-82e4-38f324572e13>
2. Kofman interviewed by Elise Kjørstad, exoplanet K2-18b (Apr 2025): <https://www.forskning.no/planeter-romforskning/eksperter-er-skeptiske-til-mulige-tegn-pa-liv-i-rommet/2497937>
3. Kofman interviewed by Elise Kjørstad, exoplanet K2-18b follow-up (May 2025): <https://www.forskning.no/planeter-romforskning-universet/forskere-fant-ikke-igjen-stoff-som-kunne-tyde-pa-liv-i-rommet/2512455>
4. Kofman interviewed by Elina Melteig, planetary system L 98-59 (Sept 2025): <https://www.titan.uio.no/universet/2025/oppdaget-ny-planet-men-det-er-ingen-som-har-sett-d.html>
5. Kofman interviewed by Lasse Biørnstad, Enceladus (Okt): <https://www.forskning.no/romforskning-universet/det-mest-interessante-stedet-for-a-lete-etter-liv-i-det-ytre-solsystemet/2561831>
6. Kofman interviewed by Lasse Biørnstad, GSFC (Oct): <https://www.forskning.no/nasa-naturvitenskap-politikk/15000-nasa-ansatte-rammet-av-nedstengning-ekstremt-stressende-situasjon/2559627>
7. Krzesinska, A., Ciocco, M., & Bultel, B. (2025). En analog for Mars. Hvordan forstå minealogien på Mars fra Jorda. *Astronomi* 2, 37.
8. Krzesinska, A. (2025). Mars-meteoritter. Steinene som har påvirket 60 år med Mars-utforskning. *Astronomi* 2, 42.
9. Shephard, G. (2025). Eksklusive øydestinasjoner som du garantert aldri har sett før. <https://api.nva.unit.no/publication/0198cc5b6e52-f7d9b25d-fabc-4948-ab3d-8c29926b8230>
10. Tjoflot, G. K., & Conrad, C. P. (2025). New research explains rapid ground uplift in Southeast Greenland. <https://api.nva.unit.no/publication/0198cc5d471a-c69b7050-37b3-4ae5-befd-883abfd783e6>
11. Trønnes, R. G. (2025). Dannelsen av solsystemet, Jorda og Månen. *Astronomi* 3-2025, 30–37. www.nhm.uio.no/english/about/organization/research-collections/people/rtronnes/3/planet-solsystemet/astr25-ss.pdf
12. Trønnes, R. G. (2025). Rifting og vulkanisme på Island og pågående aktivitet på Reykjanes-halvøya. *Naturen* 4-2025, 193–205. Forsidebildet til 4-2025-utgaven er også fra denne artikkelen. <https://www.nhm.uio.no/english/about/organization/research-collections/people/rtronnes/3/jodas-indre/nat25-island.pdf>
13. Van der Boon, A. (March 2025) University of Oslo Open Day, Ting du kanskje ikke vet om Jordens magnetfelt - Hvordan og hvorfor studerer vi Jordens magnetfelt?
14. Van der Boon, A. (April 2025) Blindern VGS school visit to the Centre of Planetary Habitability, How and why do we study Earth's magnetic field? ...and is it important for planetary habitability?

15. Werner, S. (2025). Mars' historie. <https://api.nva.unit.no/publication/0198cc788256-2cdf100-6d3b-479e-b511-06fcc48a4c38>



Stephanie Werner on UiO Open Day 06.03.25. Photo: Trine Sannesmoen.



Trond Torsvik on «Faglig Pedagogisk dag» 30.10.25. Photo: Gunn Kristin Tjøflet.

Abstracts, talks, lectures, presentations, posters

1. Ciocco, M. (2025). Reconstruction de l'histoire des chondrites L : une nouvelle approche pluridisciplinaire (minéralogique, géochimique et dynamique) [Lecture].
2. Ciocco, M. , Krzesinska, A. , Werner, S. C. , Müller, A. , Veneranda, M. , Lopez-Reyes, G. (2025). Three Forks Depot Analogues in Mars Sample Return Analogue Sample Library—Representativity Assessement Via Raman and LIBS Spectroscopy. LPI Contributions 3088, 5190 [ConferenceLecture]. <https://ui.adsabs.harvard.edu/abs/2025LPICo3088.5190C/abstract>
3. Ciocco, M. , Krzesinska, A. , Werner, S. C. , Müller, A. B. , Julve-Gonzalez, S., Veneranda, M. , Lopez-Reyes, G., Thiessen, F., Sefton-Nash, E., Mikesell, T. D., Griffiths, L. (2025). Three Forks Depot Analogues in Mars Analogue Sample Library—Representativity Assessment via Raman and LIBS Spectroscopy. Copernicus Meetings, EPSC-DPS2025-1445 [ConferenceLecture]. <https://meetingorganizer.copernicus.org/EPSC-DPS2025/EPSC-DPS2025-1445.html>
4. Conrad, C. P. (2025). Impact of Rheology on Glacial Isostatic Adjustment (GIA) Processes in Greenland [Conference presentation]. <https://api.nva.unit.no/publication/0198cc84503e-929ab214-e299-4639-94b9-b2b1c37d6671>
5. Conrad, C.P. (2025). Rapid Ground Motion Driven by Deglaciation above the Iceland Plume Track, [ConferenceLecture]. NKG Working Group of Geodynamics and Earth Observation (WGGE0), Kartverket, Oslo.
6. Conrad, C. P. (2025). Patterns of uplift around Greenland's periphery during the Early Holocene [Conference presentation]. <https://api.nva.unit.no/publication/01993fec64a3-31846ad3-8769-493d-a270-4971b1e4ddc4>Bridges J.C., Debaille V., Harrington A.D., Herd C.D.K., Hutzler A., Krzesinska A.M., Liu Y., Maurel C., Wang K. Report of the Sample Receiving Project Measurement Definition Team: Igneous Samples Working Group. 10th International Conference on Mars (LPI Contribution 3007); 2024-07-07 - 2024-07-13.
7. Conrad, C. P. (2025). Seasons and Sea-Levels from a Year in Iceland [Lecture]. <https://api.nva.unit.no/publication/019b5df6ac51-9d6a5c63-6489-4dda-bfcc-cba50077a80c>
8. Conrad, C. P., & Ramirez, F. (2025). Sensitivity of dynamic topography and gravity anomalies to lateral variations in mantle viscosity [Conference presentation]. <https://api.nva.unit.no/publication/01993feeacc6-ad2315a7-ab47-419b-a0f1-6ebf8795a446>
9. Cornet, T., Ciocco, M. , Krzesinska, A. , Mikesell, T. D., Kydland-Lysdhal, A., Kminek, G., Sefton-Nash, E. (2025). Archiving sample science data in PDS4: Challenges and solutions. Copernicus Meetings, EPSC-DPS2025-1813. [ConferenceLecture]. <https://meetingorganizer.copernicus.org/EPSC-DPS2025/EPSC-DPS2025-1813.html>
10. Escartín, J., Sautter, B., Gaina, C., Petersen, S., Granot, R., & Pubelier, M. (2025). MAPRIDGES: Geometry of global mid-ocean ridge plate boundaries, and the role of transform faults and non-transform offsets [Poster presentation]. <https://doi.org/10.5194/egusphere-egu25-18143>
11. Herbst, K. (2026). Modeling the impact of stellar space weather on (exo)planetary habitability [Conference presentation]. <https://api.nva.unit.no/publication/019ba7b1549e-75e7cc3e-2199-4126-906a-42d5c5524eb9>
12. Herbst, K. (2026). Panel Discussion "Future of Solar and Stellar Multi-scale Activity" [Presentation]. <https://api.nva.unit.no/publication/019ba7c17d06-37fa250b-3c83-4721-9260-070810f94da2>
13. Herbst, K. (2026). Space weather impact on (exo)planetary habitability [Conference presentation]. <https://api.nva.unit.no/publication/019ba7baf526-da005c84-29ee-4c8b-85e0-356cf08aaf39>
14. Jakobsen, R., & Boon, A. V. D. (2025). A PALEOMAGNETIC STUDY OF THE DEVONIAN OLD RED SANDSTONE FROM WOODFJORDEN, SVALBARD [Conference abstract]. <https://doi.org/10.1130/abs/2025NE-407489>

15. Jakobsen, R., van der Boon, A., & Nagel-Myers, J. (2025). A paleomagnetic study of the Devonian Old Red Sandstone from Woodfjorden, Svalbard [Conference poster]. <https://doi.org/10.1130/abs/2025AM-9756>
16. Kiraly, A., Wang, Y., Conrad, C. P., Dannberg, J., Fraters, M., Gassmoeller, R., & Hansen, L. N. (2025). ANIMA the journey: how we model olivine CPO-related anisotropic viscosity [Poster presentation]. <https://api.nva.unit.no/publication/0198cc3d57d5-84a855b6-9d41-40af-b936-20ca428a58a9>
17. Kiss, D., Yarushina, V. M., & Minakov, A. (2025). Hydromechanical modelling of poro-(visco-)elasto-plastic deformation and fluid flow localization [Lecture]. <https://api.nva.unit.no/publication/0198cc833a52-b6217ae7-2b00-4feb-9081-3cd72b183126>
18. Kiss, D., Yarushina, V. M., & Minakov, A. (2025). Hydromechanical modelling of poro-(visco-)elasto-plastic deformation and fluid flow localization [Conference presentation]. <https://doi.org/10.5194/egusphere-egu25-18320>
19. Kofman, V., Turnbull, M., Lobo, A., Kopparapu, R., Fauchez, T., Villanueva, G., Wolf, E., Haqq-Misra, J., & Merrelli, A. (2025). European Planetary Science Conference [Conference presentation]. <https://doi.org/10.5194/epsc-dps2025-1316>
20. Kofman, V. (2025). Contributed talk at Habitable Worlds Observatory Workshop at the European Planetary Science Conference [Conference presentation].
21. Kofman, V. (2025). Contributed talk at workshop for terrestrial analogues for lunar and martian studies [Other presentation].
22. Kofman, V. (2025). Poster contribution at Buffet 5 meeting [Conference poster].
23. Lasabuda, A. (2025). Tectonic and climatic controls on the Cenozoic paleogeographical reconstructions and sedimentary source-to-sink in the Arctic [Lecture]. <https://api.nva.unit.no/publication/01991447bd56-4c5e7049-86e9-4fc0-aa86-e741ca809956>
24. Lasabuda, A., Salles, T., Zahirovic, S., Shephard, G., Faleide, J. I., & Muller, D. (2025). Sedimentary source-to-sink of the northern Barents Shelf and its implication for the opening of the Nansen Basin [Poster presentation]. <https://api.nva.unit.no/publication/019911720aa0-dae3c094-eed2-41d3-91af-f1f4fc0501a9>
25. Lundmark, A. M., Bakken, K. B., Anell, I., Augland, L. E., Conrad, C. P., Dunkel, K. G., Blanco, L. R., Lilleøren, K. S., Svensen, H. H., & Treichler, D. (2025). “Why don’t my students come to class?” [Conference presentation]. <https://api.nva.unit.no/publication/0198cc46b6a4-ff0d3599-eb21-4473-9563-02bb5ce388a4>
26. Lundmark, A. M., Bakken, K. B., Anell, I., Augland, L. E., Conrad, C. P., Dunkel, K. G., Blanco, L. R., Lilleøren, K. S., Svensen, H. H., & Treichler, D. (2025). “Why don’t my students come to class?” [Lecture]. <https://api.nva.unit.no/publication/0198cc4ad741-90d0c40b-1f92-45f4-a238-743a85d182fb>
27. Minakov, A., Neukirch, M., Smirnov, M., Varilsuha, D., & Senger, K. (2025). Electrical conductivity structure of Miocene-Quaternary volcanic province in NW Svalbard [Conference presentation]. <https://api.nva.unit.no/publication/0198cc64afd2-c4e3c068-fd86-46e4-b9ca-88962af80ef0>
28. Minakov, A., Bohaty, S., Childress, L., Johansen, I., Kihle, J., Mazzini, A., Nooraiepour, M., Polteau, S., Silkoset, P., Uenzelmann-Neben, G., Yarushina, V. M., & Scientists, I. E. 3. (2025). Natural vs. Drilling-Induced Zebra Textures: Carbonate Precipitation in Siltstone from IODP Hole U1581B, Transkei Basin [Conference presentation]. <https://api.nva.unit.no/publication/0198cc8513b3-037e146c-7d5a-44bd-8bd3-73418268bb19>
29. Minakov, A., Yarushina, V. M., Bohaty, S. M., Childress, L., Johansen, I., Kihle, J., Mazzini, A., Nooraiepour, M., Polteau, S., & Silkoset, P. (2025). Rapid Deformation-Induced Calcite Precipitation in Siltstone from IODP Hole U1581B, Transkei

- Basin [Poster presentation]. <https://api.nva.unit.no/publication/0198cc85a129-754dd05b-10c3-4e6e-9c67-50f1ca162f4a>
30. Mohn, C. E., & Trønnes, R. G. (2025). The bridgmanite to post-bridgmanite phase loops in the systems MgSiO₃-FeSiO₃, MgSiO₃-FeAlO₃ and MgSiO₃-Al₂O₃ [Conference abstract]. FORCE Third Winter Workshop, January 14–15, 2023, Program-Abstract, pages 3, 11. www.nhm.uio.no/english/about/organization/research-collections/people/rtronnes/4/other/force-3rd.pdf
 31. MSR Campaign Science Group (MCSG), Thorpe, M. T., Velbel, M. A., Hauber, E., Tait, K. T., Thiessen, F., Sefton-Nash, E., Ciocco, M., Krzesinska, A., Werner, S.C., Müller, A., Griffiths, L., Mikesell, T. D. (2025). THE MARS SAMPLE RETURN ANALOGUE SAMPLE LIBRARY. [ConferenceAbstract]. 56th Lunar and Planetary Science Conference
 32. Patton, H., Alexandropoulou, N., Lasabuda, A., Knies, J. M., Andreassen, K. M., Winsborrow, M., Laberg, J. S., & Hubbard, A. (2025). Quaternary landscape development of the Eurasian Arctic [Poster presentation]. <https://api.nva.unit.no/publication/0198cc678170-dac83261-f436-4f7f-8947-508bd6796b6a>
 33. Paul, J., & Conrad, C. P. (2025). Craton thickening controls the onset and frequency of kimberlite volcanism [Poster presentation]. <https://api.nva.unit.no/publication/01994006b4b5-231ed37e-5c0e-4dd4-856d-09333ba3ce00>
 34. Paul, J., & Conrad, C. P. (2025). Slow Thickening of Cratons Has Increased Kimberlite Frequency Over Time [Conference presentation]. <https://api.nva.unit.no/publication/0198cc5d4ab8-d4a157dd-bade-467d-b719-63ab3f9ee07f>
 35. Robert, B., Conrad, C. P., Steinberger, B., & Domeier, M. M. (2025). Linking plate tectonics and true polar wander over the last 250 Myrs [Conference presentation]. <https://api.nva.unit.no/publication/01993ff3ca15-0dbda4f6-dd87-4f18-bfdb-b7ee07702af7>
 36. Sartell, A. M. R., Beier, C. P., Senger, K., Shephard, G., Mosociova, T., Mäkinen, K., & Rodes, N. (2025). Geochemistry of the Wallenbergfjellet intrusions, a case study of the High Arctic Large Igneous Province on Svalbard [Conference presentation]. <https://api.nva.unit.no/publication/0198cc425564-f01d4c1f-4168-4689-955d-08e239f51f5b>
 37. Sartell, A. M. R., Söderlund, U., Beier, C., Senger, K., Shephard, G., Mosociova, T., Mäkinen, K., & Rodes, N. (2025). Geochemistry and Emplacement Geometries of the Wallenbergfjellet Intrusions, Svalbard: Insights into the High Arctic Large Igneous Province [Conference presentation]. <https://api.nva.unit.no/publication/0198cc831cc9-ac07c542-f4ef-4387-84e7-da36e48a078f>
 38. Senger, K., Ammerlaan, F., Betlem, P., Dumais, M., Eagles, G., Foster, W., Geissler, W. H., Grundvåg, S., Hodson, A., Horota, R. K., Hurum, J. H., Jones, M. T., Kierulf, H. P., Majka, J., Marsden, L. H., Michalski, K., Minakov, A., Ogata, K., Olaussen, S., Osmundsen, P. T., Planke, S., Ruppel, A., Sartell, A. M. R., Shephard, G., Śliwińska, K., Smeraglia, L., Smyrak-Sikora, A., Spiegel-Behnke, C., & Zuchuat, V. (2025). Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL) [Book chapter]. <https://doi.org/10.5281/zenodo.14425478>
 39. Shephard, G. (2025). Comparing and contrasting multiple phases of Arctic Ocean development; insights on tectonics and magmatism from recent numerical modelling approaches including the surface and mantle [Conference presentation]. <https://api.nva.unit.no/publication/0198cc5b6e71-5c640c4d-a3f1-45c3-a0ea-e365d6002816>
 40. Shephard, G. (2025). Over the rainbow: making better colour bar choices for your scientific figures [Lecture]. <https://api.nva.unit.no/publication/0198cc58e116-3eb3877c-9d8c-4c07-91e5-f5714b0e67bc>
 41. Thiessen, F., Thorpe, M. T., Sefton-Nash, E., Harrington, A. D., Ciocco, M., Krzesinska, A., Werner, S. C., Griffiths, L., Mikesell, T. D., Smith, A. L., Hays, L. E., Kminek, G. (2025). Mars Analogue Sample Library. [ConferenceLecture]. Copernicus Meetings,

EPSC-DPS2025-953. <https://meetingorganizer.copernicus.org/EPSC-DPS2025/EPSC-DPS2025-953.html>

42. Thieulot, C., Ortega-Gelabert, O., Root, B., & Conrad, C. P. (2025). Benchmarking dynamic topography across codes [Conference presentation]. <https://api.nva.unit.no/publication/01993ffa918c-05cf46e2-4ae3-4b1b-9364-58b41482185c>
43. Thorpe, M. T., Velbel, M. A., Hauber, E., Tait, K. T., Thiessen, F., Sefton-Nash, E., Ciocco, M., Krzesinska, A. M., Werner, S. C., Müller, A., Griffiths, L., & Mikesell, T. D. (2026). The Mars Sample Return Analogue Sample Library [Conference presentation]. <https://api.nva.unit.no/publication/019bae27a234-e9fc43df-d3bd-4a85-8c66-aa47500da36c>
44. Van der Boon, A. (2025). Anomalous geomagnetic fields in the geologic record [Invited seminar]. IGP invited seminar.
45. Wang, Y., Kiraly, A., Conrad, C. P., & Maupin, V. (2025). Subduction dynamics and mantle anisotropy: modeling and clustering of olivine textures [Poster presentation]. <https://api.nva.unit.no/publication/0198cc3d61db-7ee08ae8-2906-467d-b86f-0c76cfffdf01b>
46. Weerdesteijn, M. F. M., & Conrad, C. P. (2025). Rapid Earth uplift in Southeast Greenland driven by deglaciation above the weakened rocks of the Iceland Plume Track [Conference presentation]. <https://api.nva.unit.no/publication/01993fe7a89f-814fa20c-b94b-43e1-81ff-5a1e8b98ea57>

Project funding in 2025

UiO project #	Projects, project leader	Total funding in 2025**
104305101	332523 Centre for Planetary Habitability, Torsvik (2023-33)	14751
100521001	301096 Maples, Callegaro (2020-24)	692
106209101	356306 GOE-PHAB, Torsvik (2025-2030)	1271
100145101	314742 Anima, Kiraly. (2021-25)	1399
102880101	326238 Polaris, Shephard. (2021-25)	1580
102820101	325567 HIDDEN, Caracas. (2021-25)	3095
103080101	325984 DYPOLE, Gaina. (2021-25)	3796
103904101	334622 PANDA, van der Boon (2023-2026)	3126
104559101	101102324, Bravo, Lasabuda (MSCA 2023-2026)	722
105131101	101106469, Balcony, Paul (MSCA 2024-2026)	-
103888101	101043844, EPIC, Domeier (ERC 2022-2027)	5400
104418100	4D Dynamic Earth, Conrad (ESA 2023-2025)	117
104887101	MSR ASL (ESA 2024-2026)	1185
105688100	SER3NE (ESA 2025)	1791
105819101	BLIMP (RANNIS 2025-2026)	204
105785101	FUGLA (RANNIS 2025-2026)	103
UiO funding	Strategy grant (2023-33)	2000
UiO funding	UiO contribution (Egenandel)	8475

* in kkr

**actual transfer is listed on RCN and international projects, not the full amount allocated



Field photo from the SOUP workshop in Drøbak, June 2025. Photo: Jaganmoy Jodder.

Professors, Researchers and Adjunct Professors

Name	Title
Andersen, Torgeir B.	Professor emeritus
Brasser, Ramon	Associate Professor
Brodholt, John	Professor II
Caracas, Razvan	Researcher
Conrad, Clinton P.	Professor
Domeier, Mathew	Associate Professor
Faleide, Jan I.	Professor emeritus
Gaina, Carmen	Professor
Gallo, Leandro C.	Researcher
Herbst, Konstantin	Associate Professor
Heyn, Björn Holger	Researcher
Kiraly, Agnes	Researcher
Kofman, Vincent	Researcher
Krzesinska, Agata	Researcher
Liow, Lee Hsiang	Professor (NHM)
Luu, Jane	Professor II
Maupin, Valerie	Professor
Minakov, Alexander	Researcher
Mojzsis, Stephen J.	Professor II
Neumann, Else Ragnhild	Professor emerita
Ramirez, Florence Dela Cruz	Researcher
Reitan, Trond	Researcher
Schubert, Brian	Professor II
Schweitzer, Johannes	Associate Professor
Shephard, Grace	Researcher
Torsvik, Trond H.	Professor
Trønnes, Reidar	Professor emeritus
van der Boon, Annique	Researcher
Werner, Stephanie	Professor

PhD candidates

Name	Funding Source
Anzulović, Ana	CompSci (EU Horizon)
Gromov, Petr	UiO
Mamonova, Elena	UiO/RCN (PHAB)
Meza Cala, Juan Camilo	RCN (Dypole)
Obren, Nicole	UiO
Ryen, Sofie Hildegard	RCN (Panda)
Xue, Yi	ERC (EPIC)

**in red: finished in 25*

Postdoc fellowships

Name	Funding Source
Ciocco, Marine	ESA (MSR-ASL)
Davis, Anne Hope	RCN (Hidden)
Evensberget, Dag	UiO
Hatalova, Petra	UiO
Jodder, Jaganmoy	RCN (PHAB)
Lasabuda, Amando P. E.	MSCA (Bravo)
Marcilly, Chloé M.	RCN (UiO/PHAB)
Paul, Jyotirmoy	MSCA (Balcony)
Sanderson, Hannah	RCN (PHAB)
Shan, Yu Tong	UiO
Straume, Eivind	UiO
Tonti-Filippini, Justin	UiO

Technical-administrative staff

Name	Title
Mesli, Melanie	Senior Engineer
Sannesmoen, Trine	Senior Adviser
Silkoset, Petter	Senior Engineer

**in red: finished in 25*

Guest researchers at PHAB

Name	Title and period at PHAB
Asphaug, Erik	Professor, 1.5.24-30.4.25
Cooper, Rebecca Brown	Postdoc, 12.12.25-11.12.27
Gaidos, Eric	Professor, 1.9.25-24.9.25
Jacobsen, Renate	Bachelorstudent, 21.7.25-22.8.25
Lee, Youngjun	Stipendiat, 3.9.25-9.12.25
Luo, Fanglu	Stipendiat, 1.1.25-31.12.25
Meert, Joseph	Professor, 16.9.25-1.11.25
Thanapalasingam, Nidarsana	Masterstudent, 2.5.25-31.8.25
Xu, Wanlong	Postdoktor, 8.11.25-
Zeng, Li	Forsker, 28.6.25-31.12.25
Zhao, Yajie	Postdoktor, 1.4.25-31.12.25



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