UNIVERSITETET
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NJORD

Annual report 2023

Our mission is to
advance the understanding
of transformation processes
in Earth- and man-made
porous materials.
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About Njord

PREFACE

"In all things of nature there is something of the marvelous."

– Aristotle

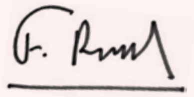
In 2023, research activities at the Njord Centre reached levels similar to those before the pandemic and developed in many directions, expanding the scientific interests of the group and the curiosity of researchers toward new topics. A strong activity of writing and obtaining successful research proposals is noticeable, with seven projects that started this year, including two highly competitive FriPro Researcher Projects and two Young Researcher Talent grants funded by the Research Council of Norway.

At the same time, many early career and experienced researchers received prestigious national and international awards (such as the UiO Education Award, Young Researcher Award from the Royal Norwegian Society of Science and Letters, leadership of a Young Centre for Advanced Study, and Fellow of the American Geophysical Union, to name a few examples). These various distinctions show that the Njord Centre is visible in the scientific community not only through individuals but also as a strong and creative academic environment.

This year, the group maintained high publication standards with more than 60 articles published in leading journals, including several in multidisciplinary journals that provide high visibility and showcase the capacity to perform research with broad impact. Three students successfully defended their PhDs, all demonstrating scientific independence and the ability to use the latest technologies in computer science. Notably, one thesis from the group will be used by the Faculty as a reference for its intelligent use of ChatGPT.

Finally, the board of the Centre and the Faculty of Mathematics and Natural Sciences have decided to extend the Njord Centre until 2027. This news is both exciting and carries a responsibility for us in the coming years to produce high-quality cross-disciplinary science and train early career researchers so they can secure competitive positions in various sectors of society, both in Norway and abroad.

Blesle, December 20th, 2023



François Renard
Director of the Njord Centre

Njord - Centre for Studies of the Physics of the Earth

The Njord Centre is a cross-disciplinary geoscience-physics research unit at the Faculty of Mathematics and Natural Sciences at the University of Oslo. The centre is shared equally between the departments of Geosciences and Physics. Our research focuses on the fundamental physics of geologically relevant processes, such as transport and reactions in porous media, fracturing, creep, and fragmentation, pattern formation in biological and geological systems, interface dynamics during geophysical flows, and coupled fluid-solid processes. We conduct research on systems that range in scales from atoms to continents, and apply methods where fieldwork, numerical modelling, experiments, and theory act together.

Our research is directly relevant to a wide range of applications, including the transport of water and pollutants in porous and fractured rocks, carbon sequestration and storage, glacier instabilities, earthquakes, volcanoes, landslides, and other geohazards, and the exploration of critical raw materials.

The prime products of the Njord Centre are high-quality fundamental research and education. We also focus on outreach and innovation through collaborations with media, renowned artists, and industry partners.

Who are we?

The Njord Centre was officially established on January 1st, 2018 and is led by director François Renard. It comprises around 60 members and includes researchers from the first generation Norwegian Centre of Excellence PGP (Physics of Geological Processes, 2003-2013), the Oslo node of the fourth generation Centre of Excellence PoreLab (Porous Media Laboratory, 2017-2027), and the Centre of Excellence in Education CCSE (Centre for Computing in Science Education, 2016-2026).

After a first period of five years (2018-2022), the Faculty of Natural Sciences and Mathematics has extended the centre for another period of five years (2023-2027).

In 2023 the Njord Centre continues to work along the areas defined in the research strategy for the period 2023-2027. The three research directions are: 1) Fluid flows in complex media, 2) Fracture, friction and creep, 3) Couplings at the nanoscale.

By merging geology and physics activities into the Njord Centre, we gain a considerable potential for increased synergies between the departments of Physics and Geosciences at the University of Oslo. We are also involved in the sustainability goals strategy implemented by the Faculty of Mathematics and Natural Sciences. Our cross-disciplinary research allows us to make progress in answering scientific questions that individuals could not solve alone, as demonstrated by our findings in this report.

We aim to:

- Develop a world leading cross-disciplinary research centre in physical sciences at the University of Oslo with a focus on a fundamental understanding of the dynamics of fluid-solid natural systems.
- Build the next generation of computational competences and experimental laboratory facilities for the study of transformation processes in fluid-rock and fluid-porous media systems in four dimensions from molecular to field scales.
- Provide a unique basis for making predictions relevant for carbon dioxide sequestration, exploitation of natural resources, transport of contaminants in the subsurface, and geohazards (e.g., earthquakes, volcanoes, glacier instabilities, landslides), and for innovations in science-art interactions.
- Generate an outstanding environment for research-based education at the Master, PhD and post-doctoral levels.
- Make the complex Earth dynamics visible in the public sphere.

Our research strategy is to:

- Create an interactive co-localized organization of geoscientists and physicists conducting field work, theory, numerical modelling and experiments in concert.
- Be an active, and often leading partner in international projects and collaborations.
- Participate in international projects (International Oceanic and Continental Drilling projects, Excite network) and be a user of large-scale national and international facilities where Norway is a partner (European Synchrotron Radiation Facility, European Spallation Source, Paul Scherrer Institute, Goldschmidt laboratory).

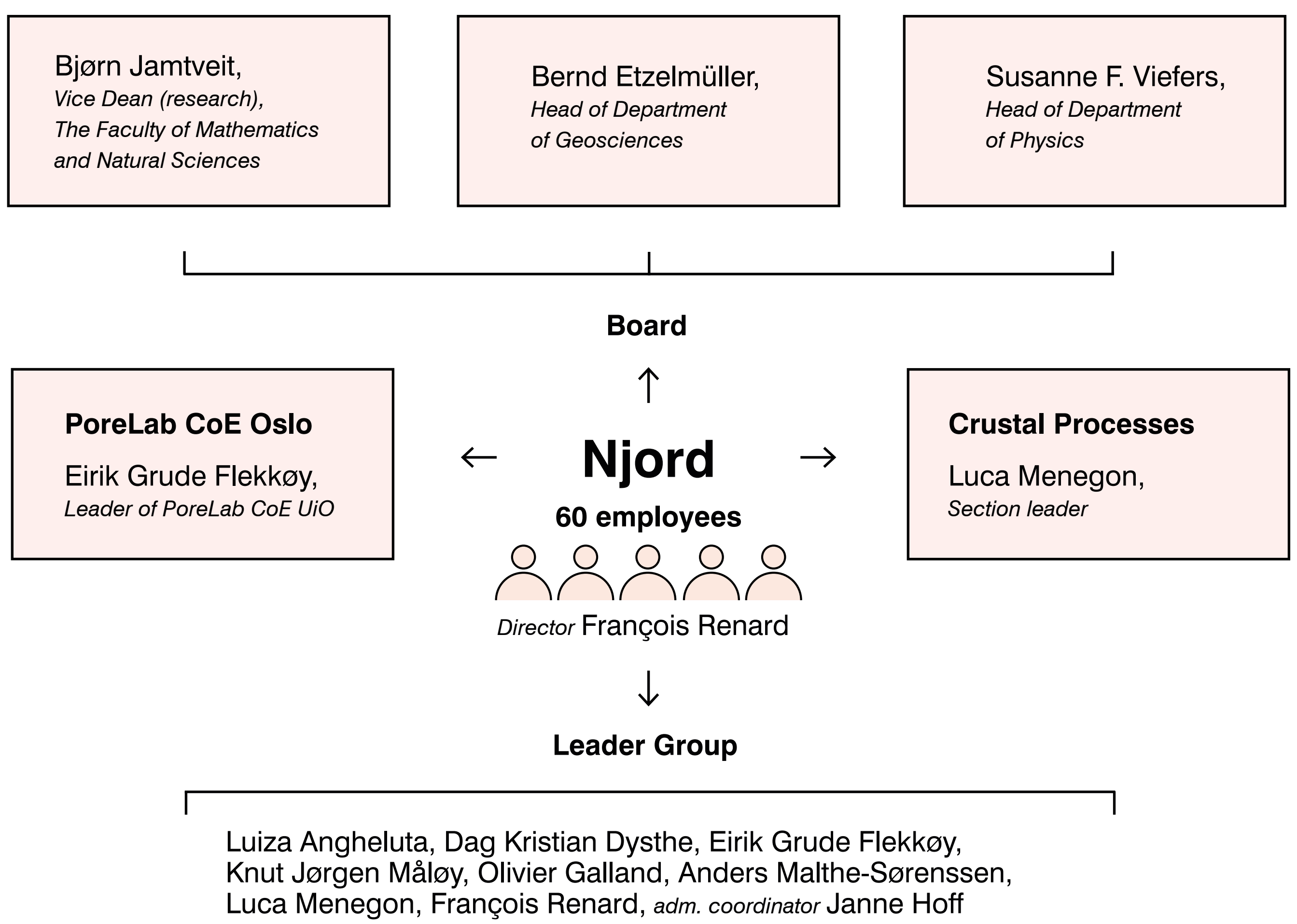
Our research is led by our research-based training activities where we value the approach 'learning by doing'. This gives our students and researchers the ability to become creative, curious, and capable geoscientists and physicists who can contribute to the scientific community and the society in general.

Organization

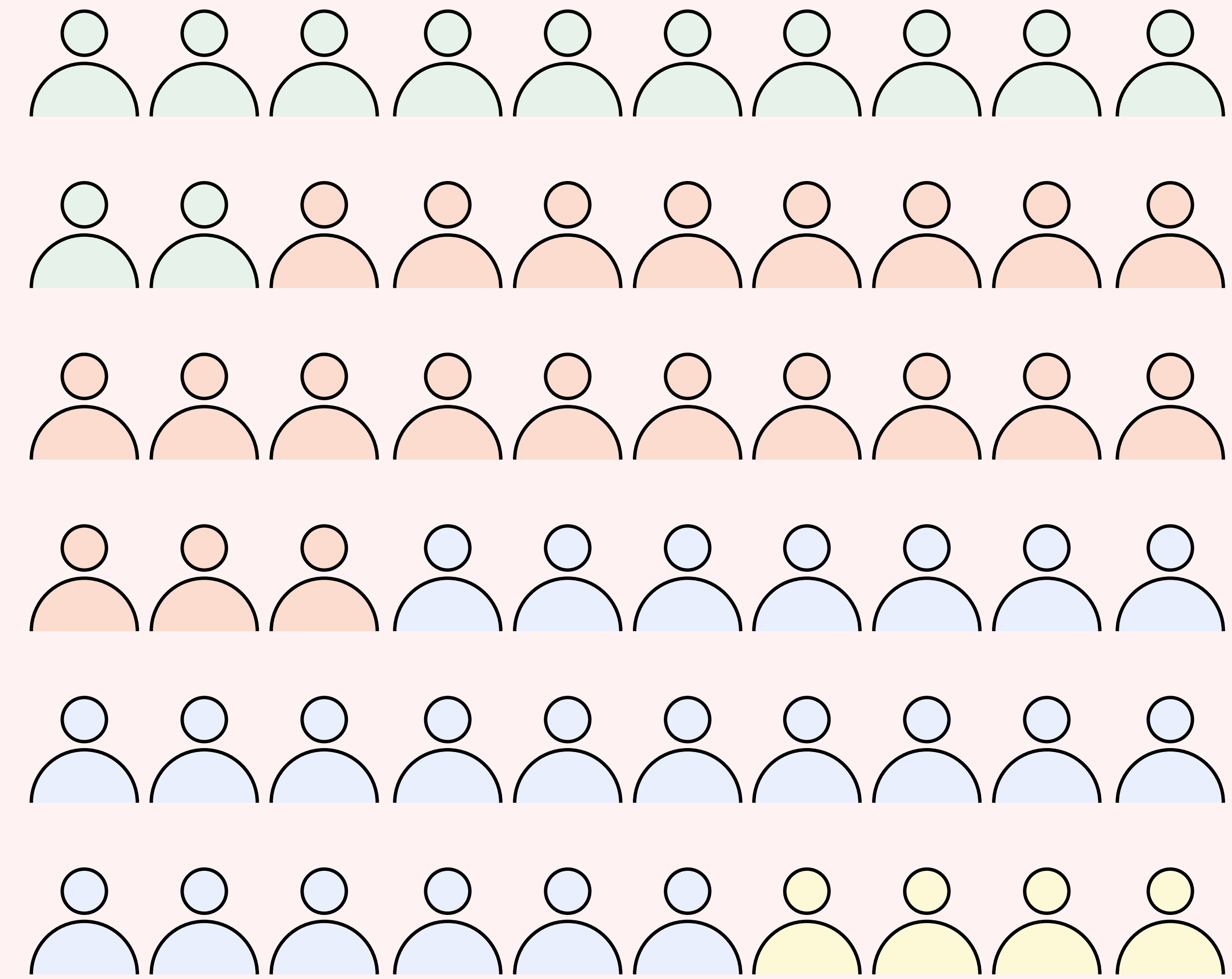
Njord is a cross-disciplinary center at the Faculty of Mathematics and Natural Sciences at the University of Oslo (UiO). We consider ourselves as one of the main UiO cross-disciplinary 'drivers' for the future development of Physical Sciences in general, and Earth-related research in particular at UiO.

In the first years of the center (2018-2020), Njord was directed by Professor Bjørn Jamtveit. Since January 1st, 2021, Professor François Renard has been director of Njord. The director is assisted by the administrative coordinator, Janne Hoff, who is responsible for project management, administration, and financial delivery. The director reports to the board. The Njord leader group includes the eight permanent professors. In total, Njord comprises about 60 members, 30% of which are women. Members are employed by the Department of Physics, the Department of Geosciences and directly by the Njord Centre.

Our staff is diverse when it comes to scientific background and nationality, and we focus on collaboration and having positive group dynamics. Njord emphasizes inclusivity and an open work environment in its pursuit of advancing Physical Sciences and Earth-related research.



Staff

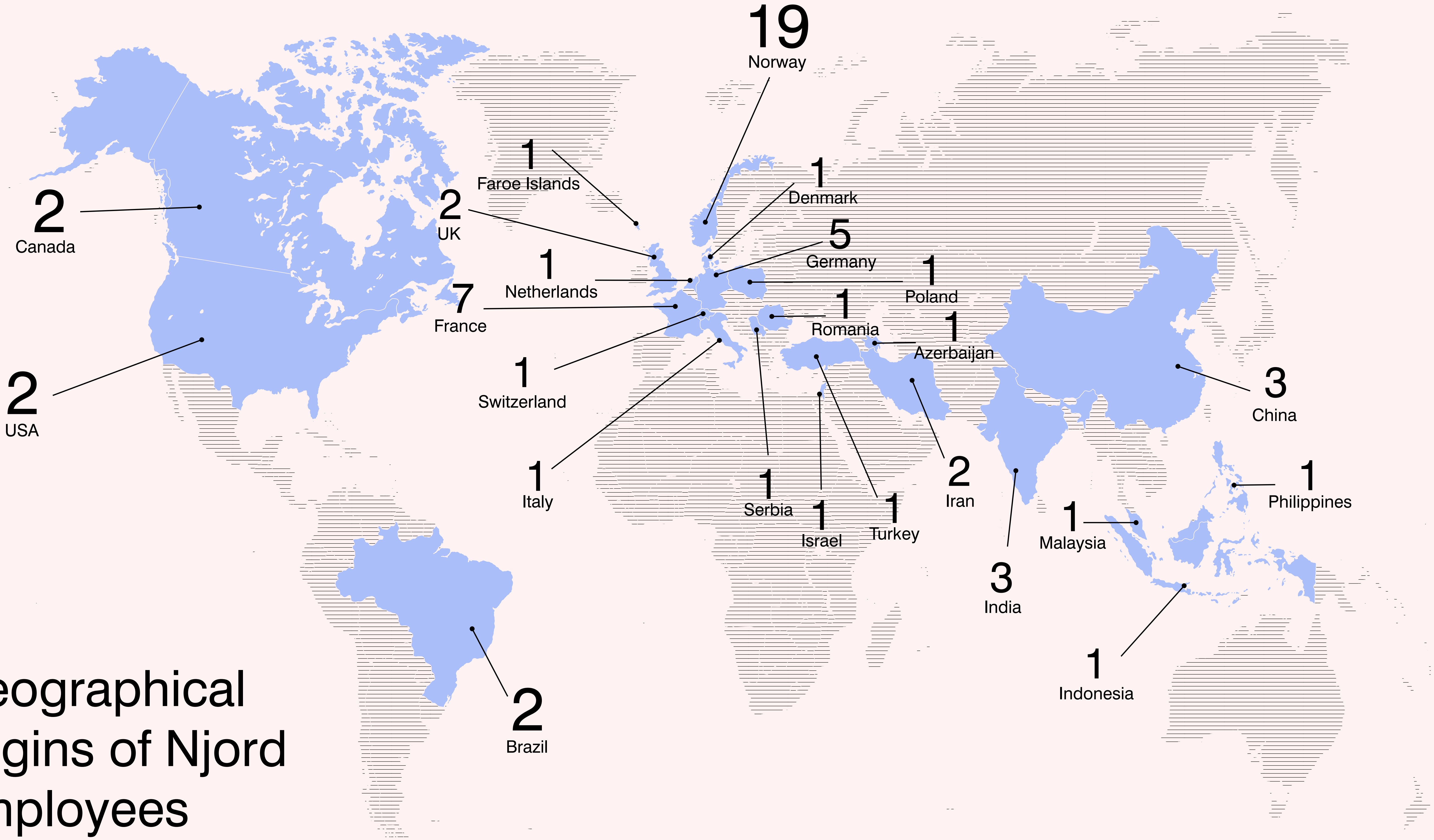


20% Professors and senior researchers (incl. prof 2)

6% Technical and administrative staff

38% Postdoc and researchers

36% PhD students



Geographical origins of Njord employees

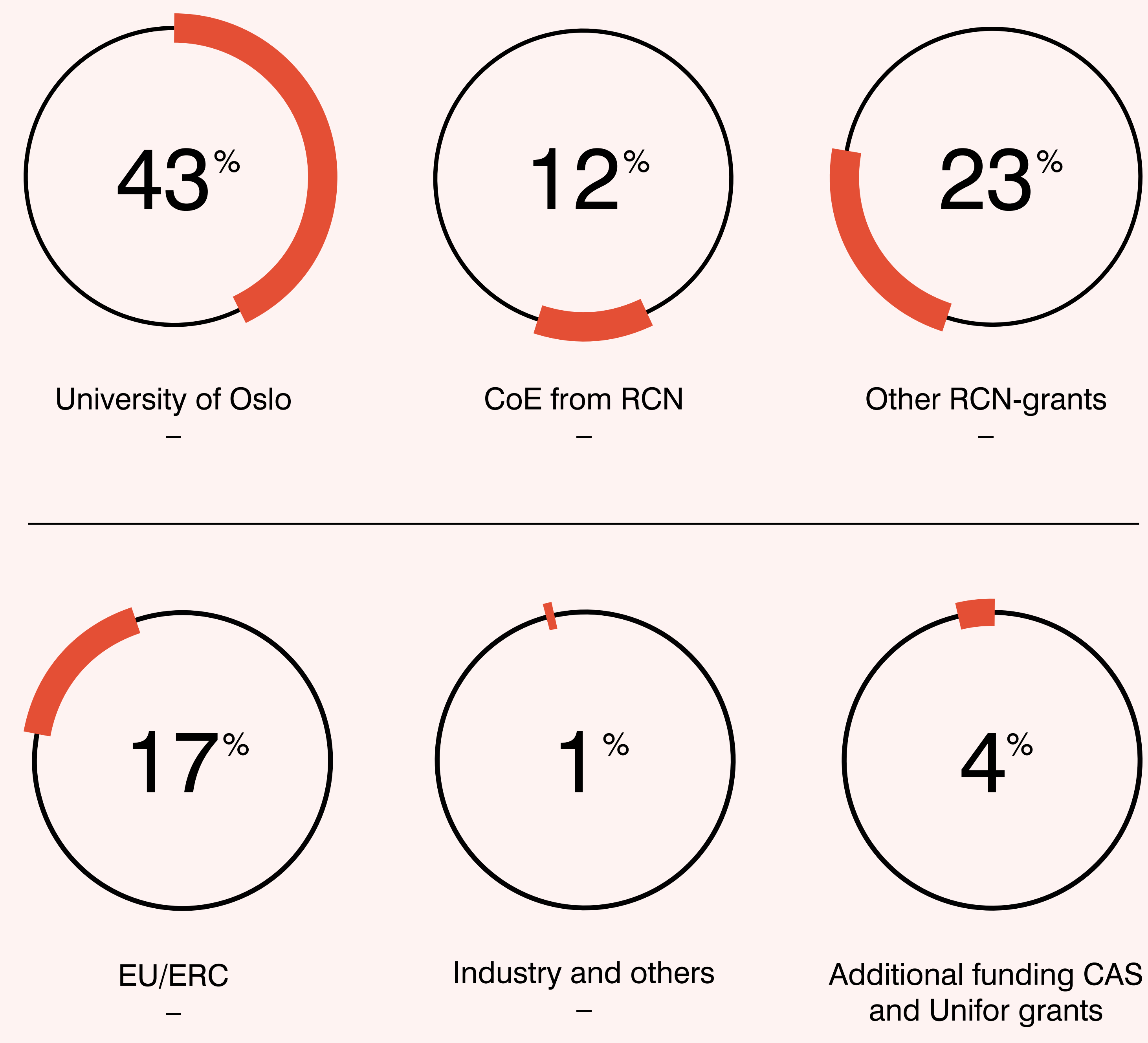
Finances and funding

The Njord Centre is funded by overheads from externally funded projects, the Department of Physics and the Department of Geosciences at the University of Oslo.

The staff at Njord is employed by either one of the departments or by projects at Njord. In the period 2018-2020, the center received contributions from both departments to cover running costs. The ambition has been that the contributions from the Research Council of Norway, the European Research Council and other sources will replace funding from the departments to cover running costs. In 2020 the center had secured enough funding for the running costs, and has since been self-sufficient. Overheads from projects at Njord are split between the center and the departments.

50 MNOK *funding in 2023*

Distribution of funding



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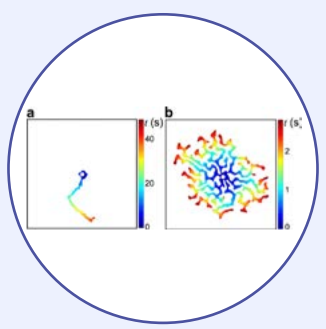
Activities at Njord

Highlights of 2023

January

The Department of Geosciences establishes the new section "Crustal Processes" that involves Njord employees.

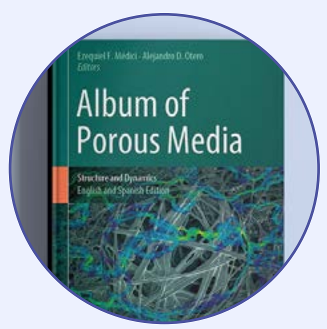


February

Zhang, Dawang; Campbell, James; Eriksen, Jon Alm; **Flekkøy, Eirik Grude; Måløy, Knut Jørgen** & MacMinn, Christopher W. (2023). "*Frictional fluid instabilities shaped by viscous forces.*" Nature Communications. 14, 3044.

March

PoreLab and Njord researchers organize an international conference in Brazil on Flow in Porous Media (INTPART project COLOSSAL).



April

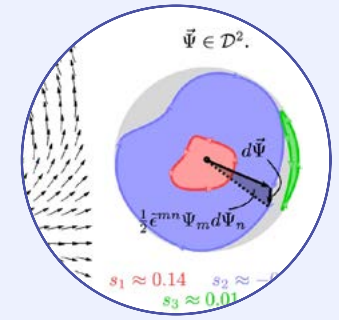
Release of the Album of Porous Media, the first book dedicated to compiling state-of-the-art visualization in porous materials with many contributors affiliated to Njord and Porelab.

May

Njord professor Dag Kristian Dysthe receives the UiO 2023 Education award.

June

Njord researchers organize the EarthFlows Meeting with more than 70 international participants.



July

Skogvoll, V., Rønning, J., Salvalaglio, M. **Angheluta, L.** (2023). "*A unified field theory of topological defects and non-linear local excitations.*" npj Comput Mater 9, 122.

August

McBeck, Jess, Benoît Cordonnier, Michele Cooke, Laura Fattaruso, and **François Renard**. (2023). *"Deformation Evolves from Shear to Extensile in Rocks Due to Energy Optimization."* Communications Earth & Environment 4, 352.

September

Gaute Linga and collaborators win a prestigious Young Centre for Advanced Study (CAS) grant awarded by the Young Academy of Norway, the Norwegian Academy of Science and Letters, and CAS.

October

Joanna Dziadkowiec and Fabian Barras win highly competitive Young Researcher Talent grants from The Research Council of Norway.

November

The board of Njord and the MN faculty extend the Njord Centre until 2027.

December

Gaute Linga and Jessica McBeck, two early career researchers trained at Njord, obtain professorship positions at NTNU Trondheim.

Interview

"I deeply admire their curiosity, passion, and patience in the pursuit of learning and research. These qualities continually motivate me to evolve as a dedicated learner every day." —— Erina Prastyani

Name:
Erina Prastyani

Current position:
Doctoral Research fellow

Been at UiO Since:
September 2022

What has led you to the kind of research you do now at Njord?

My research interest has evolved gradually over time. Initally, during my undergraduate studies, I delved into exploration geophysics, conducting an electromagnetic survey in a geothermal prospect area in Indonesia. At the time when I was finishing my master's degree, where I got interested in rock physics, Njord provided an exciting PhD position with research focus on 4D X-ray tomography imaging experiments on rocks. Despite having no prior experience with X-ray tomography, my curiosity and eagerness to learn about rock physics drove me to apply for the position. Gratefully, I was offered the opportunity to develop my research skills at Njord, where I am currently engaged in advancing our understanding of rock physics through innovative imaging experiments.

What are your current research projects?

I'm currently engaged in projects involving 4D X-ray tomography imaging, coupled with a triaxial rock deformation apparatus. This work takes me to the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, where I conduct experiments at least twice a year on two rocks: Westerly granite and Carrara marble. This study might give valuable insights into earthquake rupture mechanisms in crustal rocks.

Is there any particular research, publication or scientist that has inspired you, in your research?

I don't have a specific scientist whose work has inspired me; rather, it's the scientific community that has been my source of inspiration. Throughout my academic journey, I've had the privilege of meeting numerous scientists, each leaving a lasting impact on my quest for knowledge in higher education. I deeply admire their curiosity, passion, and patience in the pursuit of learning and research. These qualities continually motivate me to evolve as a dedicated learner every day.

How do your current projects tie in with Njord's diverse family?

At Njord, there aren't many individuals currently engaged in rock studies utilizing triaxial deformation apparatus and X-ray tomography imaging. This presents a valuable opportunity for me to introduce my research to the diverse Njord family, sparking research discussions and seeking their perspectives on my rock image data. For instance, I could collaborate with those at Njord specializing in geology to help interpret my result within a geological context.

Where do we usually find you?

You can usually find me in my office on the fourth floor, Room 427, in the Physics building. However, I also spend time working in the computer room next to my office, where I analyze my image data.

What do you think/hope your research can do beyond academia?

I believe that my research extends beyond academic contributions, holding promise for practical applications, particularly in the domain of geothermal exploration. For example, when drilling into a brittle reservoir sandstone, where rocks fracture easily, the process can enhance rock permeability and economic potential. However, it may also result in induced seismicity during drilling. On the other hand, drilling into a ductile reservoir sandstone, where rocks flow, generates fewer seismic events, but the compaction process can lead to reduced permeability, subsequently impacting reservoir productivity. Therefore, understanding the brittle to ductile transition in rocks is crucial to determine the optimal drilling depth for maximizing reservoir productivity.

What does it mean to you to be a part of a cross-disciplinary research environment like Njord?

It means a lot to me! It provides a unique opportunity to engage in discussions about science from diverse backgrounds and collaborate with fellow researchers. Additionally, it allows me to gain insights into various working cultures and communication styles, which I believe are invaluable experiences that are hard to come by elsewhere.

Interview

"As a biophysicist, I am a minority within Njord. It is the minorities that diversify the population. In spite of the differences in our field of research, we share a lot of similarities. For instance, the motion of cells in a packed monolayer seems to be similar to the motion of tectonic plates."

—— Harish Pruthviraj Jain

Name:
Harish Pruthviraj Jain

Current position:
Doctoral Research fellow

Been at UiO Since:
October 2021

What has led you to the kind of research you do now at Njord?

I hold a Bachelor's degree in Mechanical Engineering, during which I engaged in numerous experiments within a workshop setting. In my leisure time, I found myself drawn to watching a variety of lectures from universities around the globe, accessible via YouTube and other platforms. Although I regarded biology as boring during my childhood, these lectures changed my perception. During my Master's program, I enrolled in multiple courses that delved into computational biology. This academic pursuit eventually led to my role as a student research assistant, collaborating with various scientists. I explored an array of modeling tools, from cellular automata to phase-field models, in an effort to study cellular behavior. My work during this time established a solid foundation for my subsequent research at the Njord Centre.

What are your current research projects?

A cellular monolayer, where cells are tightly arranged in a two-dimensional layer, displays various flow modes. Cells can become jammed, causing the tissue to behave akin to a solid foam; however, at other times, they actively migrate to facilitate critical processes such as wound healing, bodily development, and cancer metastasis. In such scenarios, the cells seem to exhibit fluid-like motion. Currently, I am producing high-resolution simulations of monolayers to investigate different regimes of tissue flow.

Is there any particular research, publication or scientist that has inspired you, in your research?

Over time, my admiration has deepened for individuals who leave an imprint on the world not only through their scientific insights but also through their societal impact. I admire Alexander von Humboldt as he allowed his mind to be curious about everything around himself, and did not hesitate from romanticizing what he observed. I am a big fan of David Attenborough, and his documentaries played a key role in igniting my interest in biology. I am inspired by Aaron Swartz and Alexandra Elbakyan for their contributions to making science more accessible to people. I am very grateful for all the people who teach online for free through their contributions in forms of videos and blog posts. I am also immensely thankful to the community of open source contributors, whose efforts make software freely accessible to everyone.

How do your current projects tie in with Njord's diverse family?

As a biophysicist, I am a minority within Njord. It is the minorities that diversify the population. In spite of the differences in our field of research, we share a lot of similarities. For instance, the motion of cells in a packed monolayer seems to be similar to the motion of tectonic plates. Cells are also being studied as an active foam material. The material and flow properties of the cells are hotly debated, and seeking inspiration from other fields is more essential than ever. I think the more deeply we look into a problem, the artificial compartmentalization of science seems to disappear. Apart from the scientific benefit of this diversity, it is just fun to learn things that you don't know.

Where do we usually find you?

Most of the time you can find me in my office V305. When I am not at work you can find me doing yoga, attending concerts and quiz nights, reading, cooking, and watching movies.

What do you think/hope your research can do beyond academia?

I aspire for my research to be appreciated as a form of amateur art. Much like the Mandelbrot set, whose mathematical intricacies may not be fully understood by those outside the academic sphere, yet its mesmerizing beauty captivates the minds of many.

Interview

"Most of the people who have inspired me in my research are the people I work with every day. You get to see how much effort people put into their work. I also get very inspired by other female scientists who are really good at what they do."

—— Marija Plahter Rosenqvist

Name:
Marija Plahter Rosenqvist

Current position:
Doctoral Research fellow

Been at UiO Since:
August 2015

What has led you to the kind of research you do now at Njord?

The summer before I started my master's degree, in 2019 I worked as an intern at the company Volcanic Basin Energy Research (VBER). I asked the CEO, Sverre Planke, if they had any master's projects that I could take on. He sent me to Bjørn Jamtveit who was director of Njord at that point. Bjørn pitched a master's thesis working on CO_2 storage in basalts and together with Sverre we formed a project. Luckily, I was able to continue with this kind of research during my PhD.

What are your current research projects?

To understand if we can store CO_2 in basalts on a large scale, we need to better understand reactive fluid flow through the rocks. Therefore, I study how the pore network in basalt looks from the macro scale (cm-scale) to the micro-scale (down to a nm-scale). Basalt, CO_2 and water can react, and we can start precipitating carbonates, thereby trapping the CO_2 in a solid form. To understand this process, I also study how carbonates have precipitated naturally in basalt from offshore Norway.

Is there any particular research, publication or scientist that has inspired you, in your research?

Most of the people who have inspired me in my research are the people I work with every day. You get to see how much effort people put into their work. I also get very inspired by other female scientists who are really good at what they do. I am very happy to have Kristina Dunkel as my co-supervisor and Marthe Guren and Rakul Maria Johannsen as my co-workers on the CO2Basalt project. They inspire me to keep working and investigating.

How do your current projects tie in with Njord's diverse family?

My work is about understanding reactive fluid flow in porous media, a research field in which the Njord group is specialized. CO_2 storage in basalt is a research field where we need to apply geology, physics, and chemistry to understand the processes involved. The research project fits perfectly into what we do at a cross-disciplinary research centre.

Where do we usually find you?

I am a bit all over the place. Sometimes in the field, sometimes in the lab or a classroom and a lot of times in the office, sitting at my desk behind the plant and drinking tea.

What do you think/hope your research can do beyond academia?

I hope my research can bring us one step closer to achieving large-scale storage of CO_2 in mafic and ultramafic rocks. But hopefully, it can also be used for other things. A lot of countries have large groundwater reservoirs in basalts or other volcanic extrusive rocks. Perhaps my research in addition can be used to understand water flow, transport of pollutants, and geochemistry in basalt reservoirs a little bit better.

What does it mean to you to be a part of a cross-disciplinary research environment like Njord?

Working in a cross-disciplinary research group like Njord means having an exciting work environment, learning more about topics I did not think I would learn about (like the physics of food) but also sometimes realizing how truly little you know and how much there is to know.

Interview

"The range of topics people study at Njord make it impossible for any one of us to be on top of everything, and this leads to a lot of curiosity-driven and open-ended discussions, which I really like. This also helps us to have conversations that go beyond work. Njord is a perfect place to share ideas and have open scientific discussions." —— Kevin Pierce

Name:
Kevin Pierce

Current position:
Postdoctoral Researcher

Been at UiO Since:
October 2022

What has led you to the kind of research you do now at Njord?

At Njord I study the mixing of chemicals into water as it flows through rocks and soils. This topic sits somewhere between physics and geoscience. As a kid I spent most of my free time playing in the forest and river right by my house. Every few years I'd see big floods or landslides happen nearby, which was interesting and sparked my interest in geoscience. As I got older, I came to appreciate math and physics. So it was natural to combine these interests into what I'm doing now.

What are your current research projects?

My research involves both laboratory experiments and modeling of mixing in porous media flows. Mixing controls chemical reaction rates and the movements of contaminants and nutrients in soils, so it has a lot of applications in energy and environmental engineering. I also study multiphase flow in porous media and the transport of sediment in rivers. Because these types of environmental flows are often well-described as random phenomena, I am also involved in more fundamental studies of stochastic transport models.

Is there any particular research, publication or scientist that has inspired you, in your research?

Everyone knows Albert Einstein, the most famous of scientists, but Albert's son Hans was also a great scientist, who unfortunately remains relatively unknown. Hans built his career on the application of physics ideas to geoscience problems. Although the wider research community initially rejected his approach, today an entire research area has developed around it. To me, Hans is inspirational because he did interdisciplinary research early on and allowed his descriptions to include an element of randomness.

How do your current projects tie in with Njord's diverse family?

Njord is petrology, rock mechanics, glaciology, magma dynamics, porous media flow, biophysics, and more. People do field observations, lab experiments, numerical simulations, and analytical modeling. I feel lucky that my training is part geoscience and part physics, so I can at least get by talking to everyone. Njord has made it easy to get involved in a lot of different projects, from my own fluids/rocks problems to a few of the biophysical topics.

Where do we usually find you?

During working hours, I alternate between the lab and the office. My office is also too close to the coffee machine, so I'm there a lot. Outside of work I'm seasonal. Oslo is great for gravel biking, so I'm often doing that in the evenings of the warmer seasons. I'm also honestly fixing the bike as much as I'm riding it. In winter, I like having gatherings around Oslo with friends, and lately I've been experimenting with skiing. Finally I'm dabbling in beer brewing thanks to an equipment donation from Njord's own brewmaster John Aiken. Stay tuned on that.

What do you think/hope your research can do beyond academia?

Upscaling is maybe the most important problem in Earth science. Many of us study the tiny parts of much larger phenomena, like mixing at the pore scale or the fracture of tiny rock cores. Meanwhile, applications mostly require understanding at much larger scales. It's my goal to eventually make some progress on incorporating the small scale understanding I'm building now into prediction tools that can be used in applications.

What does it mean to you to be a part of a cross-disciplinary research environment like Njord?

The range of topics people study at Njord make it impossible for any one of us to be on top of everything, and this leads to a lot of curiosity-driven and open-ended discussions, which I really like. This also helps us to have conversations that go beyond work. Njord is a perfect place to share ideas and have open scientific discussions.

Do you have anything you would like to add?

This year has been great, in part because of the nice conferences and gatherings organized by Njord. Many thanks to Janne, Francois, Hugo, Franzi, Vidar, Nigar, and everyone else who worked on organization this year.

Education

Our approach to education is research-based and ‘learning by doing’. The educational activities by Njord staff include teaching, supervising, and contributing to teaching activities at the Department of Physics, the Department of Geosciences and in international schools. Njord’s staff members participate in education at all levels at their respective departments.

Laboratory work is an important part of our research-based teaching and is a substantial component of the activities in the master level courses

GEO4131 (Geomechanics),
GEO4190 (Hydrogeology),
GEO4151 (Earthquake and Volcanic Processes),
GEO4810 (Deformation Processes and Microstructures), and
FYS4420 (Experimental Techniques in Porous and Complex Systems),

as well as master-thesis project work.

We are working in close collaboration with the Centre of Excellence: Centre for Computation in Science Education, led by Njord’s Anders Malthe-Sørenssen.

In 2023, Njord staff have been responsible for or contributed to the following courses at the Department of Physics:

FYS MEK1110

Mechanics
This course gives a thorough introduction to Newtonian mechanics and special relativity and serves as the basis for further studies in physics and related sciences.

FYS1120

Electromagnetism
The course describes basic electrical and magnetic phenomena, as well as laws for electrical circuits, both at direct current and alternating current.

FYS2160

Thermodynamics and Statistical Physics
The course introduces the students to statistical mechanics and thermodynamics. Statistical mechanics is the microscopic foundation of thermodynamics.

FYS3140

Mathematical Methods in Physics
This course covers several important mathematical methods often used in physics such as basic complex analysis, differential equations, Fourier series and transforms, tensor calculus, variational calculus, orthogonal functions, and Laplace transformations.

FYS3150/FYS4150

Computational Physics
This course introduces numerical methods for solving problems in physics and chemistry, i.e. methods for solving ordinary and partial differential equations, matrix operations and eigenvalue problems, numerical integration, Monte Carlo methods, and modelling.

FYS4420/FYS9420

Experimental Techniques in Porous and Complex Systems
The course contains four projects that give students an introduction to important experimental techniques in the field of condensed matter physics. The course is adapted to the CoE PoreLab with a special focus on porous media physics.

FYS4460

Disordered Systems and Percolation
This course consists of four projects with several aims: to gain experience developing various codes relevant for problems in Statistical Physics, to develop an intuition for some of the main concepts in Statistical Physics, to learn how to measure statistical properties in simulations with many particles, and to provide a deeper insight into the role of fluctuations, finite size effects, and scaling concepts used in modern statistical physics.

FYS4465/FYS9465

Dynamics of Complex Media
The course covers hydrodynamics where capillary and viscous forces play a role. It also covers simulation methods, thermodynamics, and statistical physics relevant to porous media.

FYS4715

Biological Physics
This course provides an overall understanding of how the properties of biological systems are determined by basic physical laws. Furthermore, the course introduces physical models for molecular and cellular processes.

HON1000

Cross-Disciplinary Thematic Focus for Honours Students
The course gives perspectives from multiple disciplines on the current interdisciplinary topic. The intention is to introduce a topic known via the Honours Programme and to inspire to further work on this topic.

STK400

Special curriculum course
This course is offered to MSc students who want a more tailored curriculum for an introduction to the research topic of their MSc thesis. Self-study courses have been formulated together with the MSc supervisor on topics in condensed matter physics and statistical field theory.

Education

In 2023, Njord staff have been responsible for or contributed to the following courses at the Department of Geosciences:

GEO2110

Mineralogy

This course is an introduction to the crystallography, composition, occurrence, and behavior of minerals. The description and identification of the most common rock-forming minerals is a major part of the course.

GEO2150

Petrology and Geochemistry

This course introduces both magmatic and metamorphic petrology. The students learn to understand processes like the crystallization of melts, the development of different types of volcanoes, and the changes within rocks in different geological settings. For this, thermodynamic diagrams and basic geochemical methods are used. The students also work with petrographic microscopes to identify minerals and recognize some of the processes that they learned about in the theoretical part in natural samples.

GEO2210

Geomorphology

This course deals with the processes that shape the Earth's surface. These processes are associated with water flow (fluvial processes), glaciers (glacial processes), frozen ground (periglacial processes) and slopes (gravitational processes).

GEO4420

Glaciology

The course aims to give knowledge of how the glaciers respond to climate changes. A global perspective is discussed, with emphasis on examples from polar regions. The focus is on understanding the processes and impacts of the climate on glacier behaviour.

GEO3131/GEO4131

Geomechanics

This course focuses on the mechanics of Earth's materials (e.g. rock, soil, snow, and ice), in particular on how these materials deform, yield, flow, and fail under applied loads or external forcing (both natural and man-induced).

GEO4840/GEO9840

Tectonics

The course provides an overview of the Earth's evolution in the context of plate tectonics. The course includes one week of obligatory field teaching where many of the phenomena discussed in the lectures are presented.

GEO4190

Hydrogeology

This course teaches the physical processes that control the flow of water below the ground, surface-water groundwater interactions, transport of solutes, and well hydraulics.

GEO4810

Deformation Processes and Microstructures

This course is designed to provide an overview of the deformation and metamorphism of the Earth's lithosphere, and practical training in the interpretation of microstructures using the polarized light and the scanning electron microscope.

GEO4151

Earthquake and Volcanic Processes

This course teaches the physics of earthquake and volcanic processes integrating laboratory, numerical, and theoretical approaches. Topics include key controls on earthquakes, the strength of faults, magma transport processes, and volcano deformation.

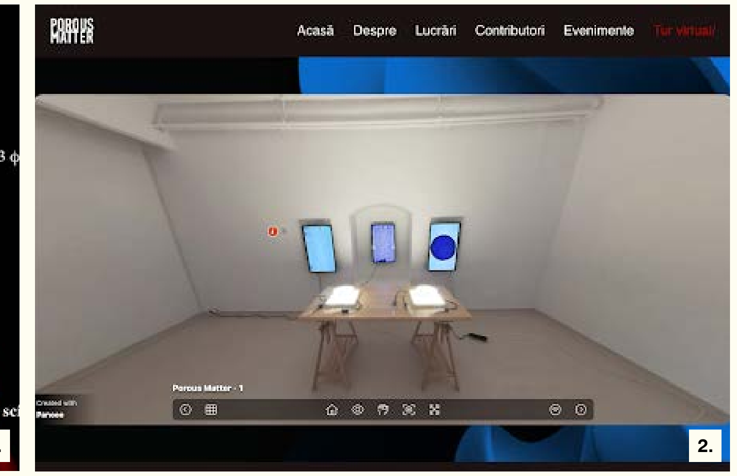
GEO4012

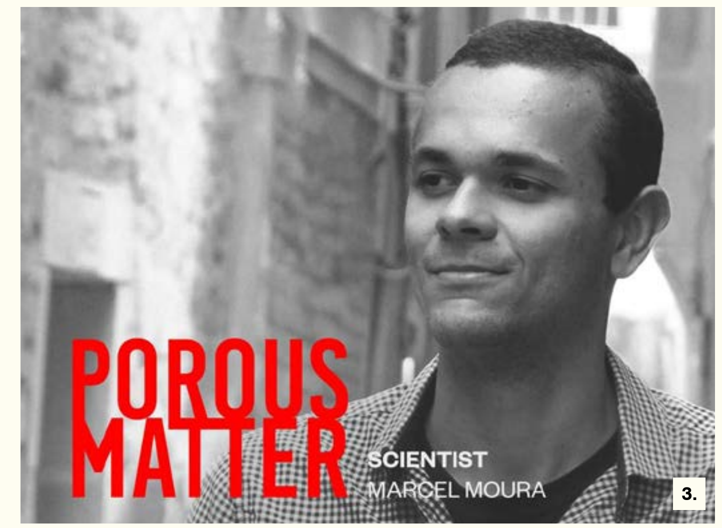
Scientific Writing and Presentation

This course teaches key aspects of academic writing, centred around the traditional IMRAD-style of writing (Introduction, Methods, Results, And Discussion). The course is practical and involves discussions about writing routines and academic genres, as well as experience in reviewing and presenting scientific literature.

Njord's Artistic and Media Outreach Initiatives

Driven by curiosity, our research produces scientific results that have a significant impact on society. With broad applicability, our research directly relates to various areas, including the transportation of water and pollutants in porous and fractured rocks, the storage of carbon to combat climate change, the dynamics of landslides and glaciers, and the occurrence of earthquakes and other geohazards. As a result, our research findings are easily comprehensible and relatable to the general public.





1. Snippet from exhibition's permanent online version, which can be accessed at https://porousmatter.art/
2. Snippet from a virtual tour of the exhibition displayed at https://porousmatter.art/tur-virtual/
3. Photo credits: Benjamin Bledea for META Spațiu contemporary art gallery, MV Sci-Art gallery.

Njord has consistently embraced developing synergies between art and science. This commitment to this fusion was exemplified in 2021 when PoreLab curated a public art exhibition held in the vicinity of Oslo City Hall. The exhibition not only showcased the intersection of art and science but also demonstrated Njord's ongoing commitment to the connection between these disciplines.

Building upon this momentum, 2023 further demonstrated Njord's activities in showcasing the fusion of art and science. In collaboration with the art curator Mirela Vladuti, researchers from PoreLab worked on the development of a sci-art project that culminated in the opening of the exhibition **POROUS MATTER. Void fractions in Materials, Ideas, and Society**. The exhibition is hosted by the MV Sci-Art center in Timisoara, Romania and happens in the context of Timisoara being chosen as the 2023 European Capital of Culture. Marcel Moura and Alex Hansen collaborated with artists and scientists from Norway and Romania in this project. Marcel Moura also contributed with two experimental models turned into art pieces that are now on display at the exhibition. The works entitled "Porous Hypnosis 1" and "All roads are porous" allow visitors to interact with the systems and get a feeling for the intermittent dynamics characteristic of porous media flows.

A brief description of the Sci-Art project **POROUS MATTER. Void fractions in Materials, Ideas, and Society** from the curatorial team:

"POROUS MATTER. Void fractions in Materials, Ideas, and Society delves into the concept of "porous matter" and explores its implications in various contexts. Through an interdisciplinary approach that combines art, science and societal perspectives, the exhibition aims to shed light on the hidden beauty and deeper meaning of the "void fractions" in our world."

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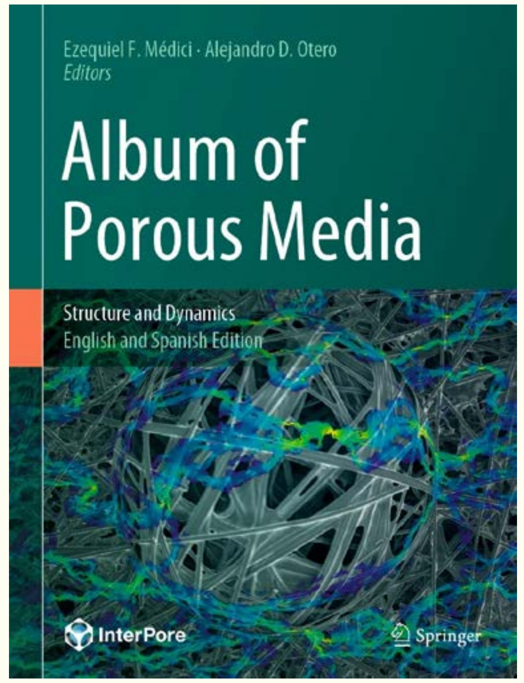
In addition to in-person artistic scientific outreach, a number of scientific results from Njord's researchers have been featured in the first edition of the "Album of Porous Media, Structure and Dynamics" book, which is "dedicated to compiling state-of-the-art visualization in porous materials, serves as a reference for teachers, scientists, and engineers working with porous materials and provides background on how different fields in science and engineering, which might not otherwise be aware of each other." Njord's research is featured in eight different chapters, showcasing images of paths to failure in rocks, fingerprints of chaos in a two-phase porous media flow, capillary fingering and invasion patterns, granular and frictional finger labyrinths as well as viscous fingering fractals in porous media.



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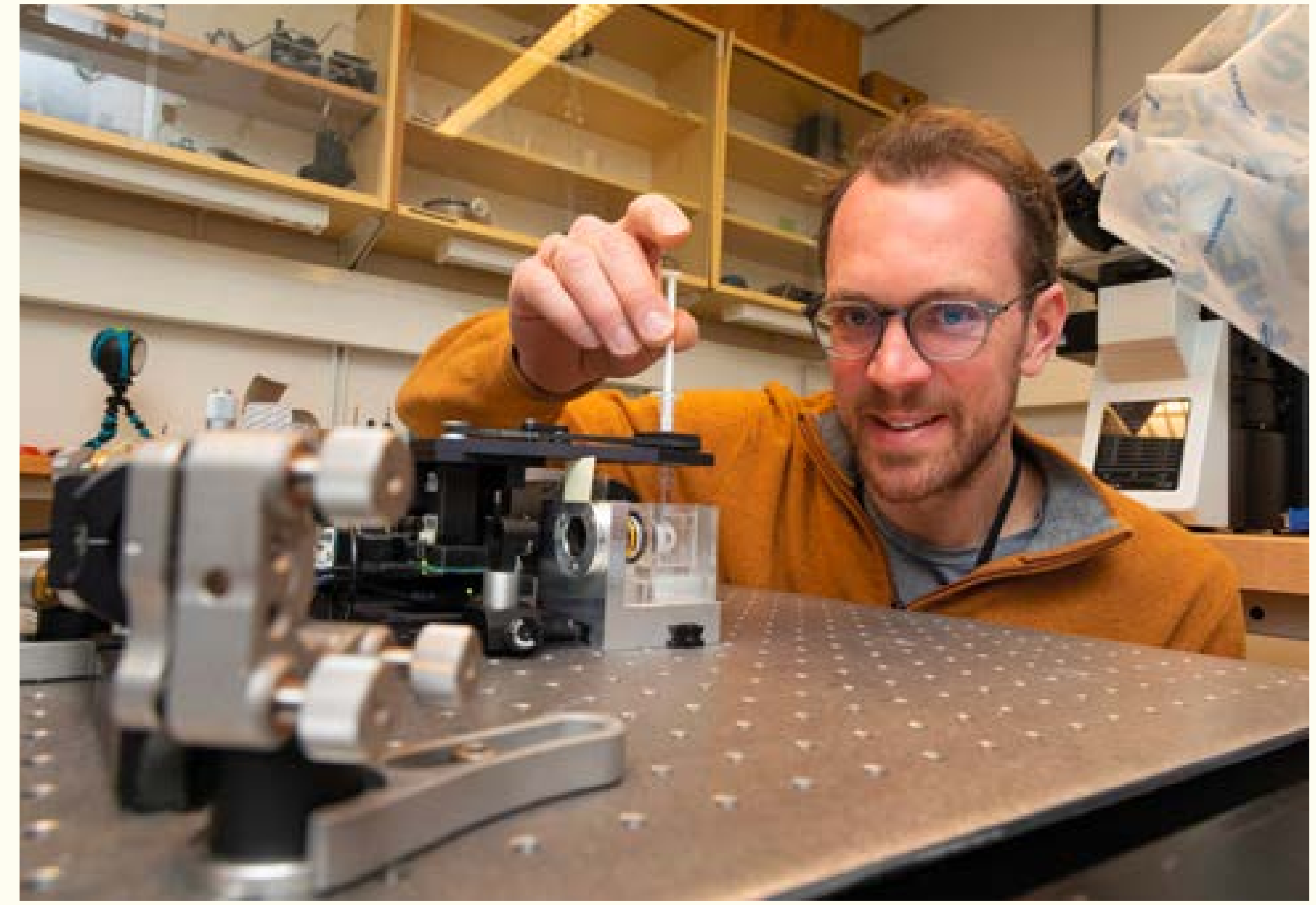
Moreover, Njord demonstrates a strong dedication to sharing research with the broader public via other outlets. This year, Njord achieved strong activities in this regard, highlighted by Olivier Galland's presence in popular Norwegian media outlets such as Dagbladet, Nettavisen, VGTV, and NRK TV. Additionally, Galland extended a special invitation to French school students, providing them with an invaluable opportunity to visit Njord's laboratories. This initiative not only ignited a spark of curiosity and passion within the younger generation, but it also unveiled the interplay between different fields of study such as biology, geophysics, and porous matter that Njord actively pursues. By encouraging a spirit of interdisciplinary exploration and nurturing curiosity, the aim was to inspire the students to discover the endless possibilities that arise when seemingly unrelated disciplines intersect and collaborate.

Volcanologist **Olivier Galland** welcomed the 4th year pupils to discover the physics department at the University of Oslo. Image and caption credits: Lycée français René Cassin d'Oslo



Joachim Mossige has constructed an advanced microscope that enables the study of the surface of cells inside a three-dimensional gastruloid. Photo and caption credits: Yngve Vogt.

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Another great example of interdisciplinarity of Njord was highlighted by an interview given by Joachim Mossige, Dag Kristian Dysthe and Luiza Angheluta to Apollon, the research-oriented popular science magazine published by the University of Oslo, where the researchers highlighted the pivotal role of interdisciplinary collaboration in their groundbreaking research on artificial organs.

In the spirit of effectively disseminating our research, Njord's researchers have gathered invitations as guest speakers at various renowned popular science talks. Among these captivating events was Kristina Dunkel's presentation on mineral reactions under the magnifying glass at GeoOnsdag event, organized by the Science Library at the University of Oslo, where Dunkel delved into the depths of mineralogy, unveiling the secrets of past and presenting innovative solutions for the future.

Equally captivating was Joachim Mossige, who took the stage to enlighten audiences on the nature of porous media physics, even within the realms of our own kitchens. Through an engaging series of talks, including appearances on the Vett and Vitenskap podcast, NRK P2 Abels Tårn program, and Felleskollokvium organized by the Department of Physics at the University of Oslo, Mossige's thought-provoking insights revealed the connections between everyday kitchen experiences and the underlying principles of scientific phenomena. Njord's researchers have also made an appearance at NRK P2's Abels Tårn program before with Vidar Skogvoll as a guest physicist, who also hosts his own popular science podcast on superheroes called "Under Kappa".

↑ Picture taken at Kråkeneset. In this area along the western coast of Norway, we find mafic rocks that were subjected to temperatures of 700 - 800 °C and pressures exceeding 2 GPa during the Caledonian orogeny (~420 Ma). However, deformation is largely restricted to localized small-scale shear zones, on the order of a few centimeters but sometimes up to a few meters wide. At this particular location, we abruptly found a several meter wide anastomosing shear zone that wrapped around less deformed rocks of a different composition.

Fieldwork

Several projects at Njord are grounded in fieldwork, be it mapping, structural observations, or sampling. Discussions in the field with different members of Njord and colleagues from elsewhere also inspire new projects. In 2023, we worked in Western Norway, Svalbard, Lofoten, Argentina, Namibia, and – last but not least – Oslo.

Olivier Galland started the field season in March by visiting the Neuquén Basin in Argentina together with Dougal Jerram (UiO) and Ezequiel Lombardo. The aim was to study the structure and evolution of a partly eroded large volcanic system of Lower Miocene age, the Huantraico volcanic complex. The exceptional outcrop conditions provide a 40 km long natural cross-section of the volcanic complex, including the contact with the sedimentary substratum and volcanic conduits such as dykes and laccoliths. Olivier and Dougal returned in November to extend the mapping work conducted in March by sampling for geochemistry and geochronology.

During the year, Olivier Galland organised several day trips to Hovedøya in the Oslo Fjord to explain and discuss dyke emplacement mechanisms with colleagues from UiO and beyond, using examples of dykes that have been published. These examples were used to illustrate the main research question motivating the FRIPRO project "Beyond Elasticity".

In June, a group from Njord (Luca Menegon, Sascha Zertani, Stephen Michalchuk, Hugo Van Schrojenstein Lantman, and Kristina Dunkel) and the University of Vienna (Anna Rogowitz and Bernhard Grasemann) visited classic localities in Western Norway where lower continental crust that was affected by the Caledonian orogeny is exposed. They discussed well-known areas with new colleagues and identified localities that are suited to address new problems in the course of the CONTINENT project, such as the stress state of the lower crust and the possible role of fluid pressure for seismic faulting.

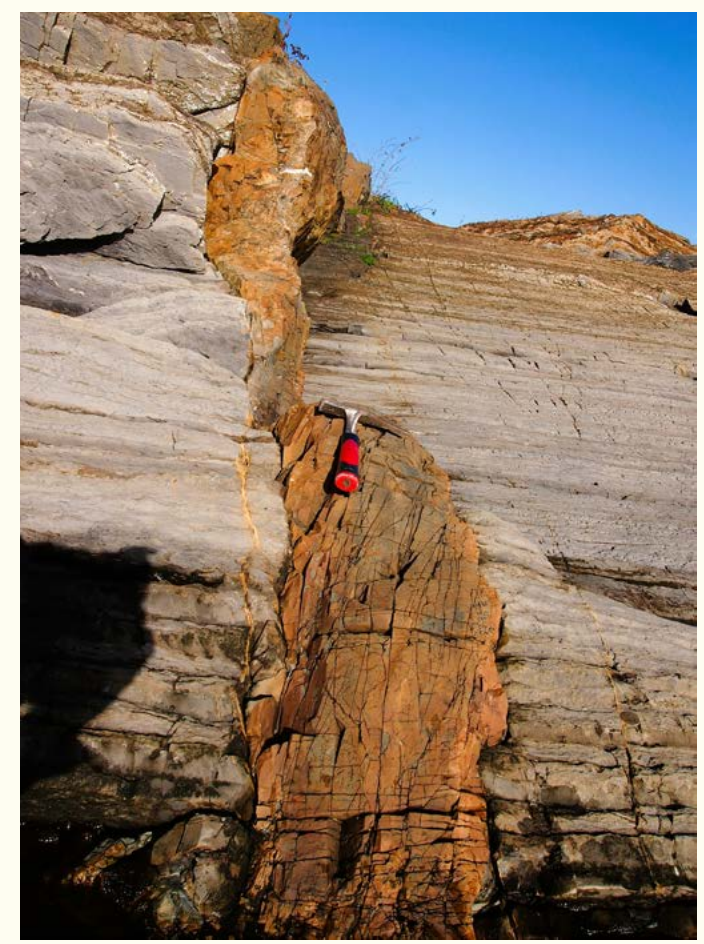
At the same time, Olivier Galland from Njord joined a 2-week trip to Namibia led by Ivar Midtkandal, Alvar Braathen and Dougal Jerram (Department of Geosciences, UiO). Dougal Jerram shared his immense geological experience of the Namibian geology. The aim was to bring together scientists from different sections of the Department of Geosciences in front of exceptional, under-studied outcrops to identify new possibilities of collaborations within the department.

One of our goals for 2023 was to involve physicists more in the field activities. In August, a colourful mix of geoscientists, physicists, and an artist including François Renard, Thomas Schuler, Anders Malthe-Sørenssen, Erina Prastyani, and Ugo Nanni from UiO, Wenlu Zhu from the Univ. of Maryland, Åke Fagereng (Univ. Cardiff), Olivier Gagliardini (Univ. Grenoble Alpes), Yehuda Ben-Zion (Univ. Southern California) and Ellen Karin Mæhlum travelled to Ny Ålesund, the international research station in Svalbard. The researchers participate in the project "Fracture, Friction, and the Onset of Geohazards" at the Centre for Advanced Study in Oslo. The main goal was to perform observations of deformation instabilities in the Kongsvegen glacier, such as calving events and glacier surge. Glaciers are strongly affected by climate change and their melting contributes to sea-level rise. Developing new models to study glacier instabilities that are rooted in field observations is therefore an important goal of the project.

↓ The FricFrac group was very satisfied with the examination of the geology and glaciers of Svalbard.

The 6th EGU Summer School "Structural Analysis of Crystalline Rocks" took place in late August, with Njord members as part of the organizing committee (Luca Menegon) and participants (Stephen Michalchuk). The summer school is held in South Tyrol, in the Neves area, where glacially polished outcrops illustrate brittle and ductile deformation and their connection with fluid-rock interaction in textbook-quality.

A geologist identifying tiny minerals in the field.



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The Lofoten archipelago has been a common destination for the researchers at Njord in the last years, mainly as a natural laboratory to study earthquakes and shear zones in the lower curst. In August 2023, Olivier Galland and Kristina Dunkel build upon Njord's previous knowledge of the area and started a new project with their master student Laura Agadad, who investigates processes of magma emplacement in the crust using the large pegmatites dykes at Å i Lofoten.

←
After many years of traveling all over Norway and abroad to do fieldwork, Njord has rediscovered the Oslo area. In October, PhD student Katharina Bierbaumer started exploring the Inner Oslo Fjord islands as part of her PhD project on magma emplacement processes in general and the evolution of the Volcanic and Igneous Plumbing System in the Oslo Rift in specific. The Oslo Rift experienced long-lasting magmatism in the Permian, which produced numerous sills and dykes in heterogeneous host rocks the had previously been folded and faulted. The aim of this fieldwork is to examine the role of these heterogeneities on the magma emplacement.

Laboratories

The research in Njord relies on unique experimental data acquired in our laboratories that have been fully equipped in the past years. Together with collaborations with large instruments (neutron and synchrotron sources), the development of the national Goldschmidt laboratory at the Geoscience Department, and the integration of some our facilities in the EXCITE European platform, our laboratories are state-of-the art, are open to national and international collaborations, and master and PhD students can use them for their training.

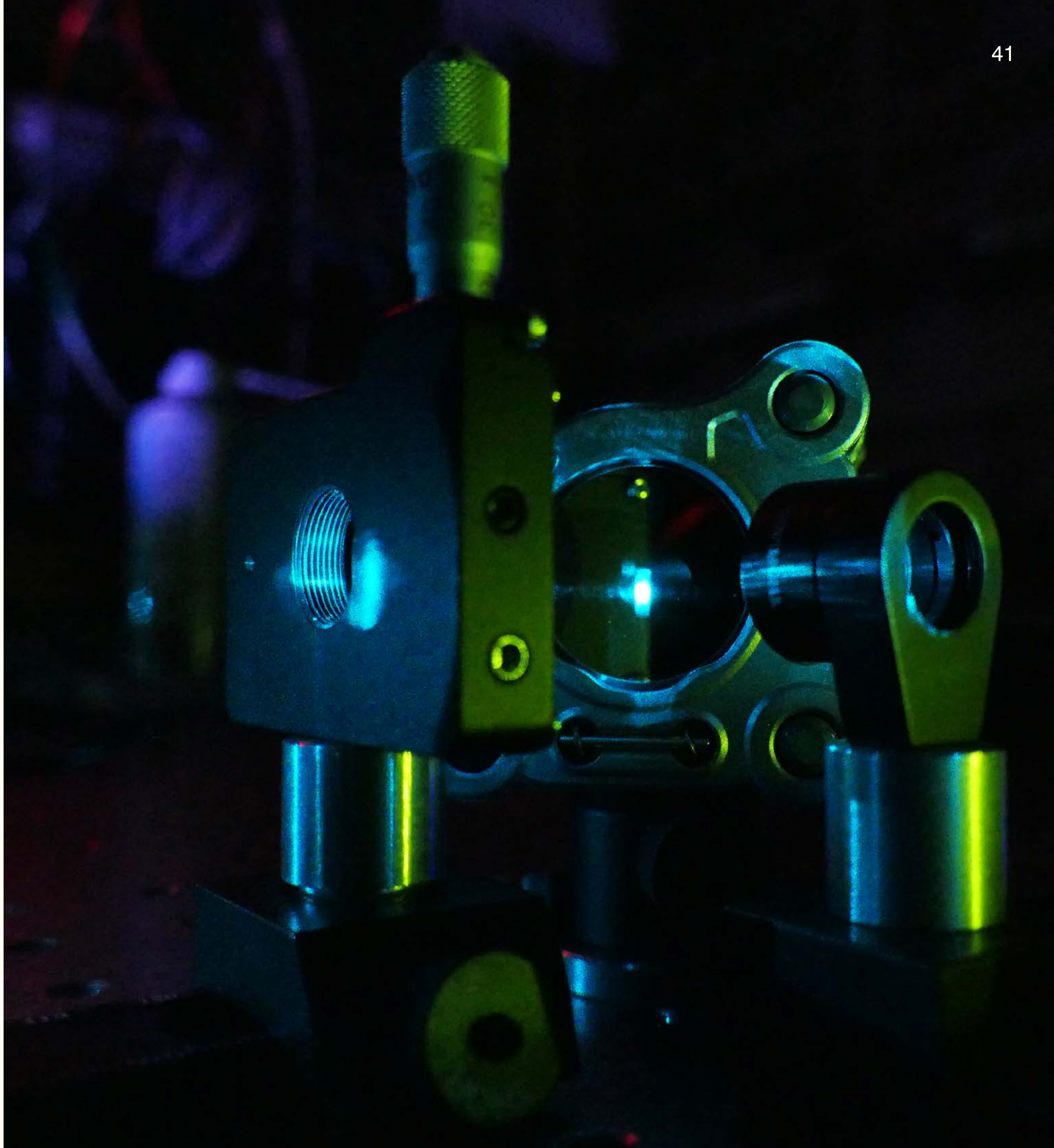
Njord's researchers from both Departments of Physics and Geosciences uses several laboratory facilities: the four experimental rooms of the Centre of Excellence PoreLab, the two rooms of the FrictionLab, NI-Earth Lab, and OsloVolcanoLab, the three rooms of the FlowLab and the two rooms of the LaglivLab, which all are equipped with state-of-art techniques and apparatuses.

PoreLab laboratories at UiO are specialized in studying the dynamics and structure of flow in 2D and 3D porous media. The laboratories have a wide range of high-resolution and high-speed imaging equipment, including two ultrafast Photron Ultima (SA5 and APX) cameras. We have also acquired two new high-speed cameras (Photron WX100) capable of taking 4 MP images at 1000 fps. PoreLab has also a high-resolution FLIR SC300 infrared camera used for real-time measurements of heat dissipation and a wide variety of DSLR cameras and accompanying optics. Microscale experiments can be imaged via far field microscopy using a Zeiss Stemi 2000-C distortion-free stereomicroscope that couples to our high-speed and high-resolution cameras. Illumination sources tailored for the different applications (including high-speed microscopy) are also available.

PoreLab uses a Krüss DSA25 drop shape analyzer to perform direct measurements of surface tension, wetting properties and surface free energy.

The laboratories are equipped with Formlabs Form3 family of 3D printers that are based on the Low Force Stereolithography technology. Our 3D printing cluster consists of two smaller capacity Form 3 and two larger volume Form 3L printers. This setup meets our ever increasing need for the printing capacity. This technology allows for 3D printing of very fine, high resolution models in a variety of resin types. It is used to quickly design and 3D print synthetic porous materials. In addition, we use the Carbide Shapeoko XL CNC milling machine for fabricating or finishing experimental setup components.

The labs are well equipped to perform homodyne correlation spectroscopy for the measurement of particle velocity fluctuations in fluids, diffusion constants, and viscosities. PoreLab has have developed a 3D optical scanner which makes it possible to measure 3D fluid structures in refraction index matched porous media.



↑ Percolation of reactive fluids within Faroe Island basalt rock can induce carbonate precipitation and alter porosity characteristics.

To perform quick action compression or tension tests, PoreLab experimentalists use force and torque gauges, Mark-10 ESM303HE and Mark-10 TSA750H, respectively.

Currently PoreLab is working actively on acquiring Hamamatsu ORCA-Flash4.0 V3 Digital camera with a 16-bit depth CMOS sensor. This piece of equipment is going to be used in the studies of solute mixing and chemically reactive transport in flows through porous materials.

At **FrictionLab**, we have a white light interferometer microscope (Bruker ContourGT), which provides the highest performing non-contact surface measurements. We have a CT5000 in-situ testing stage from Deben, which can be mounted on the X-ray microtomograph at the National Science Museum in Oslo for imaging samples during deformation. We have developed triaxial rock deformation apparatus, the HADES rig and KORE rig, which are installed at the beamline ID19 at the European Synchrotron Radiation Facility. These rigs allow imaging rocks during deformation using dynamic X-ray microtomography. We have also developed three rock core holders that can reach up to 10 MPa confining pressure. These core holders are installed on neutron sources (Institut Laue Langevin in Grenoble and Paul Scherrer Institute in Villigen near Zürich) for neutron tomography imaging of fluid flows in rocks.

Within the FrictionLab, the NI-Earth lab hosts a G200x Nanoindenter from KLA, which is capable of measuring Young's modulus, hardness and creep of geological materials at room temperature and at up to 500 °C using a laser heating system.

"Acquiring data in the field or in laboratory experiments exposes scientists of different disciplines to the true reality of nature, which can generate new ideas and projects among Njord members."

At **FlowLab**, we have a Surface Forces Apparatus (SFA 2000) equipped with a Spectrometer IsoPlane SCT320 that enables directly measurements of the static and dynamic forces between surfaces. Surface forces can also be measured using our Atomic Force Microscope (JPK Nanowizard 4), mounted on an inverted microscope, used for force spectroscopy and nanoscale imaging in air and liquids. This is also used for Magnetic Force Microscopy to image magnetic nanoparticles in bacteria. We have a whole set of photolithographic equipment that can fabricate microfluidic channels. The whole system includes UV-KUB 1, photo resist spinner model 4000, Zepto from Diener plasma surface technology and Graphtec CE 6000. The experiments can be imaged via different sets of microscopes mounted with high-resolution cameras both Andor and iDS. Olympus upright microscope BX 62, Olympus inverted microscope GX 71, Olympus PMG 3, Olympus IX 81 and Olympus IX 83 are installed in different labs for imaging collection and processing. We also have a white light interferometer microscope, NT1100 and a home-built Selective Plane Illumination Microscopy system to view 3D biological samples. The newly implemented fiber laser system, which incorporates multiple wavelengths, has been integrated into our custom-designed Selective Plane Illumination Microscopy setup. This integration facilitates the acquisition of 3D fluorescence imaging data of specimens over extended periods of time.

The **LagLivLab** is partially in the Njord laboratories, and supported by both the physics department and the Hybrid Technology Hub at the department of medicine. The laboratory is equipped to build lab-on-a-chip and study cell biology. We have a clean room which is dedicated to cell culturing and contains a MARS Class II biological safety cabinet, a PHCBi CO_2 incubator which is used to grow cells. In addition, we have recently introduced a state-of-the-art phase holographic live cell imaging system from Phase Holographic Imaging PHI AB, which enables continuous imaging and analysis of live cells.

The **OsloAnalogueLab** (previously VolcanoLab) focuses on the quantitative simulations of various geological-scale processes, including magma transport through, and emplacement within, the Earth's crust on various scales, caldera collapse, tectonic processes, and shear localization in brittle fault zones. An important aspect of the analogue laboratory is imaging through high-resolution/precision monitoring tools and cutting-edge laboratory materials of variable and controlled rheology.

In 2020 the University of Oslo received 20.3 million NOK from the Research Council of Norway based on the 2018 call for National Research Infrastructures. This funding has established the geochronology part of the **Goldschmidt Laboratory**, a national infrastructure for geochemical, microstructural, and geochronological characterization of solid Earth materials. The Goldschmidt Laboratory is coordinated by the Department of Geosciences, and Njord has a leadership role in it. The laboratory hosts a new isotope dilution thermal ionization mass spectrometry laboratory (ID-TIMS) at UiO, a new Noble gas mass spectrometer (NGMS) at the Geological Survey of Norway in Trondheim, and a microscope slide scanner, two high-end petrographic microscopes, and a scanning electron microscope (SEM) equipped with high-angular resolution electron backscatter diffraction (HR-EBSD) at UiO.

Njord is playing a leading role in the UiO's participation in the H2020 INFRAIA "EXCITE" project, which has been funded in 2020. EXCITE has established a European expert community in electron and X-ray microscopy for structural and chemical imaging techniques for Earth materials. The continuation of EXCITE, EXCITE2, has been funded in 2023. Through EXCITE2, UiO and Njord will continue to give access to their state-of-the-art imaging technologies, to train researchers and develop new collaborations.

3

Research projects

About Chapter 3

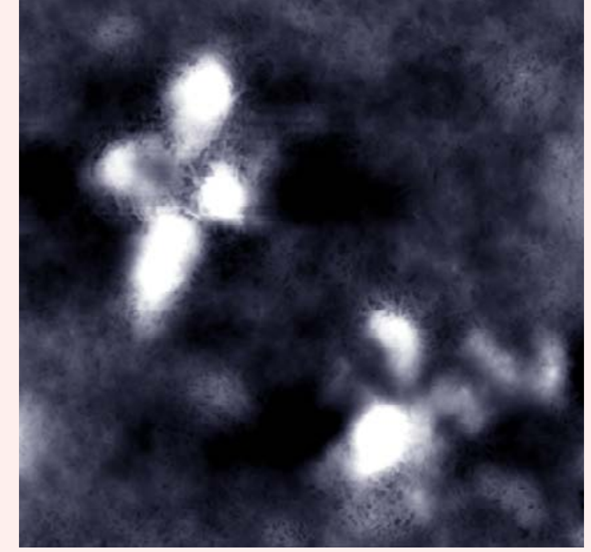
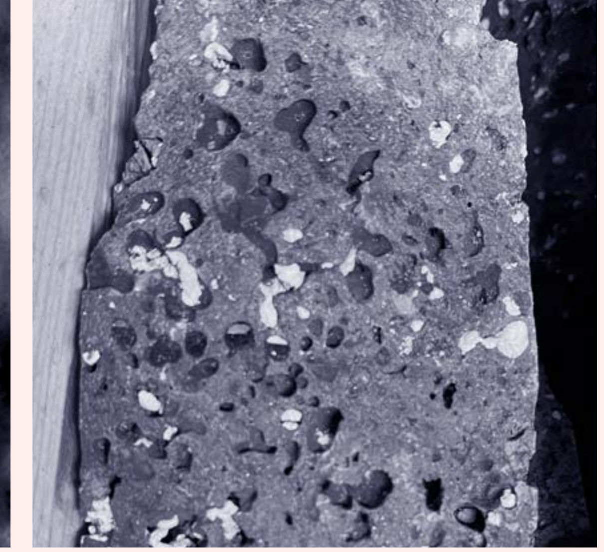
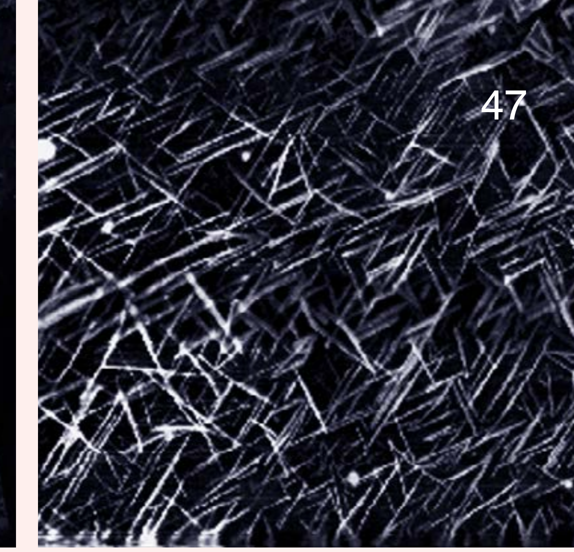
The research at the Njord Centre is organized around three main topics: 1) Fluid flows in complex media, 2) Fracture, friction and creep, and 3) Couplings at the nanoscale. These topics represent the core of the research strategy the centre has defined for the period 2023-2027.

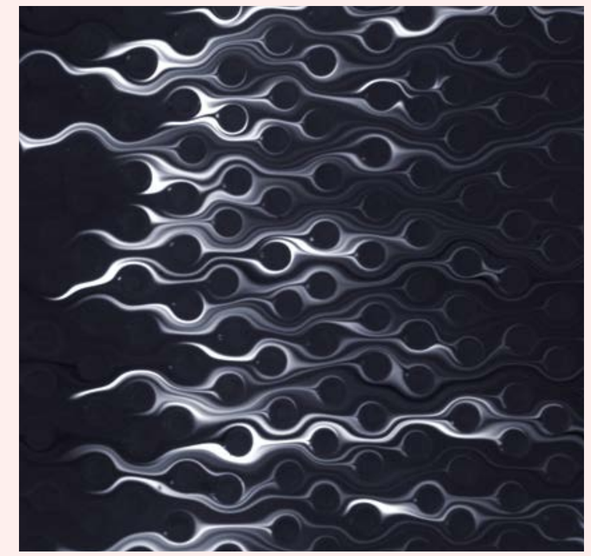
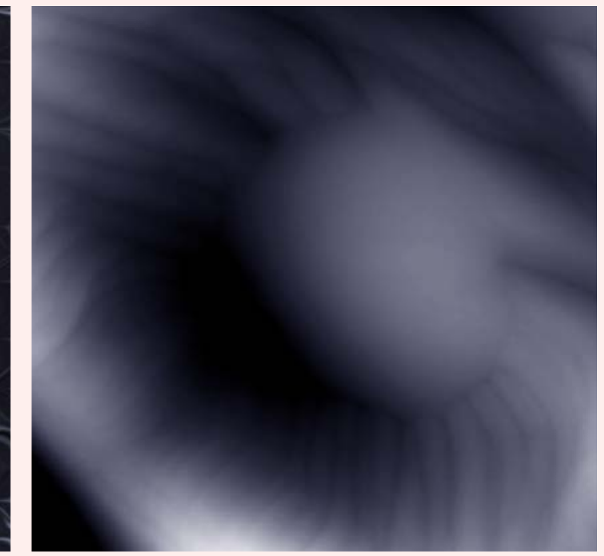
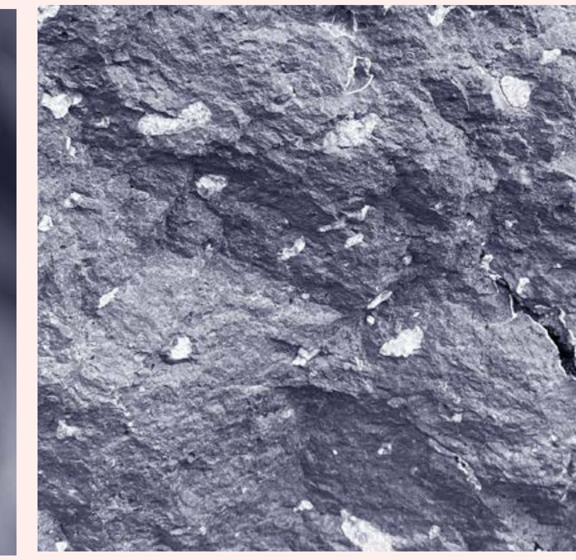
Many researchers at the Njord Centre focus on the dynamics of fluid migration through porous materials and geological media (Part 1). Some of them address single or multi-phase fluid dynamics in the confinement of a complex pore space where fluid-solid interactions vary along the interfaces. The interplay between friction, capillary and viscous forces becomes important, as well as the effect of fluid pressure gradients and external forces on the solid confinement that is being studied.

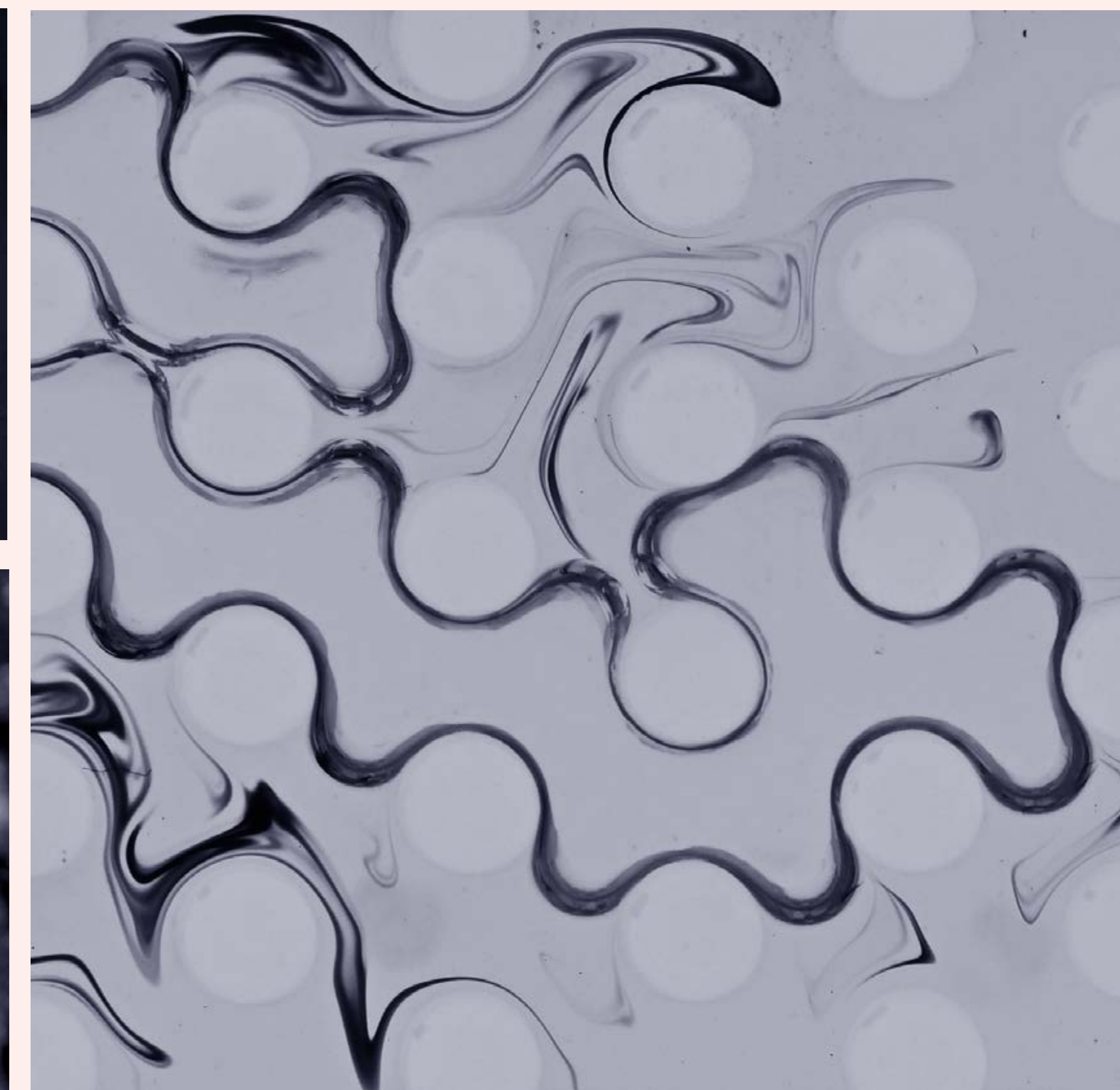
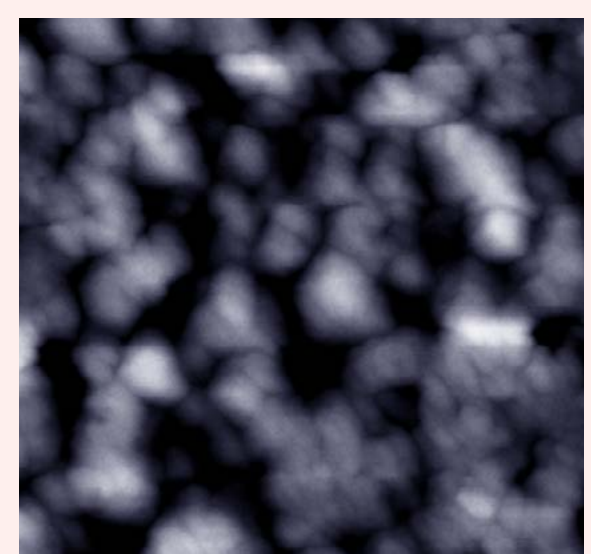
Fluids often enter the solids through fractures. Hence, the physics of fracturing and deformation is a central Njord activity (Part 2). In natural systems, fracturing is often associated with displacement along the fracture surface and the frictional properties of fractured surfaces control energy dissipation. This situation applies to the slow slip and creep encountered in aseismic deformations of faults, landslides, glaciers, and volcanos and to the high slip rates associated with natural earthquakes or glacier surges.

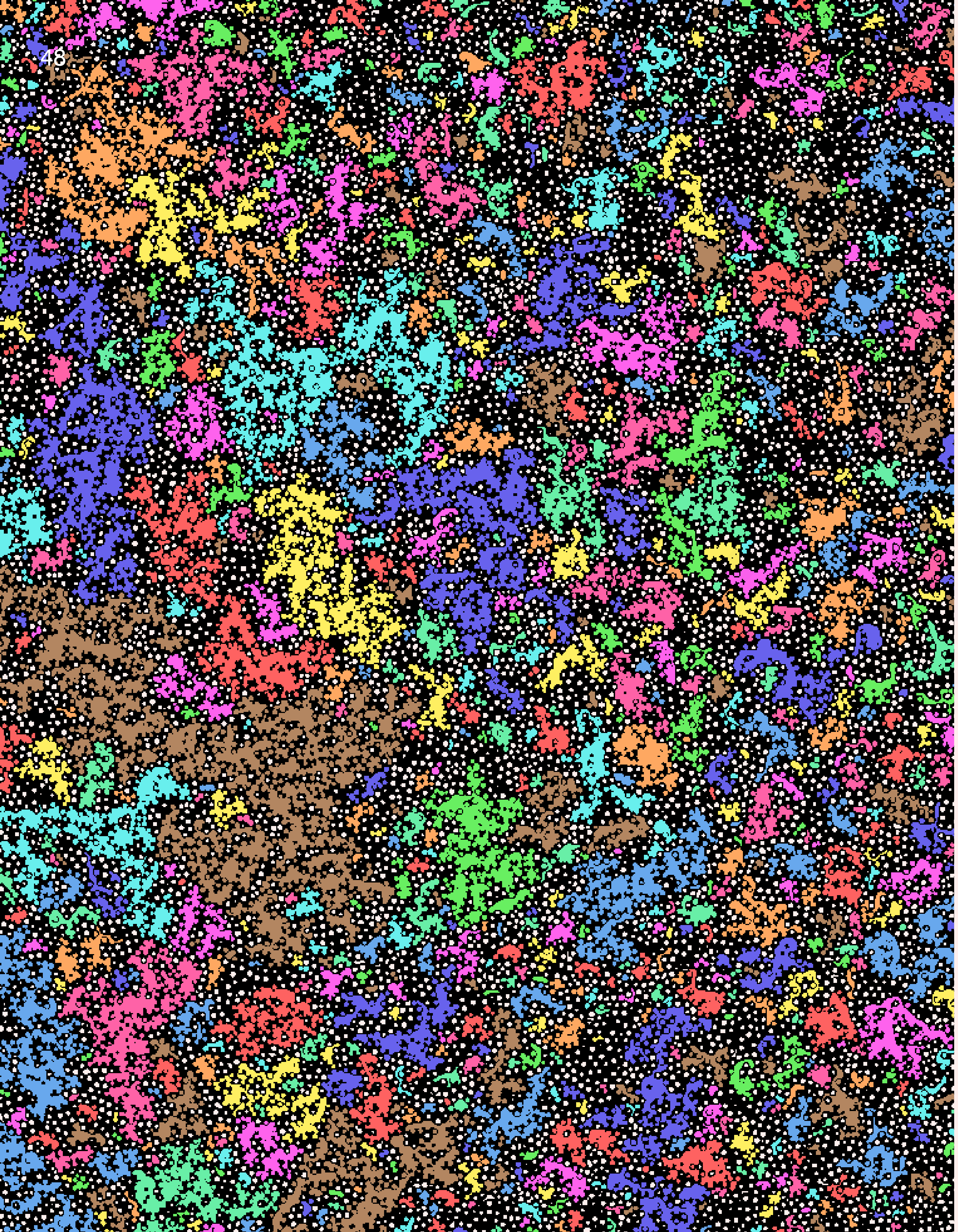
Many geological processes occur in dissipative coupled systems where first principles physics at the nano- and microscales describe the separation of spatial and temporal scales during the injection, transport, and dissipation of energy (Part 3). The solid may interact chemically with the pore-filling fluid at the nanoscale. In this case, the pore space may evolve both by dissolution or precipitation of solids and by stress perturbations induced by growth processes.

A significant focus in Njord's research is studying systems that evolve far from equilibrium, and are often characterized by nonlinear relations between forces and fluxes and the emergence of 'self-organized' patterns. Such patterns may contain valuable information about underlying processes. This is especially crucial in geoscience, where patterns preserved in rocks serve as the only source of information to understand ancient geological processes, as well as in the study of porous materials where various processes are at interplay to create emergent structures observed.



3
Part 1

Fluid Flows in Complex Media

Capillary washboarding during slow drainage of a frictional fluid

Funding
The Research Council of Norway, SFF PoreLab

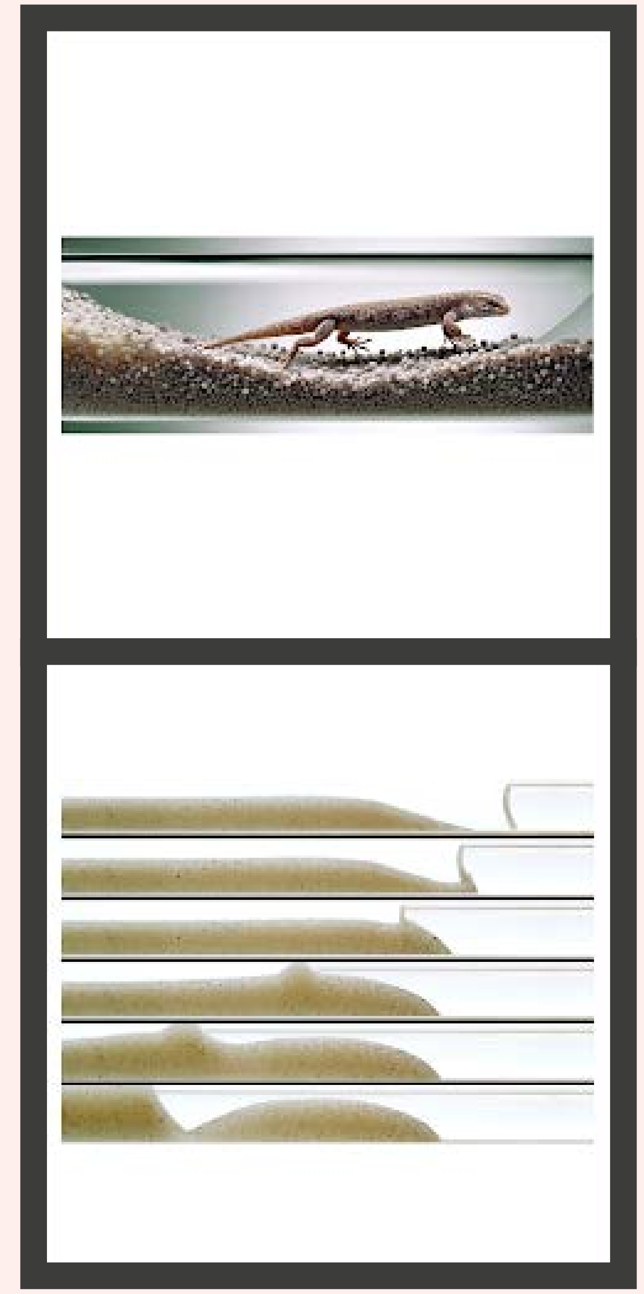
Participants
Louison Thorens[1,2], Guillaume Dumazer[1], Knut Jørgen Måløy[1], Eirik Grude Flekkøy[1], Bjørnar Sandnes[3], Mickael Bourgoin[2], Stephan Santucci[2]

Affiliation
1) PoreLab, The Njord Centre, University of Oslo, Norway
2) ENSL, Laboratoire de Physique, Lyon, France
3) Department of Chemical Engineering, Swansea University, United Kingdom

We consider a model configuration where an immersed sedimented layer is slowly drained out of a horizontal capillary tube. By systematically modifying the wettability and surface tension of the draining liquid, as well as the initial height of the granular bed, we were able to identify the necessary conditions for the emergence of a bulldozing process, resulting in various drainage instabilities with the formation of ripples and plugs.

We discover a new unstable drainage regime with periodic dunes generation, similar to the road washboarding instability due to the repeated passage of vehicles. A 2D theoretical approach based on the competing roles of friction and capillarity, quantitatively supported by 2D numerical simulations of a meniscus bulldozing a front of particles, captures all of the qualitative aspects of the varied drainage dynamics observed experimentally. In the modeling we had to take the fact into account that the friction force exerted by the granular front on the invading meniscus depends on the local angle of attack. Actually, animals such as lizards take advantage of such frictional enhancement with the local angle of attack to move and even run effectively on a flowing granular media.

The intricate interplay between capillary forces and frictional and viscous dissipation is also responsible for the creation of different displacement regimes as the injection rate is increased. In flow circumstances dominated by viscous dissipation, the result of viscous forces is the gradual fluidization of the entire granular material.



→ **Top:** A lizard walking on a granular material taking advantage of frictional enhancement with the local angle of attack (frontpage of Soft Matter volume 18, number 48).

Bottom: Formation of dunes during slow drainage of a frictional fluid.

PoreLab
NTNU-UiO Porous Media Laboratory

Production in highlight

Louison Thorens, Knut Jørgen Måløy, Eirik Grude Flekkøy, Bjørnar Sandnes, Mickael Bourgoin, Stephan Santucci, Capillary washboarding during slow drainage of a frictional fluid, Soft Matter **19**, 9369, (2023)

Guillaume Dumazer, Bjørnar Sandnes , Knut Jørgen Måløy, and Eirik Grude Flekkøy. Capillary bulldozing of sedimented granular material confined in a millifluidic tube. Phys. Rev. Fluids, **5**, 034309, (2020)

Guillaume Dumazer, Bjørnar Sandnes, Monem Ayaz, Knut Jørgen Måløy, Eirik Grude Flekkøy, Frictional Fluid Dynamics and Plug Formation in Multiphase Millifluidic Flow, Phys. Rev. Lett., **117**, 028002 (2016)

Interface dynamics in geophysical flows: EarthFlows

Funding
University of Oslo,
Strategic Research Initiative

Participants
Luiza Angheluta-Bauer[1,4] (PI), Francois Renard[1,2] (co-PI)
Supervisors: Anders Malthe-Sørenssen[1,4], Anja Røyne[1,4], Knut Jørgen Måløy[1,4], Olivier Galland[1,2], Joe LaCasce[2], Andy Kääb[2], Karen Mair[1,2], Atle Jensen[3], Kent A. Mardal[3], Thomas V. Schuler[2], Andreas Carlson[3], Luca Menegon[1,2]
PhD students: Vidar Skogvoll[1,4], Coline Bouchayer[2], Torstein Sæter[3]

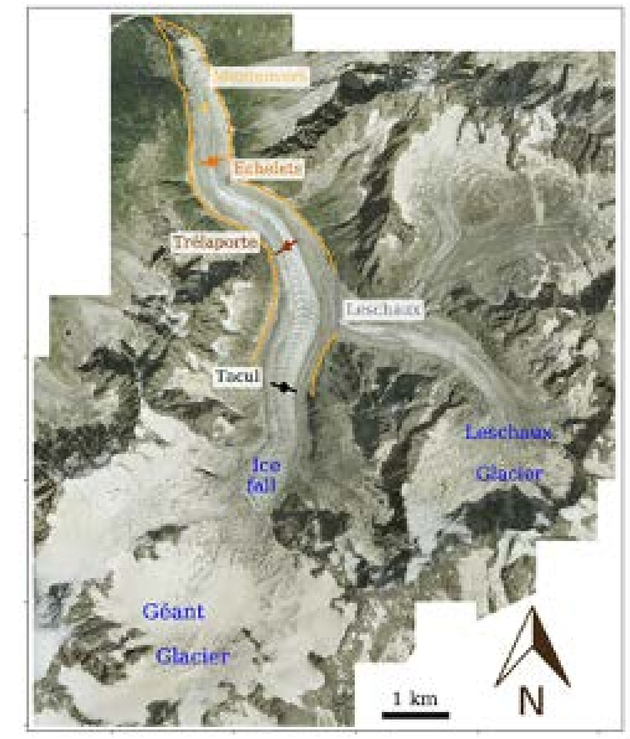
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway

Fluid flows in the hydrosphere, the atmosphere, the cryosphere, the subsurface rocks, and even the biosphere shape the evolution of the Earth's crust. Such geophysical flows include water and air, magma, as well more complex fluids such as hydrocarbons, CO_2-water mixtures, and fluid-solid mixtures. Solid rocks and ice can also behave like fluids on geological timescales. Nonlinear physical processes like friction, fracture and plasticity in complex materials are example of dissipative processes that occur along interfaces and grain boundaries.

The EarthFlows project is a strategic initiative at UiO that promotes the paradigm of "complex Earth systems" through interdisciplinary research and using an integrated approach of linking flow, deformations, and chemical reactions across relevant length scales. The first phase of EarthFlows (2014-2020) had enabled a successful synergy and cross-disciplinary research across five interlinked themes including magma dynamics, glacial surges, fluid migration in stressed rocks, and multiphase turbulent flows. In the second phase of the EarthFlows (2019-2023), we focus on understanding the evolution of fluid-solid interfaces in geosystems and the tipping point phenomena related to interfacial dynamics. The new concepts and theoretical developments will concern three geosystems with a highly complex dynamics: friction and surge of glaciers, low-temperature plasticity, and dynamics of fluid flow during fracturing of elastic solids. Albeit these are different systems, the crosslinks between them rely on analogous statistical physics models and similar theoretical approaches based on non-equilibrium phase transitions and critical phenomena.

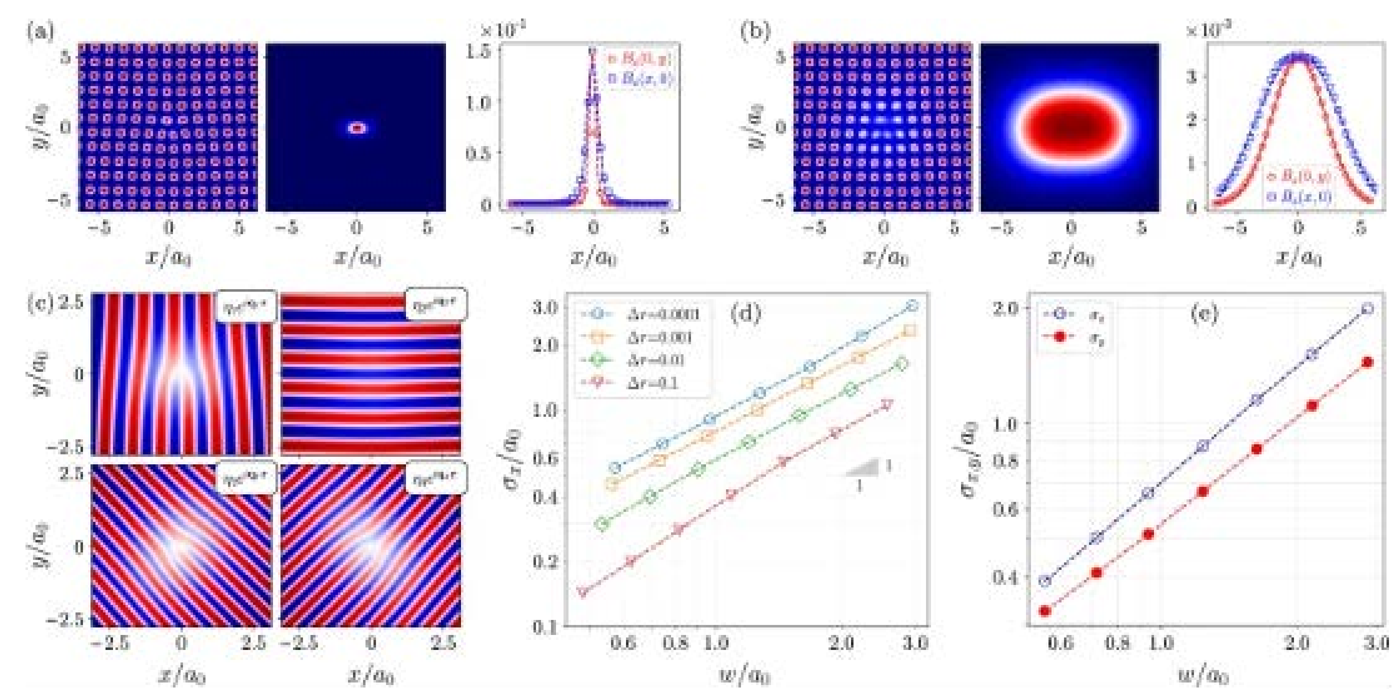
Project highlight 1: Machine-learning unravels glacier instabilities (Bouchayer 2023). Surge-type glaciers are present in many cold environments in the world. These glaciers experience a dramatic increase in velocity over short time periods, the surge, followed by an extended period of slow movement, the quiescence. Here, we develop a machine learning framework to classify surge-type glaciers, based on their location, exposure, geometry, climatic mass balance, and runoff. We apply this approach to the Svalbard archipelago, a region with a relatively homogeneous climate. The framework shows robustness on classifying surge-type glaciers that were not previously classified as such in existing inventories but have been observed surging (Figure A). Our methodology could be extended to classify surge-type glaciers in other areas of the world.

Project highlight 2: As geomaterials are scaled down, microstructural defects become increasingly important for material responses. Crystalline solids are characterized by lattice defects, such as dislocations which are topological defects controlling the plastic response in stressed crystals. We have developed a generic formalism for systems with persistent order where we are able to bridge the dissipative material response on continuum scales with the structural defects on discrete scales where broken symmetries manifest themselves (Skogvoll et al., 2023, Figure B). Within the phase-field crystal (PFC) model, we have shown how the dislocation motion is determined by topological constraints due broken rotational and translation symmetries and impacts the plastic response on large scales (Skogvoll 2023b).



→ **Figure A:** Map of Mer de Glace (orthophoto acquired in 2008 ©RGD74). The orange contour delimits the area modeled in this study. The location of the four cross sections (Tacul, Trélaporte,Echelets and Montenvers) and the Leschaux gate are indicated by the colored lines. The Tacul and Leschaux gates represent boundary gates where data are used to force the model, whereas the three other profiles represent internal gates where data are used to validatethe model. (Bouchayer 2023).

↓ **Figure B:** Crystal density and Burgers vector density small (a) and large (b) defect core size. Periodic mode decomposition (c) for the crystal density in panel (a&b). (d,e) Defect core size as function of the quenching depth. (Skogvoll et al. 2023a)



Production in highlight
Bouchayer, C (2023) Transient glacier dynamics and subglacier hydro-mechanical processes. PhD thesis.

Skogvoll, V., Rønning, J., Salvalaglio, M., & Angheluta, L., (2023a). A unified theory field theory of topological defects and non-linear local excitations. npj Computational Materials 9 (122).

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Sæter, T., Galland, O., Feneuil, B., Jorstein, H. & Carlson, A. (2023). Growth of a viscoplastic blister underneath an elastic sheet. Journal of Fluid Mechanics ISSN 0022-1120.

PoreLab
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Collaboration on flows across scales

(Brazil, France, Norway, USA)

Funding
The Research Council of Norway (project INTPART COLOSSAL, #309073)

Participants
François Renard[1], Gaute Linga[1,2], Fabian Barras[1], Knut Jørgen Måløy[1,2], Marcel Moura[1,2], Tanguy Le Borgne[1,3], Luiza Angheluta-Bauer[1], Anders Malthe-Sørenssen[1], Dag Kristian Dysthe[1], Thomas Vikhamar Schuler[4], Eirik Grude Flekkøy[1,2], Clara Sena[4], Atle Jense[5], Luca Menegon[1], Antônio Murilo Santos Macêdo[6], Ernesto Carneiro Pessoa Raposo[6], Giovani Lopes Vasconcelos[7], Olivier Gagliardini[8], Jérôme Weiss[8], Stéphane Santucci[9], Mickaël Bourgoin[9], Razvan Caracas[9], Yehuda Ben-Zion[10], Felipe de Barros[10], Jorge Vinals[11], Peter Kang[11], Cristina Marchetti[12]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Geosciences Rennes, University of Rennes, France & Njord
4) Department of Geosciences, University of Oslo, Norway
5) Department of Mathematics, University of Oslo, Norway
6) Universidade Federal de Pernambuco, Recife, Brazil
7) Universidade Federal do Parana, Curitiba, Brazil
8) University Grenoble Alpes & CNRS, Grenoble, France
9) Ecole Normale Supérieure de Lyon, France
10) University of Southern California, USA
11) University of Minnesota, USA
12) University of California Santa Barbara, USA

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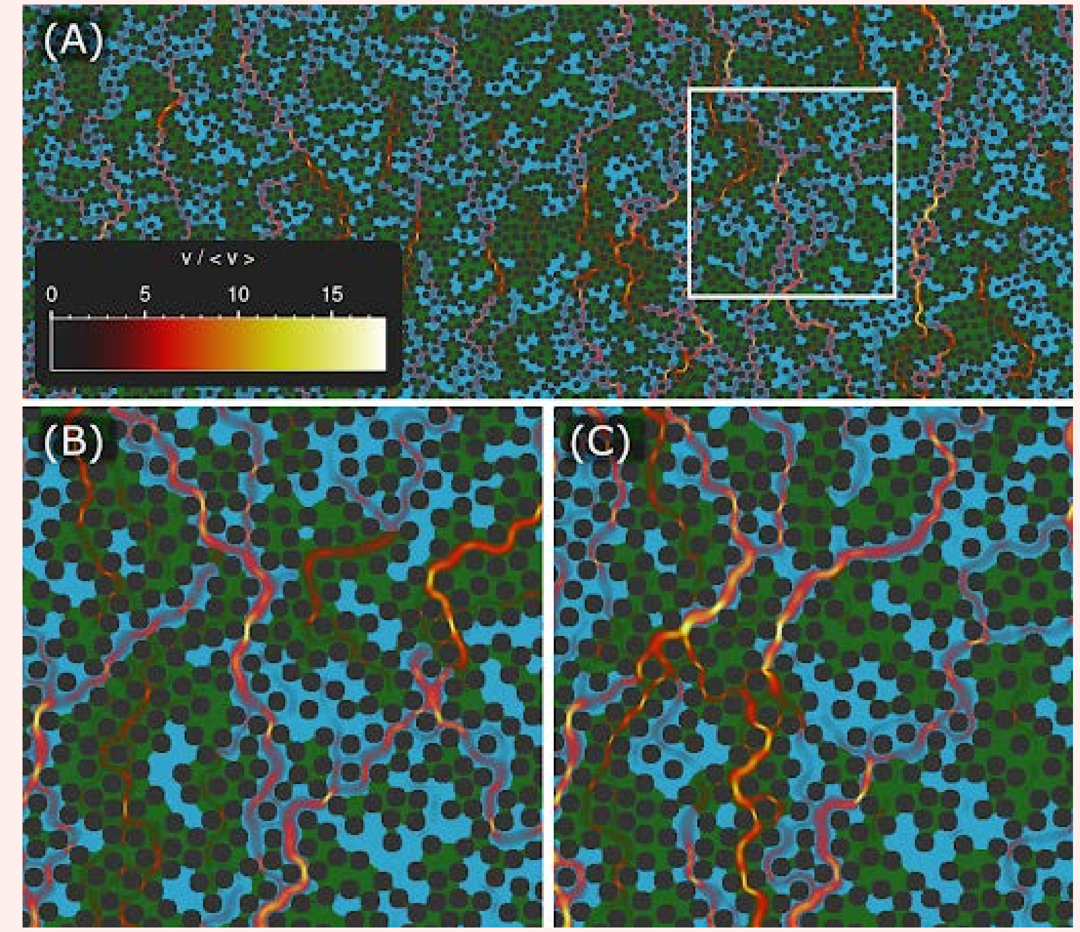


↑ Numerical simulations of two-phase flow in a porous medium (Mathiesen et al., 2023).

Through a wide international collaboration between geoscientists and physicists in Norway, Brazil, USA, and France, we study the couplings between flows, chemical evolution, deformation, and fracturing that cover a wide range of time and length scales of natural geological processes. In this project, that funds mobility only, we train a cohort of MSc and PhD students and organize international exchanges of researchers from and to Norway. We also train researchers during geological field trips, international conferences, and scientific article workshops. The research and education has relevant societal implications in the domains of geohazards (earthquakes, landslides, glacier collapse), groundwater resource (production and protection of aquifers, reactivity and transport of contaminants in the subsurface), and geo-resources (geothermal energy, carbon dioxide sequestration, solution mining).

In 2023, the main highlight has been the organization of an international conference in Porto de Galinhas, Brazil, where around 40 participants from the partner universities exchanged and created new links. One article was finished during the conference (Mathiesen et al., 2023).

Dr. Moura visited Peter Kang's group at the University of Minnesota to collaborate with postdoc Sang Lee. Sang has developed a microfluidic porous medium setup to study bioremediation of contaminated soils by means of a fungus that grows in the pore space. The fungus used was isolated from a local coal-tar contaminated site. The experiments have shown how the growth of the fungus induced a flow instability which dramatically mobilized the contaminant phase out of the sample. Dr. Véronique Dansereau, from the University Grenoble Alpes, spent the spring 2023 in Oslo to start a collaboration on the modelling of sea ice using a phase-field approach, in collaboration with Pr. Luiza Angheluta.

A writing workshop with early career and senior researchers from Norway and France was held in Blesle in June 2023. The project contributed to the international EarthFlows conference in June 2023, with more than 70 participants from Norway and abroad. Finally, the project contributed to two illustrations in the Album of Porous Media (Linga et al., 2023; Renard, 2023)

Production in highlight

Mathiesen, J., Linga, G., Renard, F., Le Borgne, T. (2023) Dynamic fluid connectivity accelerates solute dispersion in multiphase porous media flow, Geophysical Research Letters, 50, e2023GL105233.

Linga, G., Mathiesen, J., Renard, F., Le Borgne, T. (2023). Fingerprints of Chaos in a Two-Phase Porous Media Flow. In: Médici, E.F., Otero, A.D. (eds) Album of Porous Media. Springer, Cham.

Renard, F. (2023). Imaging the Path to Failure in Rocks. In: Médici, E.F., Otero, A.D. (eds) Album of Porous Media. Springer, Cham.

Mixing in multiphase flow through microporous media

Funding
The Research Council of Norway (project M4)

Participants
Gaute Linga[1,2], Kevin Pierce[1], Tanguy Le Borgne[1,3], Knut Jørgen Måløy[1], Francois Renard[1], Luiza Angheluta[1], Eirik G. Flekkøy[1], Marcel Moura[1], August Johansson[4], Francesca Watson[4]

Affiliation
1) PoreLab, The Njord Centre, University of Oslo, Norway
2) PoreLab, Department of Physics, Norwegian University of Science and Technology, Norway
3) Geosciences Rennes, University of Rennes, France
4) SINTEF Digital, Norway

Solute mixing is a key process across a wide range of porous geophysical, industrial and biological systems, with important applications including environmental remediation and CO_2 storage. Despite this, little is currently known about how chemicals mix under multiphase flow conditions, i.e. when two or more phases are flowing together in a porous medium.

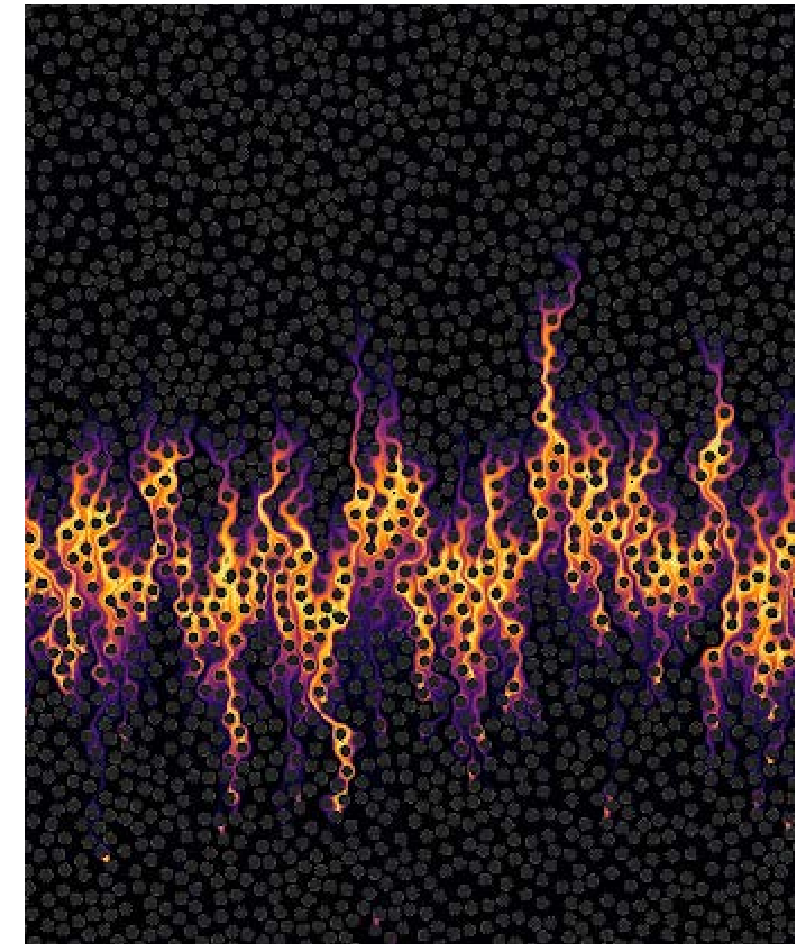
The goal of M4 is to establish the laws of mixing in multiphase porous media flows. We aim to predict mixing in multiphase flows in a wide class of porous materials. To do so, we develop numerical methods for highly accurate simulation of mixing in multiphase flows, and we design and execute novel experiments which directly image the stretching and diffusion of solute plumes within porous media flows.

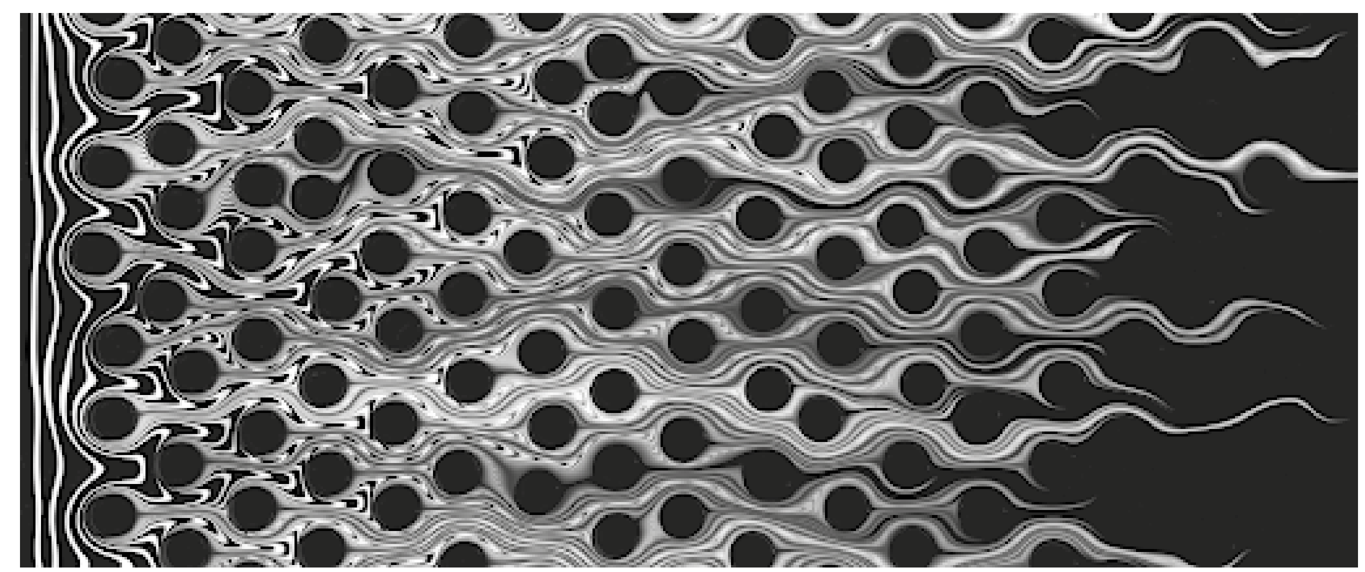
In M4's second year, we have continued developing simulation methods for multiphase transport in 2D and 3D. We have produced highly resolved multiphase flow simulations in porous media across a wide range of capillary numbers. Using the generated velocity fields, we have measured solute stretching dynamics and compared them to an idealized model we developed for oscillatory flow. We have also studied computationally and theoretically the mixing of solutes near solid boundaries.

On the experimental side, we have improved our stereolithographic 3D printing of transparent porous models. We have established new imaging methods to resolve the concentration and stretching of fluorescent dye plumes, both in single and multiphase flows. With two summer students, we constructed a new particle tracking velocimetry setup to resolve the local flow velocities driving mixing. This work provides new capabilities to resolve the physics of mixing and reactive transport in flows through porous media.

→ Simulation of the reaction between two chemical species in a flow through a porous medium. The color indicates the local reaction product concentration (black: low, yellow: high). The filamentary structure of the reaction fronts reveals persistent concentration gradients at the pore scale.

↓ A time lapse image of a laboratory mixing experiment. Flow velocity gradients shear an initial line of dye into a brush-like plume. The sharp concentration gradients across the plume amplifies diffusion and drives mixing.





Production in highlight
G. Linga, J. Mathiesen, F. Renard, T. Le Borgne, Fingerprints of chaos in a two-phase porous media flow. In Album of Porous Media Structure and Dynamics, Springer (2023).

J.F. Brodin, K. Pierce, P.A. Rikvold, M. Moura, M. Jankov, and K.J. Måløy, Interface instability of two-phase flow in a three-dimensional porous medium. In Prep. (2024).

J. Mathiesen, G. Linga, M. Misztal, F. Renard, T. Le Borgne, Dynamic fluid connectivity controls solute dispersion in multiphase porous media flow, Geophysical Research Letters 50, e2023GL105233 (2023).

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Frictional fluid instabilities shaped by viscous forces

Funding
The Research Council of Norway, SFF PoreLab

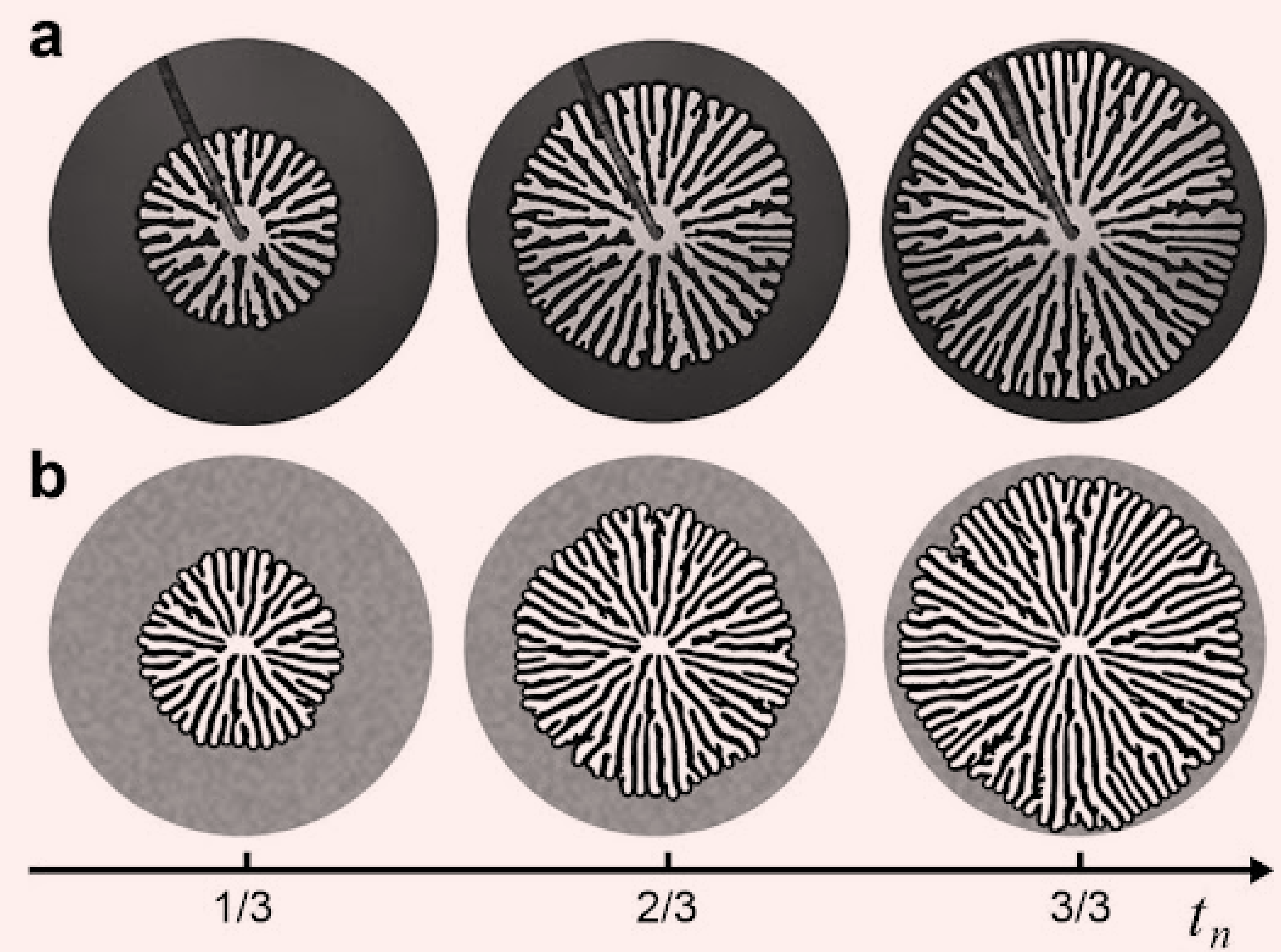
Participants
Dawang Zhang[3], James M. Campell[1,2,3], Jon A. Eriksen[1,2], Eirik G. Flekkøy[1,2], Knut Jørgen Måløy[1,2], Christopher W. MacMinn[4], Bjørnar Sandnes[3]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Department of Chemical Engineering, Swansea University, Swansea, UK
4) Department of Engineering Science, University of Oxford, UK

An invading meniscus between two fluids may bulldoze loose granular material. The flow becomes 'frictionally unstable', with the invading fluid shaped into fingers that plough the granular material to the side. Previous studies found that air injection into a viscous granular mixture produced frictional fingers at low injection rate, giving way to viscous fingers at high rate; the system became 'viscously unstable'. But what happens if the viscosity ratio is swapped, and the high viscosity fluid is the invading one?

From classic fluid dynamics we know that a high viscosity invading fluid will be viscously stable, just a simple expanding disc in a radial Hele-Shaw cell. With grains in the system, however, Zhang et al. discovered a new family of pattern formation caused by the interplay between friction and viscous effects. The experiments used glass beads made hydrophobic by chemical treatment. Invading water therefore pushed the dry hydrophobic grains to the side, creating a single finger at low injection rate. By increasing the injection rate the viscous forces in the system became more dominant relative to friction. A surprising finding was that the role of viscous stabilization was to sprout more fingers: Viscous pressure within the invading fingers caused breakout of new fingers as the injection rate was ramped up. At extreme levels of viscous stabilisation (injection of pure glycerol as fast as the pump could go) the fingers grew in a spoke pattern, all fingers moving radially outwards from the central injection point, side-by-side like petals on a flower.

Multiphase frictional flows are a distinct class of fluid displacement problems, and the study has revealed new flow behaviour caused by the interplay between frictional, capillary and viscous forces. Such frictional flows with loose granular material embedded in viscous fluids are found everywhere in nature and industrial processing, and this new insight brings us a step closer to finally unpicking the fluid dynamics of these systems which are notoriously complex and difficult to control.



↑ Time evolution of spoke pattern. (a) Experiment and (b) simulation of glycerol injection producing a viscously stable spoke pattern. Time t_n is normalized by the time the first finger reaches the boundary.

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Production in highlight

Dawang Zhang, James M. Campell, Jon A. Eriksen, Eirik G. Flekkøy, Knut Jørgen Måløy, Christopher W. MacMinn, and Bjørnar Sandnes, Frictional fluid instabilities shaped by viscous forces, Nature Communications, 14:3044.

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Modelling and imaging flow in rocks across scales

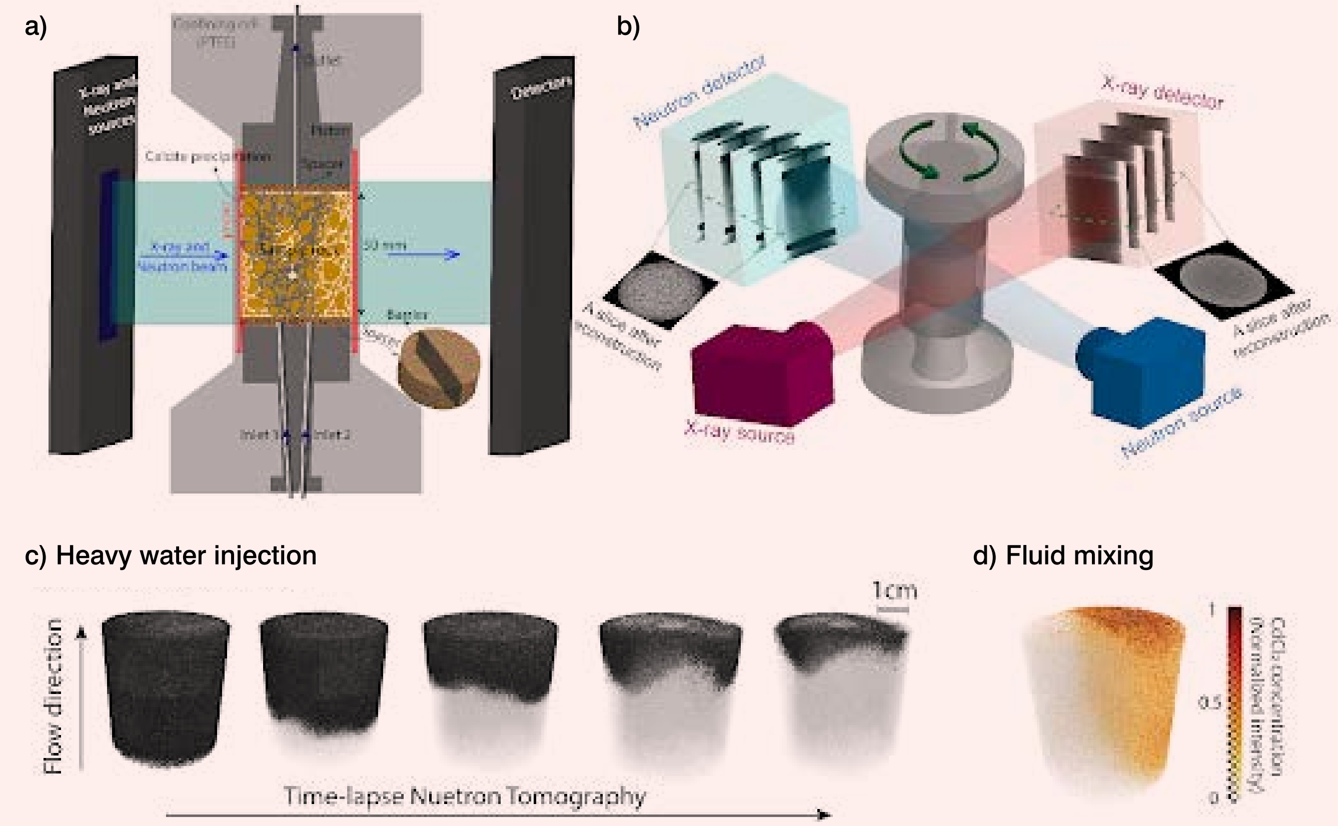
Funding
Akademia agreement between Equinor and the University of Oslo (project MODIFLOW), Swiss National Science Foundation Early PostDoc Mobility fellowship

Participants
Paiman Shafabakhsh[1], Gaute Linga[1,2], Fabian Barras[1,2], François Renard[1], Joachim Mathiesen[1,3], Tanguy Le Borgne[1,4]

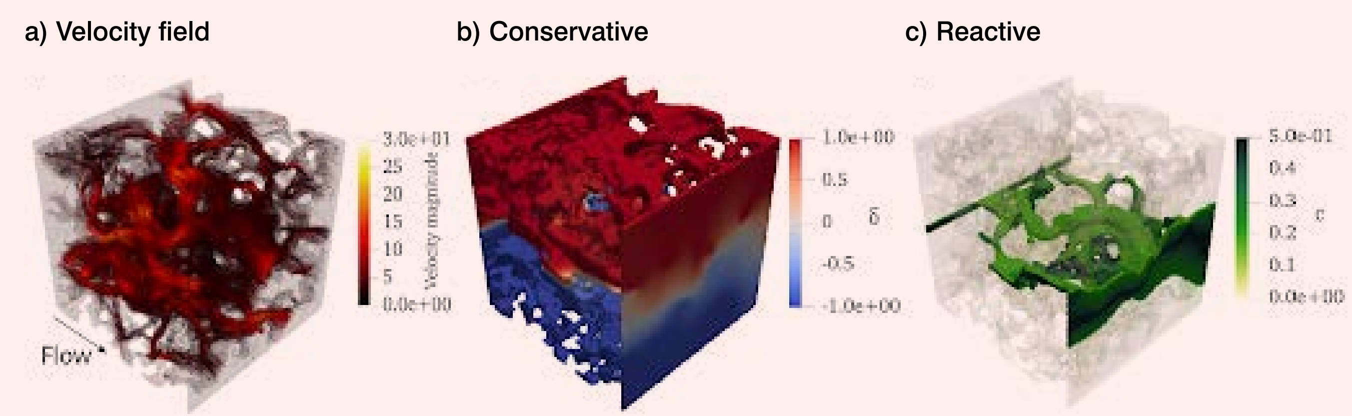
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Niels Bohr Institute, University of Copenhagen, Denmark & Njord Centre
4) Geosciences Rennes, University of Rennes, France & Njord Centre

Understanding the mechanisms of how fluids flow in porous and fractured rocks is of prime importance for many geological processes where fluids are naturally present (earthquakes, landslides, aquifers) or artificially injected in the subsurface, such as in the process of geological carbon storage and the exploitation of geothermal reservoirs. This project tackles the modelling of flows in rocks from the pore to core scales, including the presence of fractures.

An important goal of this project is to better understand how mixing of miscible and immiscible fluids occurs in complex porous solids. We study these questions using lattice Boltzmann, finite element, and particle simulations at the pore scale and combine these numerical simulations with theoretical approaches. We have investigated how the flow intermittency that arises when two phases are flowing concurrently influences how solutes are transported. We found that the dynamic interaction between different phases significantly affects solute transport in complex porous solids, yielding crucial insights for applications in geological processes and subsurface fluid management.



→ Experimental study of fluid flow in porous rock presented in Shafabakhsh et al. 2023. **a)** Schematic of the experimental set-up on beamline ICON at SINQ at Paul Scherrer Institute. **b)** The sample rock is imaged with combined X-ray and neutron tomography. **c)** Neutron tomograms during injection of heavy water (D2O) into porous sandstone. **d)** Neutron tomogram after co-flow injection of D2O and CdCl2 solution to study fluid mixing.



→ Numerical simulation to study reactive mixing on a Berea sandstone sample. **a)** steady-state velocity field obtained by solving Stokes equations. **b)** Distribution of conserved species δ based on the velocity field. **c)** The product c resulting from assuming instantaneous first-order bimolecular reaction kinetics, computed based on the conservative solution.

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Production in highlight

Shafabakhsh, P., Cordonnier, B., Pluymakers, A., Le Borgne, T., Mathiesen, J., Linga, G., Hu, Y., Kaestner, A., Renard, F. (2024) Dynamic neutron imaging of solute transport and fluid flow in sandstone before and after mineral precipitation, Water Resources Research, in revision.

Mathiesen, J., Linga, G., Renard, F., Le Borgne, T. (2023) Dynamic fluid connectivity accelerates solute dispersion in multiphase porous media flow, Geophysical Research Letters, 50, e2023GL105233.

Connectivity enhancement due to thin liquid films in porous media flows

Funding

The Research Council of Norway, NFR Researcher Project for Young Talents. Project number: 102657101, FlowConn.

Participants

Marcel Moura[1,2], Paula Reis[1,2], Knut Jørgen Måløy[1,2], Eirik Grude Flekkøy[1,2], Carl Fredrik Berg[1,3], Renaud Toussaint[1,4], Per Arne Rikvold[1,2]

Affiliation

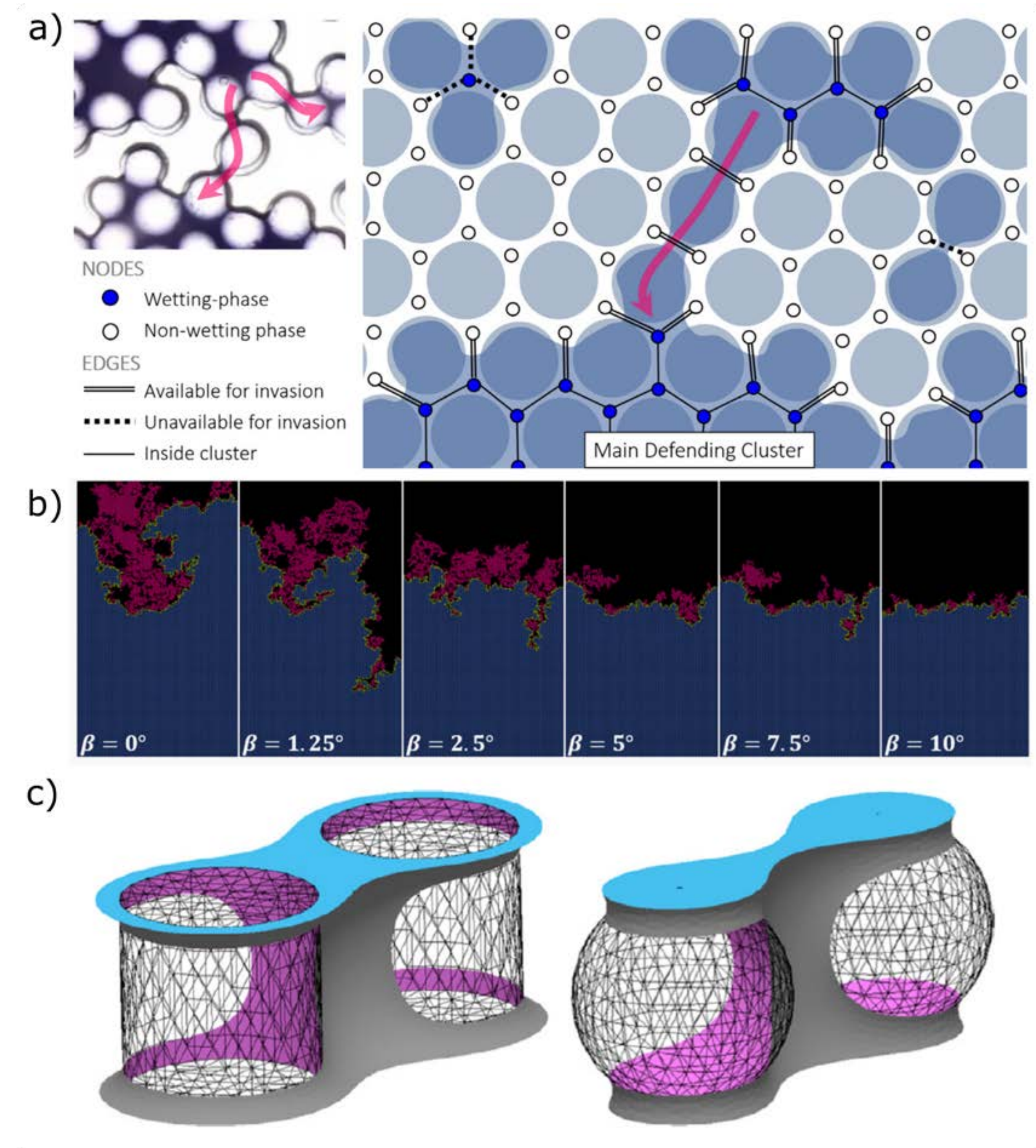
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) PoreLab, Norwegian University of Science and Technology, Norway
4) ITES/Institut Terre et Environnement de Strasbourg, Université de Strasbourg, France

The flow of liquids and gases inside porous networks is a rather common process. It happens for example when rain falls on the soil: as the water moves in, it displaces air from the pores between the soil grains. It is also very important for many industrial and environmental applications related for example to the storage of CO_2 inside depleted oil reservoirs and the remediation of contaminated soils.

In many of those fluid displacement processes, thin layers of liquid are left on the surface of the grains forming the porous network (for example, seemingly dry soils frequently have thin layers of water covering their grains). Those thin layers play a significant role: they can connect distant parts of the system. This effect brings some positive and negative consequences. The enhanced thin film connectivity is used by plants to obtain water and nutrients, but it also provides a pathway for the fast-spreading of pollutants inside the soils. It is very important to understand these effects and this is the primary goal of this project: to produce a physics-grounded explanation for the stability and transport properties of a thin liquid film network in a porous medium. Our investigation is performed via experiments, numerical modeling and theoretical methods.

Our experimental approach is based on the use of custom-built transparent porous samples, where we can directly observe the fluids in the material and map the whole thin film network. The ability to map this network will serve as an input for a new theoretical analysis of the problem, based on solid concepts from network theory (graph theory). On the numerical side, we developed a simplified model for slow drainage in granular materials under gravitational effects, by incorporating liquid-film connectivity on an invasion-percolation model (see Reis et al., 2023). Basically, the idea was to acknowledge that liquid is connected not only by pore bodies and pore throats filled with liquid, but also by pendular rings formed between grains, see Figure 1a). With the proposed model, experimentally observed phenomena related to drainage through films and capillary bridges could be adequately reproduced. Examples are the formation of a limited region for film-induced drainage, and how this region is affected by gravity, as seen in the Figure 1b). Additionally, due to the low computational cost associated with the simulations, we could expand the set of parameters previously investigated with experiments only, and compare results obtained using numerous randomly generated pore-networks representing granular media, which added robustness to the FlowConn project findings.

This was an important step in our quest for a comprehensive understanding of the role of films in the connectivity of liquid in porous-media flows. Currently, a new dynamic pore-network model is under development to describe the same flows, so that we can also investigate the effects of viscous forces on the prevalence of film-induced drainage. A crucial step is the understanding of the shapes of the liquid films and their respective hydraulic conductivities. We are currently studying the properties of these shapes using an algorithm based on energy minimization principles, see Figure 1c). This experimental, analytical and numerical approach allow us to have a much wider understanding of the physics of the problem.



↑ **Figure 1: a)** Thin liquid films and capillary bridges can create new pathways for the transport of fluids in a porous medium (as those shown by the pink arrows), effectively enhancing the overall fluid connectivity of a sample. In the FlowConn project we study the basic physical mechanisms responsible for the transport of fluids through such films. On the right part we show a diagrammatic representation of a pore network model employed in the study, where the film connectivity pathway is again shown by the pink arrow. **b)** Snapshots of the simulations for an increasing tilt angle β with respect to the horizontal plane (increasing gravitational effects). In pink we see the region for film-induced drainage, i.e., the portion of the system connected to the invasion front via the film network developed during drainage in a 2D rectangular porous medium. In each image, liquid is drained from an outlet at the bottom of the rectangle, while air invades the medium from an inlet at the top. In blue we see the portion of liquid connected to the outlet directly by pores bodies and pore throats. The yellow line bordering this region delineates the air invasion front, above which the film network appears. We can notice that, as the effect of gravity becomes larger, the region for film-induced drainage gets smaller. This trend was observed experimentally and is well reproduced by the proposed numerical model. **c)** The shape of thin liquid films is important to determine their hydraulic conductivities. Here we show the result of a study to investigate such shapes using the Surface Evolver software package where the geometry of the solid grains forming the porous medium is either cylindrical or spherical. Figure adapted from Reis et al., 2023.

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Production in highlight

Reis P., Moura M., Linga G., Rikvold P. A., Toussaint R., Flekkøy E. G., Måløy K. J., "A simplified pore-scale model for slow drainage including film-flow effects ," Adv Water Resour. 182, 104580 (2023).

Moura M., Flekkøy E. G., Måløy K. J., Schäfer G. and Toussaint R., "Connectivity enhancement due to film flow in porous media," Phys. Rev. Fluids 4, 094102 (2019).

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3
Part 2

Fracture, Friction and Creep

History-dependent friction

Funding
The Research Council of Norway
EU Horizon 2020 MSCA CoFund

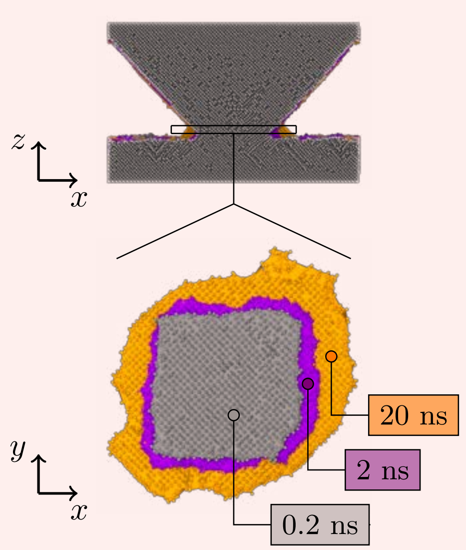
Participants
Henrik Andersen Sveinsson[1], Even Marius Nordhagen[1], Fahimeh Najafi[1], Julien Scheibert[2], François Renard[1], Evangelos Korkolis[1], Anders Malthe-Sørenssen[1]

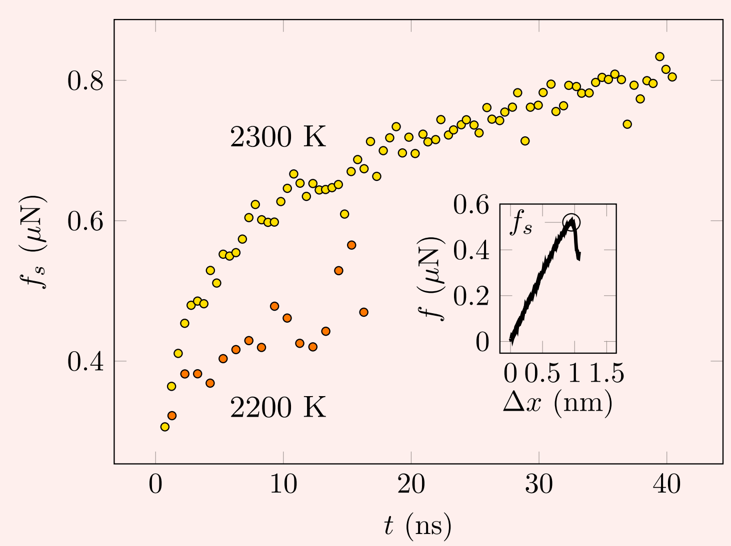
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) CNRS, Laboratoire de Tribologie et Dynamique des Systèmes, Ecole Centrale de Lyon, France

Friction is a topic of huge practical, technological and scientific interest that has challenged mankind for thousands of years. However, it still remains poorly understood, probably due to the inherent multi-scale and multi-physics nature of processes at the frictional interface. The empirical laws of friction were introduced by Amontons and Coulomb, and later refined into the rate and-state friction law, which is commonly used today. The rate-and-state friction law states that the coefficient of friction depends on the rate – on how fast the surfaces are moving relative to each other – and the state – how long the surfaces have been in contact and under what conditions. However, we have recently made a startling discovery: The coefficient of friction may also strongly depend on the history of the frictional contact, on how the two surfaces stopped relative to each other, changing the research focus from detachment to reattachment. In this project we will address how to reformulate the laws of friction to include the history of the contact – a history-dependent law of friction. We will determine under what circumstances history-dependent friction is important, develop a theory for history-dependent friction, test and apply this theory on atomic-, meso- and macroscopic scales and apply it to key problems in glaciology and geoscience.

On the atomic scale, we have developed a model for a silicon carbide asperity under conditions where aging takes place on the nanosecond timescale. We are establishing how the area of frictional contacts grows through time, and how this in turn affects the frictional properties. The static friction is not necessarily proportional to the contact area. Moreover, we look at how the velocity-history affects the static friction under various temperatures, normal pressures, and crystal orientations. We are also creating more complex surfaces using simplex noise and use neural networks to perform an accelerated search for surfaces with some prescribed behavior such as high or low friction.

↓ Contact area evolution for a single silicon carbide asperity. The effective contact area grows with contact time. The contact area increase seems to be driven by capillary forces to minimize the surface free energy. The mechanism can be modeled based on the theory of volume-conserving chape changes in faceted crystals.





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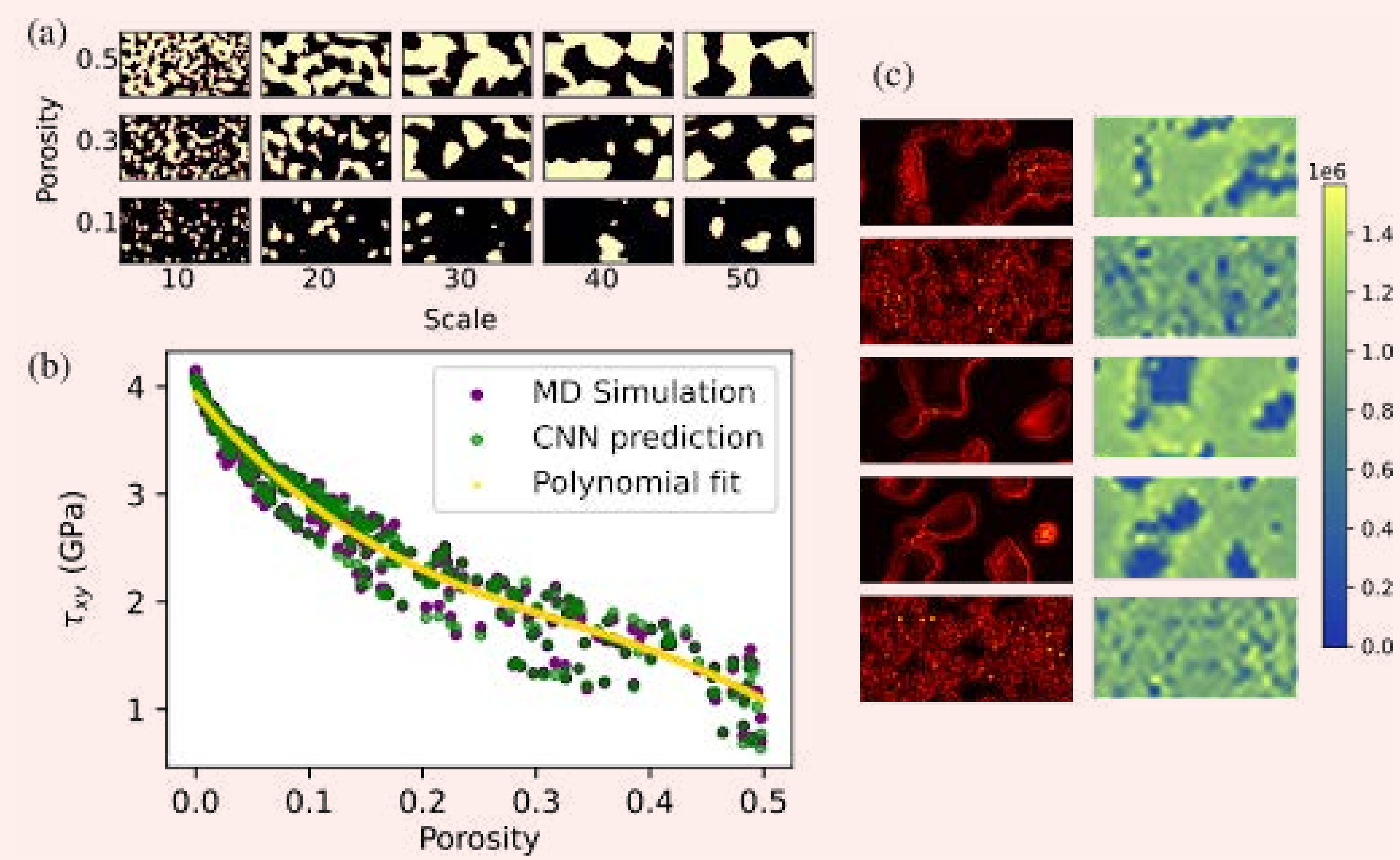


↑ (a) α-quartz blocks with a weak porous layer, i.e. randomly created defects, with different geometries over different scales and porosities.
(b) We found the mechanical strength of these defected blocks using molecular dynamics simulations. Next, we used the structure of the porous layers and the yield stress as the features and labels to train a convolutional neural network. We established that a CNN can predict the yield stress of these systems based on the geometry of the defects. This trained CNN can capture the effect of geometry on yield stress beyond the correlation of porosity with yield stress. Using an active learning algorithm to select more informative data for the training set iteratively, we could improve the training process.
(c) Saliency maps created with the trained model show that the model predictions are most sensitive to altering structures near high-stress regions, when compared with von-Mises stress fields, indicating that the model makes predictions based on reasonable physics.

Production in highlight
E. M. Nordhagen, H. A. Sveinsson, and A. Malthe-Sørenssen, *Diffusion-Driven Frictional Aging in Silicon Carbide*, Tribol Lett **71**, 95 (2023).

F. Najafi, H. A. Sveinsson, C. Dreierstad, H. E. B. Glad, and A. Malthe-Sørenssen, *Modeling the Relationship between Mechanical Yield Stress and Material Geometry Using Convolutional Neural Networks*, Applied Physics Letters **123**, 111601 (2023).

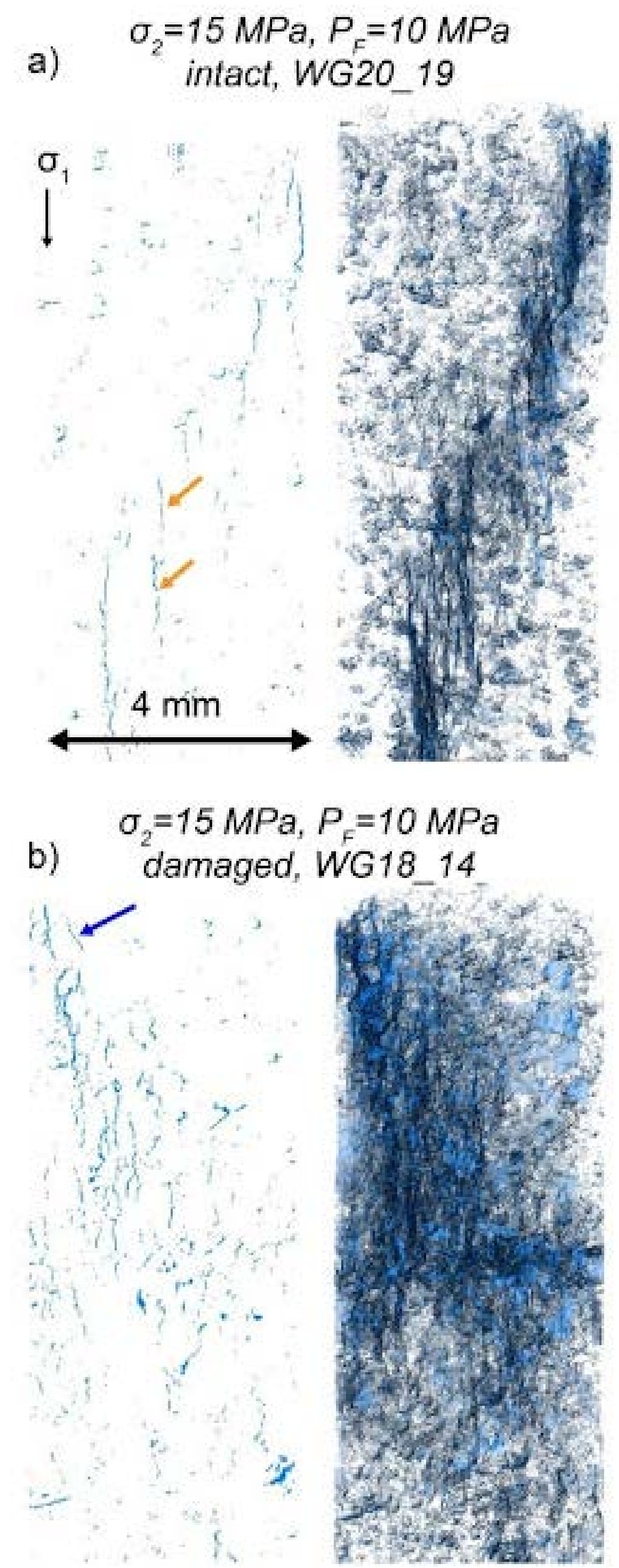
Emergent networks

Funding
The Research Council of Norway, U.S. Department of Energy

Participants
Jess McBeck[1], Francois Renard[1], Yehuda Ben-Zion[2], Xiaoyu (Bruce) Zhou[2], John Aiken[1], Joachim Matheisen[3], Michele Cooke[4], Laura Fattaruso[4]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) University of Southern California and the Southern California Earthquake Center, USA
3) University of Copenhagen, Denmark
4) University of Massachusetts Amherst, USA

How can we estimate the timing of the next large earthquake? The ability to estimate when the next large earthquake will occur at a particular location (i.e., Los Angeles) would provide immediate societal and economic benefits. Observations of natural, crustal earthquakes, and laboratory earthquakes indicate that the precursory processes tend to accelerate in activity leading up to the dynamic, macroscopic, system-scale failure of a system. This project aims to quantitatively describe and characterize these precursory processes that signal the onset of earthquake preparation. Following the characterization of these processes in laboratory experiments, the project aims to predict the timing of laboratory and crustal earthquakes using machine learning. Following the development of successful machine learning models that predict the timing of earthquakes, the project will examine which characteristics of fracture networks and strain fields provide the greatest predictive power of the timing of earthquakes. The project will then use numerical models to examine how the processes identified at the laboratory scale with fine temporal and spatial resolution may up-scale to the processes operating at the km-scale within natural tectonic systems, such as the San Andreas fault in California.



→ Two-dimensional slices and three-dimensional volume renderings of fractures identified in X-ray tomography scans of experiments performed on intact **(a)** and damaged granite **(b)** with confining stress, σ_2=15 MPa, and fluid pressure, P_F=10 MPa, at 99.9% of the differential stress at macroscopic failure. The largest fractures develop parallel to the direction of the maximum compression direction, σ_1, indicative of extensile-dominated deformation (orange arrows in a). Some fractures are aligned more obliquely to the direction of σ_1, indicative of shear-dominated deformation (blue arrow in b). From McBeck et al. (2023) Nature Communications Earth & Environment.

Production in highlight
E. M. Nordhagen, H. A. Sveinsson, and A. Malthe-Sørenssen, *Diffusion-Driven Frictional Aging in Silicon Carbide*, Tribol Lett **71**, 95 (2023).

F. Najafi, H. A. Sveinsson, C. Dreierstad, H. E. B. Glad, and A. Malthe-Sørenssen, *Modeling the Relationship between Mechanical Yield Stress and Material Geometry Using Convolutional Neural Networks*, Applied Physics Letters **123**, 111601 (2023).

Break-through rocks

Funding

The European Research Council, Advanced Grant (project ERC BREAK)

Participants

François Renard[1], Benoît Cordonnier[2], Erina Prastyani[1], Jean-Baptiste Jacob[1], Kristina Dunkel[1], Luca Menegon[1], Jessica Ann McBeck[1], Fabian Barras[1], Yehuda Ben-Zion[3], Mai-Linh Doan[4], Jerome Weiss[4], Wenlu Zhu[5], Daniel Eakins[6]

Affiliation

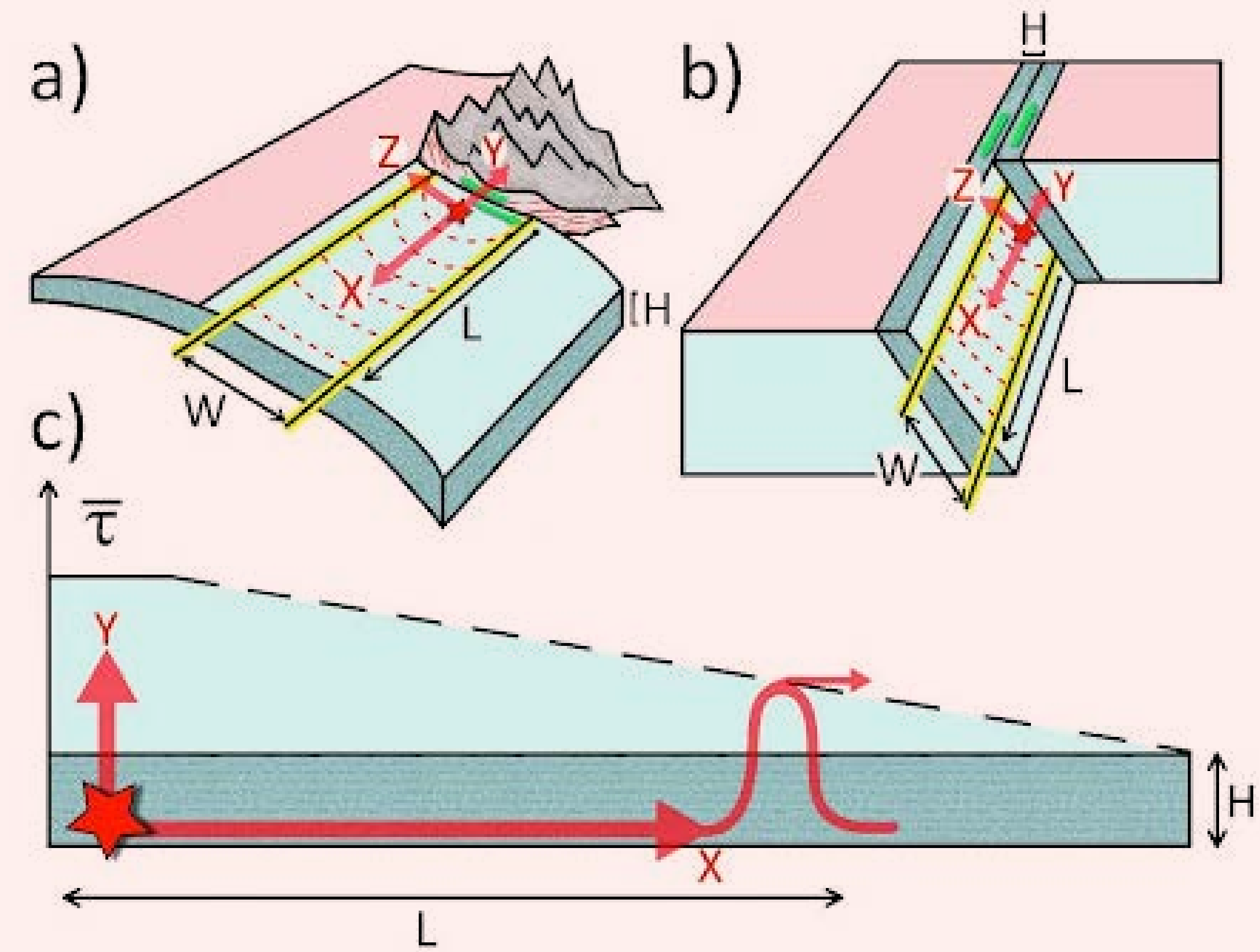
1) The Njord Centre, University of Oslo, Norway
2) The European Synchrotron Radiation Facility, Grenoble, France
3) University of Southern California, USA
4) University Grenoble Alpes, France
5) University of Maryland, USA
6) University of Oxford, UK

Deformations in the Earth's crust can localize onto faults that may rupture rapidly producing earthquakes or undergo slow aseismic slip. The detailed mechanisms that control the transition between the seismic and aseismic regimes and the onset of earthquakes remain unknown. These mechanisms control the geophysical processes preceding catastrophic failure, such as fracture development and strain localization on faults and in the rock volumes surrounding them. The main goal of BREAK is to provide quantitative laboratory observations of the full displacement field in rocks before and during fault slip and separate the aseismic and seismic components of it. The project relies on a joint-collaboration between the Njord Centre at the University of Oslo and the European Synchrotron Radiation Facility (ESRF) in Grenoble.

The two main approaches are:

1. Develop a new rock deformation apparatus, ZEUS, that couples dynamic X-ray imaging and acoustic emission monitoring to study the earthquake preparation process in dry and wet rocks.
2. Unravel the microstructures of dynamic rupture and slip in faults, residual strain, and the effects of water during and between earthquakes.

We use the results obtained in these experiments and observations of microstructures in natural fault rocks to validate numerical and data driven models of the processes that occur as the accumulation of elastic energy drives faults towards rupture. The overarching goal is to progress toward a general model of the path to brittle failure in rocks by advancing knowledge of how fractures accumulate before and during both slow and fast earthquakes, under dry conditions, and in the presence of water. In 2023, we have continued the experimental programme of the project by performing shock experiments on rocks, measuring residual strain under confinement in rocks, and performing a series of experiments to image the brittle-ductile transition in Carrara marble. In parallel, we have progressed on a new minimal model of earthquakes to unravel the mechanisms of rupture arrest and on the experimental and numerical modelling on how fracture networks evolve toward system-size failure.



↑ A minimal model to study the arrest of frictional ruptures arising along two types of plate boundaries (Barras et al., 2023).

Production in highlight

Bouchon, M., Guillot, S., Marsan, D., Socquet, A., Jara, J., Renard, F. (2023) Observation of a synchronicity between shallow and deep seismic activities during the foreshock crisis preceding the Iquique megathrust earthquake. Seismica, 2(2), https://doi.org/10.26443/seismica.v2i2.849.

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McBeck, J., Cordonnier, B., Ben-Zion, Y., and Renard, F. (2023) The influence of confining stress and preexisting damage on strain localization in fluid-saturated crystalline rocks in the upper crust, Journal of Geophysical Research: Solid Earth, 128, e2023JB026987.

Barras, F., Thøgersen, K., Aharonov, E., Renard, F. (2023) How do earthquakes stop? Insights from a minimal model of frictional rupture, Journal of Geophysical Research: Solid Earth, 128, e2022JB026070.

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Conditions for earthquake nucleation in the lower crust

Funding
The Research Council of Norway (FRIPRO), project CONTINENT.

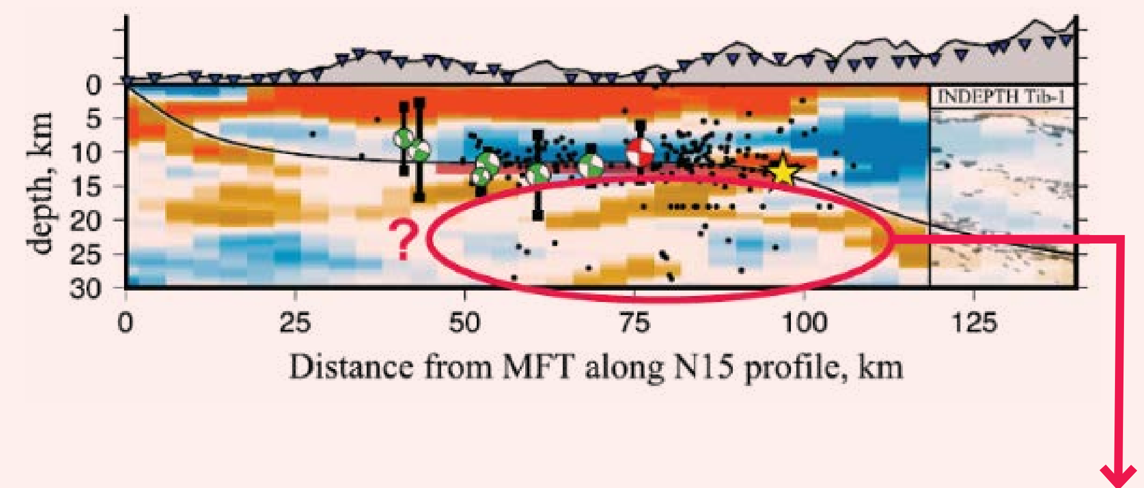
Participants
Luca Menegon[1], Stephen Michalchuk[1], Hugo van Schrojenstein Lantman[1], Francois Renard[1], Bjørn Jamtveit[1], Kristina Dunkel[1], Dani Schmid[1], Luiza Angheluta-Bauer[1], and various international collaborators

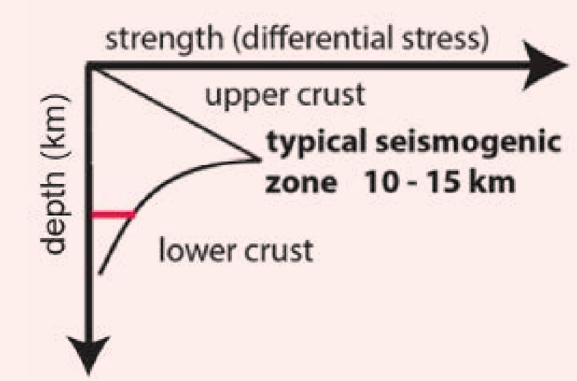
Affiliation
1) The Njord Centre, University of Oslo, Norway

Earthquake initiation within the deep crust requires very high stresses (at the gigapascal, GPa, level), which are not expected elsewhere in the Earth's crust. This requirement contrasts with the current models of continental lithospheric deformation, which typically favour a distributed flow of weak viscous lower crust. Such flow would limit the capability of rocks to build up the high stresses necessary for seismic brittle failure (see Figure). Several mechanisms have been proposed to generate these unusually high stresses, but direct measurements are lacking. Furthermore, seismic slip (producing pseudotachylytes: quenched frictional melt) may trigger fluid infiltration, weakening, and a transition to viscous creep (producing mylonites during post- and interseismic creep) along faults initially characterized by frictional melting and wall-rock damage. However, is the resulting weakening long-lived or short-lived, and what does it depend on?

The project CONTINENT, funded by the RCN, started in August 2023, and aims to understand the state of stress of seismogenic faults in the lower crustal. We propose to achieve this goal using high-angular resolution electron backscatter diffraction (HR-EBSD) coupled to numerical models of stress distribution in lower-crustal fault systems. We will use HR-EBSD to measure the residual stress retained in mineral grains that experienced seismic deformation in single-rupture seismogenic faults exhumed from the lower crust and use the measurements to inform numerical models of stress distributions in lower-crustal fault networks. Furthermore, we aim to identify the mechanisms controlling the cyclical switches from aseismic to seismic behaviour in lower-crustal shear zones. We suspect that such switches reflect progressive hardening of the shear zones, and we will test this hypothesis by combining nanoindentation experiments with modelling of low-temperature plasticity and dislocation interactions in mineral grains subjected to stress variations.

Our preliminary results indicate that (1) intragrain residual stress heterogeneities at the GPa level are preserved in seismically shocked minerals and result from unrelaxed crystal defects that are generated during the earthquake rupture propagation (Toffol et al., in revision), and (2) earthquake-induced weakening of the lower crust is intermittent and occurs only when a fluid can infiltrate a transiently permeable shear zone, thereby facilitating diffusive mass transfer and creep (Michalchuk et al., 2023).





Distribution of aftershocks (black dots) of the 2015 Gorkha earthquake in Nepal (yellow star), and relationships with the main current model of crustal strength. Viscous flow in the lower crust would limit the capability of rocks to build up the high stresses necessary to nucleate earthquakes in the lower crust (red ellipse). Modified from Duputel et al. (2016). MFT = Main Frontal Thrust.

Production in highlight

Toffol, G., Pennacchioni, G., Menegon, L., Wallis, D., Faccenda, M., Camacho, A., Bestmann, M. On-fault earthquake energy density partitioning from shocked garnet in an exhumed seismic mid-crustal fault. *In revision, Science Advances.*

Michalchuk, S.P., Zertani, S., Renard, F., Fusseis, F., Chogani, A., Plümper, O., Menegon, L., 2023. Dynamic evolution of porosity in lower-crustal faults during the earthquake cycle. *Journal of Geophysical Research: Solid Earth*, 128, e2023JB026809.

Dynamics of volcanic plumbing systems

Funding
The Research Council of Norway (Beyond Elasticity), The MatNat Faculty (EarthFlows)

Participants
Olivier Galland[1], Luca Menegon[1], Andreas Carlson[2], Sonja Greiner[3], Freysteinn Sugmundsson[3], Steffi Burchardt[4]

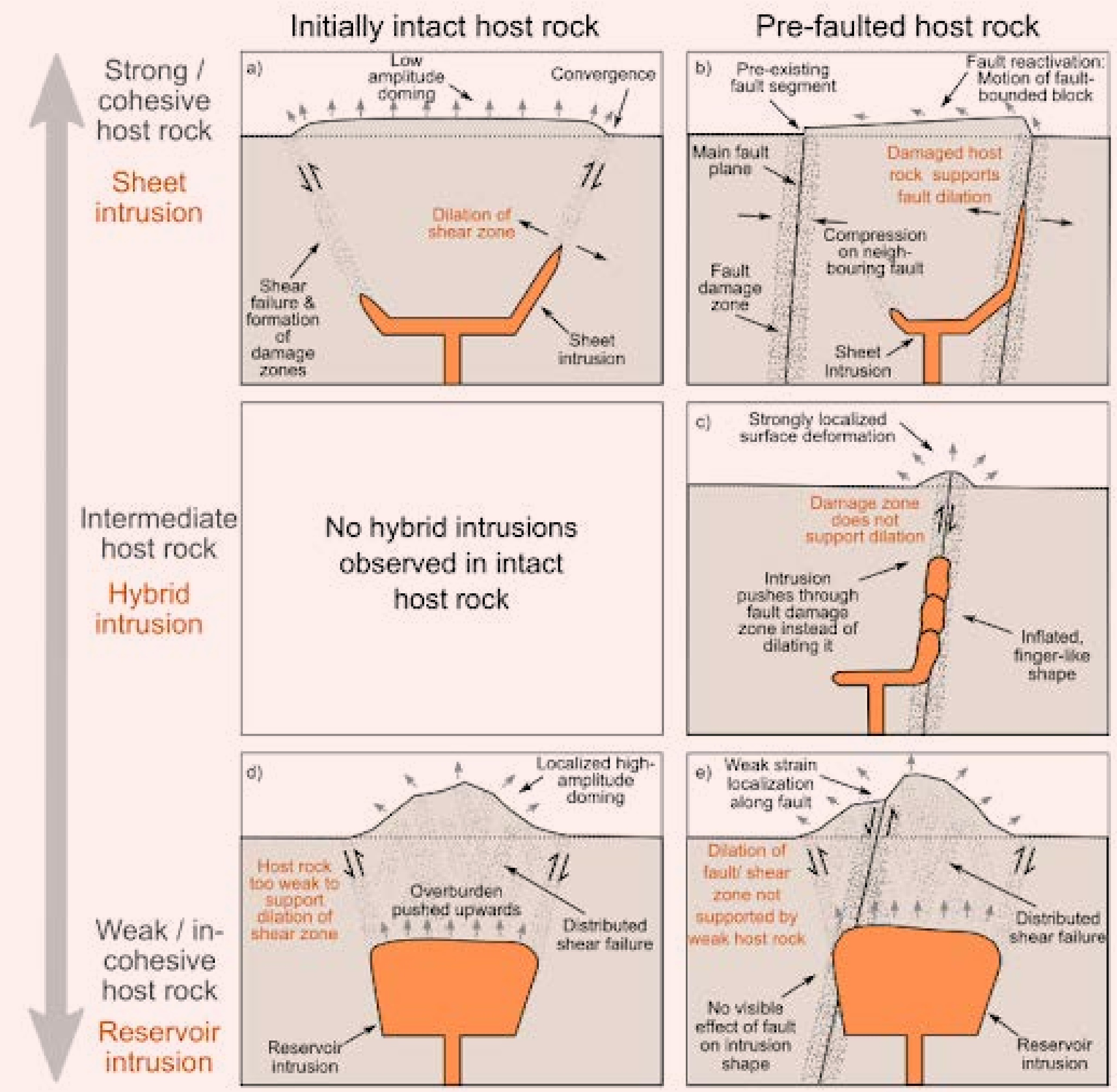
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) Mathematics department, University of Oslo, Norway
3) University of Iceland
4) Uppsala University, Sweden

Understanding the dynamics of volcanoes' roots is of paramount importance to predict volcanic eruptions, assess volcanic hazards, and explore for natural resources (geothermal, ore deposits, hydrocarbons) associated with active and ancient volcanoes. The main conduits transporting magmas in volcanic plumbing systems exhibit planar, sheet shapes, such as vertical dykes and horizontal sills. The current paradigm of sheet intrusion emplacement in based on the Linear Elastic Fracture Mechanics (LEFM) theory, which states that they propagate by tensile opening and elastic bending of the host rock, like a crack. However, geological observations show that a fundamentally distinct mechanism, so-called viscous indenter, can control the propagation of igneous sheet intrusions, where the intrusion tip indents the host rock that fails by compressional inelastic deformation. Even if both mechanisms have been documented, first-order questions remain unsolved. Are they two end-member propagation mechanisms or are there intermediate regimes combining them? In which geological environments do the LEFM and viscous indenter propagation mechanisms occur? And in general, what are the effects of inelastic deformation on volcano-tectonic processes, such as caldera collapse?

To address these questions, this project addresses the following topics related to volcanic plumbing systems:

- Field structural geology and laboratory modelling of the structural control of pre-existing fractures on magma emplacement (Greiner et al., 2023; in preparation);
- The effects of viscoelastic properties of rocks and magma on the dynamics of sill and laccolith emplacement (Sæter et al., 2023);
- The effects in Mohr-Coulomb layering on the structure and onset of caldera collapse (Reutz and Galland, 2023).
- Laboratory modelling of the structural control of layering on dyke emplacement (Wen et al., in preparation).

Galland is the PI of a funded FRIPRO Research-er project to be implemented in 2024-2028. The aim of this project is to establish novel mechanical understanding of dyke and sill emplacement that reconciles the LEFM theory and the viscous indenter model.



↑ Conceptual model of intrusion regimes in strong host, intermediate and weak host rock with intact and pre-faulted host rock. From Greiner et al. (in preparation).

Production in highlight

Reutz, E., Galland, O., 2023, The effect of weak layers on the onset of caldera collapse – Insights from limit analysis modelling. Journal of Volcanology and Geothermal Research, doi: https://doi.org/10.1016/j.jvolgeores.2022.107727

Sæter, T., Galland, O., Feneuil, B., Carlson, A., 2023, Growth of a viscoplastic blister underneath an elastic sheet. Journal of Fluid Mechanics, v. 964, p. A7.

Greiner, S. H. M., Burchardt, S., Sigmundsson, F., Galland, O., Geirsson, H., 2023, Interaction between propagating basaltic dykes and pre-existing fractures, Journal of Volcanology and Geothermal Research, v. 442, p. 107891.

Greiner, S. H. M., Galland, O., Sigmundsson, F., Burchardt, S., Geirsson, H., Pedersen, R., in preparation. Laboratory modelling of magma-fault interactions, Journal of Geophysics Research.

Wen, X., Galland, O., Guldstrand, F., Body, N.S. – Dynamics of dyke emplacement in the layered brittle crust. In prep. for Earth and Planetary Science Letters.

The impact of volcanism on petroleum systems

Funding
Department of Geosciences (Småforsk), The MatNat Faculty (EarthFlows), Chevron Argentina

Participants
Olivier Galland[1], Ole Rabbel[1], Dougal Jerram[2], José Mescua[3], Octavio Palma[4], Daniel Yagupski[5], Ezequiel Lombardo[5], Héctor Villar[6], Juan Spacapan[7], Hans Jørgen Kjøll[8], Kim Senger[9], Anna Sartell[10]

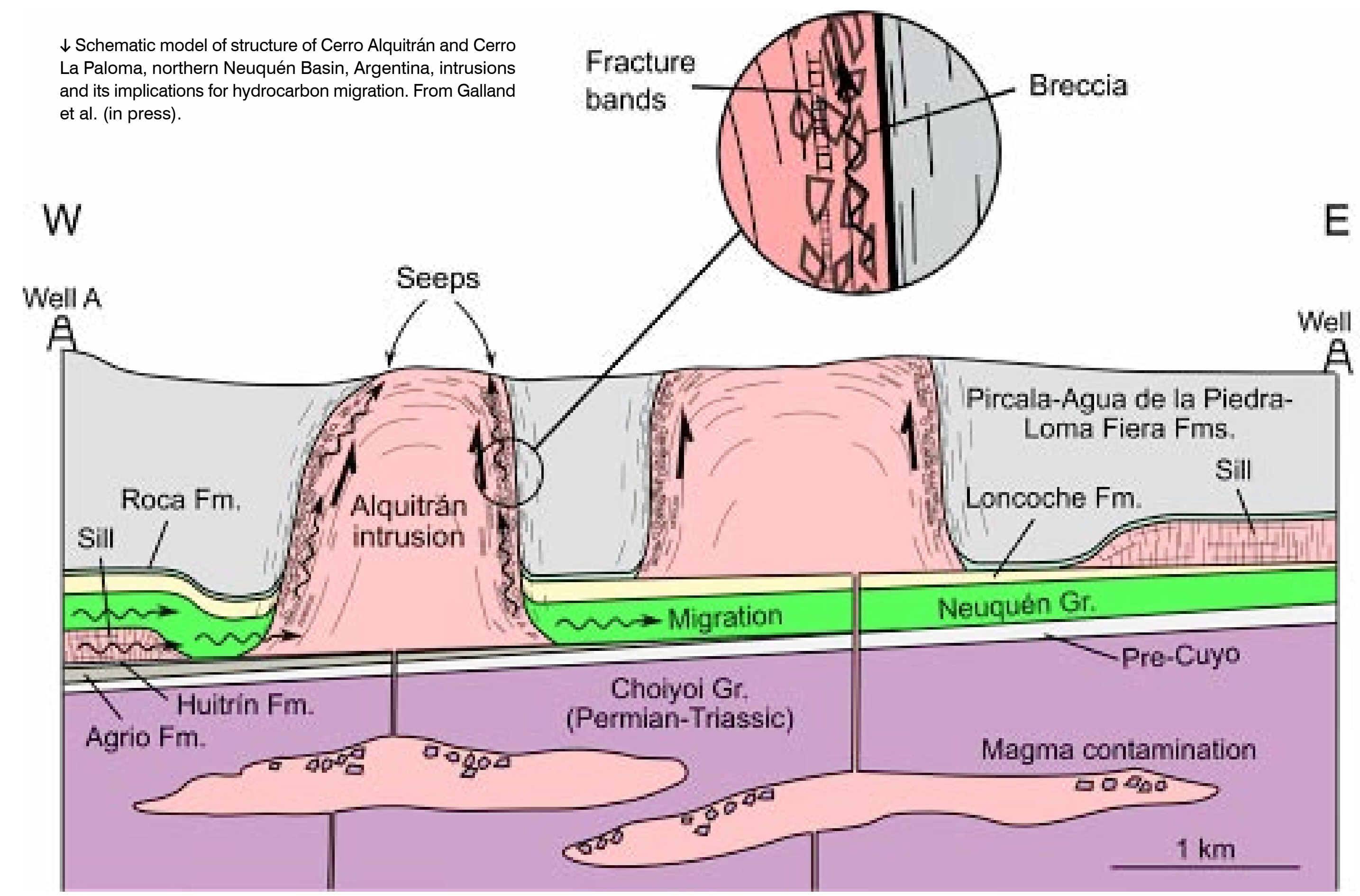
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) DougalEarth Ltd., UK
3) CONICET Mendoza, Argentina
4) Y-TEC, Argentina
5) University of Buenos Aires, Argentina
6) GeoLab Sur, Argentina
7) YPF, Argentina
8) University of Oslo, Norway
9) UNIS, Svalbard
10) University of Helsinki, Finland

Emplacement of magma has led to the development of extensive networks of igneous intrusions in the subsurface of many sedimentary basins worldwide. These intrusions commonly occur as (1) layer-parallel and transgressive sills, (2) saucer-shaped intrusions, (3) layer-discordant sub-vertical dykes, (4) domed intrusions such as laccoliths, and (5) localized volcanic centers. Both dykes and sills form contact metamorphic aureoles caused by localized heating of the adjacent host rock. Moreover, in addition to subsurface emplacement, significant volumes of magma may have reached the surface, resulting in volcanic activity with significant volumes of extrusive lava flows covering the volcanic plumbing system. There are several examples of hydrocarbon fields associated with igneous rocks around the world. For instance, hydrocarbons are currently produced commercially from fractured igneous intrusions in the Argentinian Neuquén basin. Besides forming reservoirs, igneous intrusions may be emplaced at a wide range of burial depths, affecting all basic elements of the petroleum, such as basin-scale permeability architecture and trapping structures.

Numerous aspects of the influence of volcanic and subvolcanic systems on basin evolution remain poorly known. In this project, mainly through geological study in the Neuquén Basin, Argentina, and in Svalbard, we address the following aspects:

- The development of a structural trap associated with doming structure induced by the emplacement of a volcanic plumbing system (Lombardo et al., in press);
- The effect of magma cooling and fracturing on basin-scale fluid circulations (Rabbel et al., 2023);
- The long-term effects of solidified igneous intrusions on fluid migrations (Galland et al., 2023; in press);
- The thermal and structural impacts of an intrusive complex on hydrocarbon generation, migration and storage (Palma et al., in press);
- The anatomy of large sills emplaced in carbonates and their associated contact metamorphism (Galland et al., in preparation; Kjøll and al., in preparation).

↓ Schematic model of structure of Cerro Alquitrán and Cerro La Paloma, northern Neuquén Basin, Argentina, intrusions and its implications for hydrocarbon migration. From Galland et al. (in press).



Production in highlight

Galland, O., Mescua, J., Villar, H. J., Medialdea, A., Zanella, A., Leanza, H. A., Jerram, D. A., and Planke, S., 2023, An igneous conduit erupting petroleum: the Cerro Alquitrán, Neuquén Basin, Argentina. *Basin Research*, v. 35, no. 5, p. 1840-1855.

Rabbel, O., Galerne, C., Hasenclever, J., Galland, O., Mair, K., Palma, J.O., 2023, Importance of permeability evolution in igneous sills for hydrothermal flow in volcanic basins. *Solid Earth*, v. 14, no. 6, p. 625-646.

Galland, O., Villar, H.J., Mescua, J., Augland, L.E., Jerram, D., Medialdea, A., Midtkandal. I., Palma, J.O., Planke, S., Augland, L.E., Zanella, A., in press, Structural control of igneous intrusions on fluid migrations: the case study of bitumen seep at Cerro Alquitrán and Cerro La Paloma, northern Neuquén Basin, Argentina. In: The Impacts of Igneous Systems on Sedimentary Basins and Their Energy Resources, Eds: B. Kilhams, D. Watson and S. Holford, *Geological Society, London, Special Publications.*

Lombardo, E., Galland, O., Yagupsky, D., Jerram, D., in press, The volcanic origin of the structural trap of El Trapial oil field, Cerro Bayo de la Sierra Negra volcanic complex, Neuquén province, Argentina. In: The Impacts of Igneous Systems on Sedimentary Basins and Their Energy Resources, Eds: B. Kilhams, D. Watson and S. Holford, *Geological Society, London, Special Publications.*

Galland, O., Horota, R., Sartell, A., Kjøll, H. J., Runge, J., Midtkandal, I., Senger, K., in preparation. 3-dimensional structure of a large mafic sill: the case study of James I Land, Central Spitsbergen, Svalbard. Geochemistry, Geophysics, Geosystems.

Constraining peridotite alteration rates with AI

Funding
The Research Council of Norway, project SerpRateAI.

Participants
John M. Aiken[1,2], Elliot Dufornet[1], Robert Sohn[3], Oliver Plümper[4], Hamed Amiri[4], Lotta Tierneten[5]

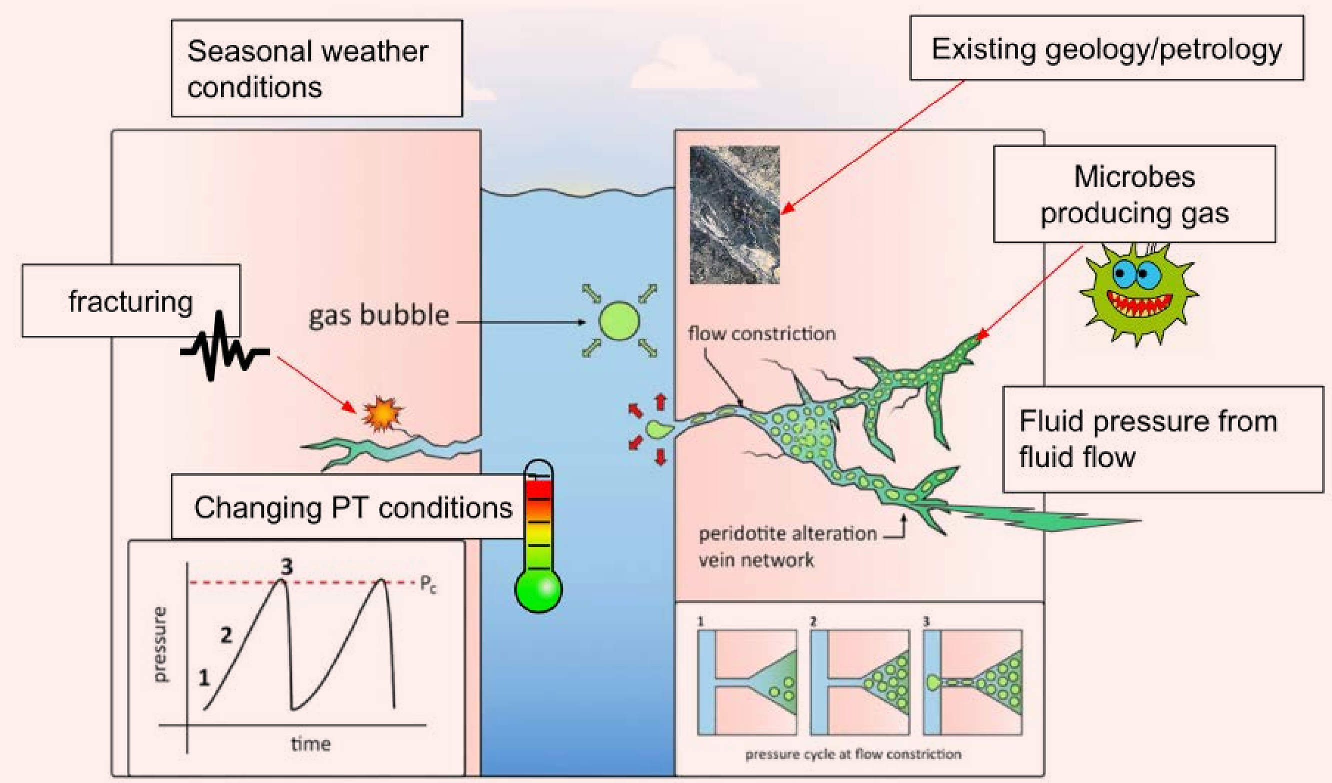
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) Expert Analytics
3) Woods Hole Oceanographic Institution USA
4) Department of Geosciences, Utrecht University, The Netherlands
5) NIOZ, Royal Netherlands Institute for Sea Research, The Netherlands

Climate change is having lasting effects such as changing ocean acidity, temperatures, and heights, increasing the chances of natural hazards such as forest fires and hurricanes, and leading to the disappearance of water sources supplied by glaciers and snow. Carbon dioxide (CO_2) produced by humans is a primary contributor to man-made climate change thus finding storage mechanisms for human produced CO_2 is necessary to mitigate climate change. Mantle rocks, like peridotite, offer a storage option for CO_2: In the presence of water, peridotite will alter into new kinds of rocks. If CO_2 is present in the water this CO_2 will be stored as a solid in the rocks, keeping it trapped underground over long timescales. Currently, this chemical alteration process is well understood; however, the physical process that allows water to reach unaltered peridotite is not. SerpRateAI will discover the physical processes that allow water to be pumped underground to understand how peridotite alters. Ultimately, we will produce natural alteration rates, i.e., how fast the rock changes over time. This can be used to estimate how much CO_2 we can store in a region. Given that mantle rocks like peridotite are common, this could feasibly be used to store a large fraction of human produced CO_2.

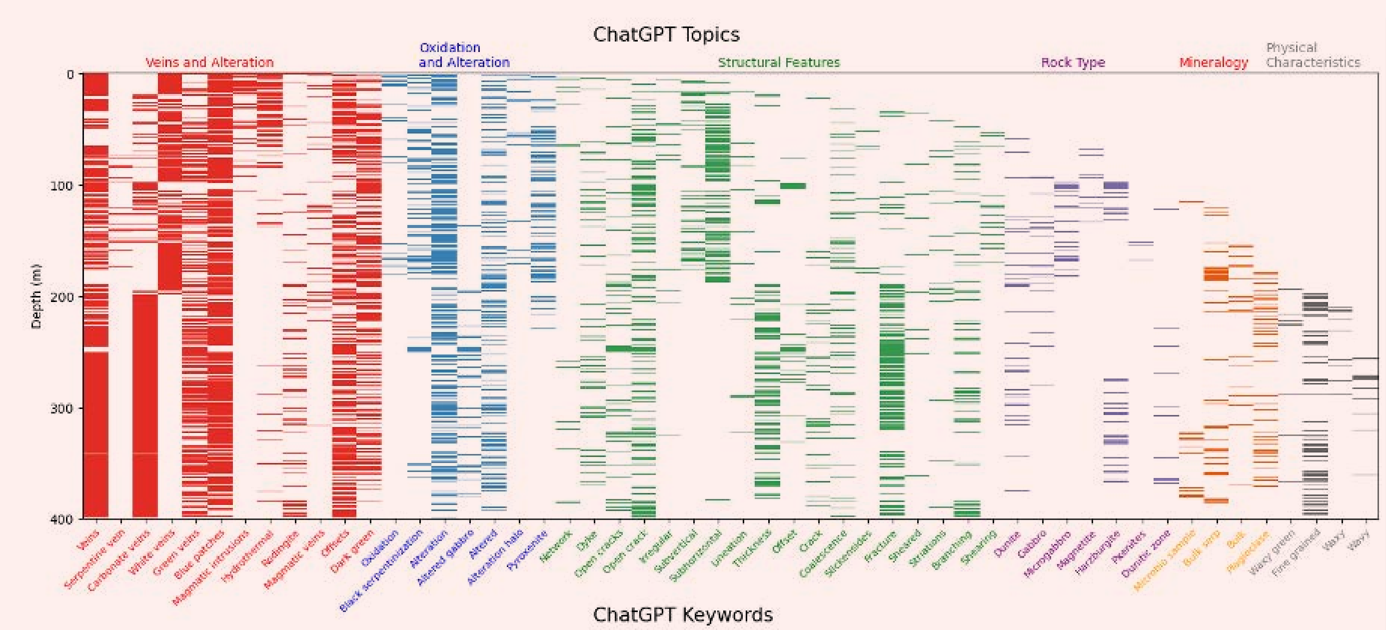
We have three step approach:

- Work Package 1: Build time series data sets from acoustics, temperature, pressure, and other loggers deployed into the multi-borehole observatory to explore multiphase fluid flows, cracking events, and other phenomena.
- Work Package 2: Build depth wise database of geological features found in the multi-borehole observatory including a fracture network database for cored boreholes, summarization of expert reports, and other physical, chemical, and biological measurements to better characterize alteration and it's covariates.
- Work Package 3: Build artificial intelligence (AI) / machine learning (ML) models that analyse and understand ongoing processes such as carbonation, fluid migration, and cracking.

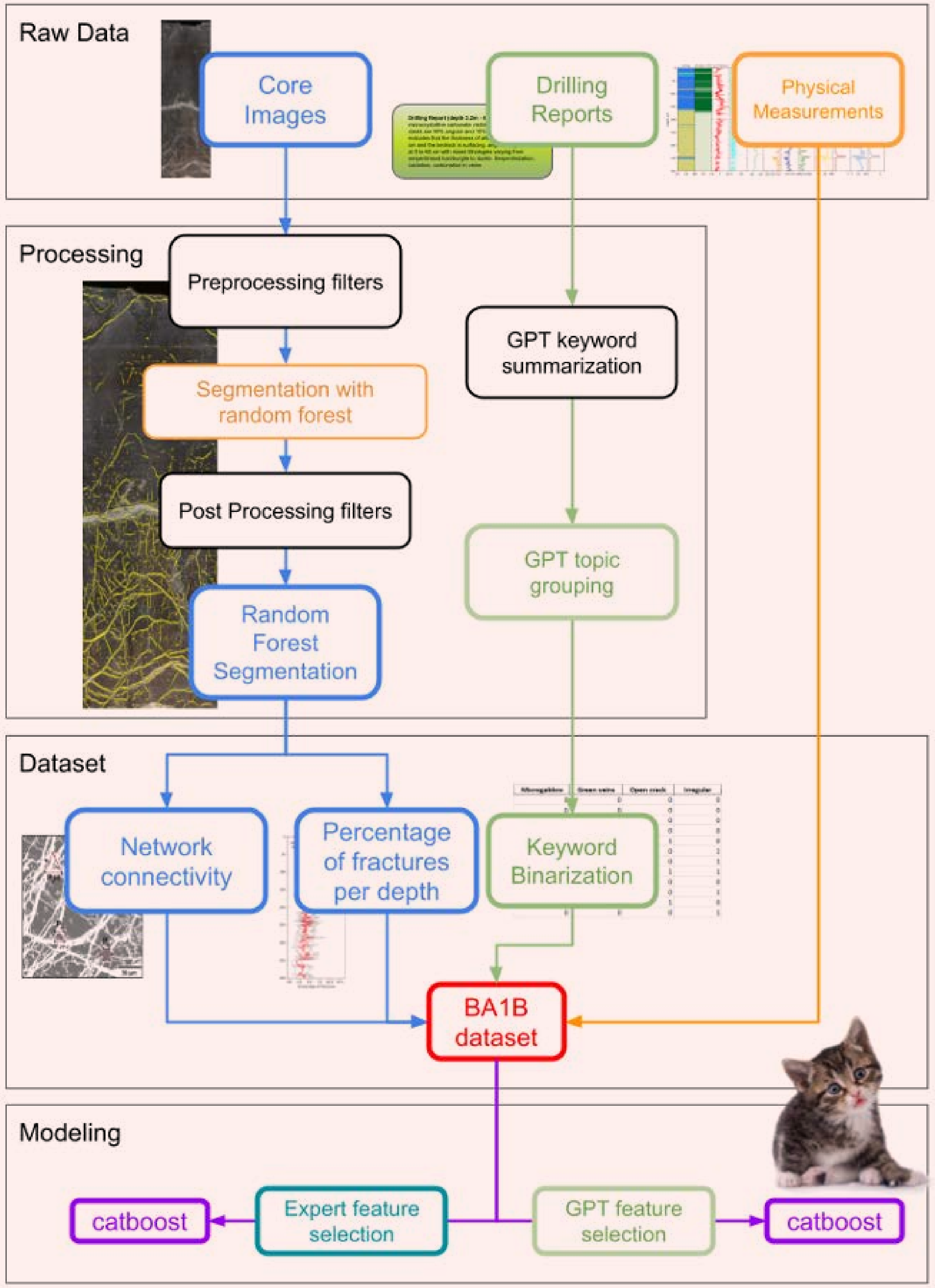
During his internship at Njord, Elliot Dufornet worked on the following project: Researchers analyzing data collected from borehole drilling projects can be faced with dozens of terabytes of seismic, hydrologic, geologic, and rock mechanics data, including complex imagery, physical measurements and expert written reports. These diverse data sets play a pivotal role in our understanding of solid earth processes. Ingesting and analysing such data presents a colossal challenge that typically demands a team of experts. The utilization of AI and ML emerges as a compelling approach to help tackle the volume and complexity of drilling data. This paper presents an AI based pipeline for ingesting data from the Oman Drilling Project's Multi-borehole Observatory. The study focuses on the alteration of peridotite core segments taken from Borehole BA1B, utilizing a catboost classification model trained on an integrated data set of machine learning segmented core images, physical measurements, geological, lithographic data, and AI →



↑ Different physical processes that could lead to acoustic emissions in the Oman multi-borehole observatory.



↑ Depth dependent keywords identified by ChatGPT within the drilling reports written by field geologists.



↑ An AI-enabled pipeline for ingesting drilling report data.

summarized expert texts and feature selection. This paper's central objective is to establish a repeatable, efficient pattern for processing such multifaceted borehole data, while also addressing the critical research question of the impact of non-tectonic fracturing on peridotite alteration.

Drilling expeditions generally produce at least three kinds of raw data: Images taken from borehole cores, drilling reports written by expert geologists identifying various features of each meter of core that comes from the borehole, and physical, chemical, and biological measurements taken using various kinds of equipment inside the borehole. Raw images have their fractures segmented using a random forest classifier trained on hand labeled fracture data.

Raw wrap-around core images are first pre-processed using a Gaussian, Hessian, Roberts, and Sobel edge enhancing filters. This flattens differences in color content of the image, highlights abrupt changes in edges, making it ultimately easier to pick out fracture veins. Twenty images taken from 20 m segments distributed depthwise along the borehole were then labeled using the Ilastik software. We then used the built-in random forest algorithm within Ilastik to label the remaining 485 images. We drop all labeled pixel groupings with less than 50 pixels. We then apply a post-processing eccentricity filter to remove small round erroneously labeled pixel groupings as they are not physically representative of a fracture or vein network. These are coupled with other physical, chemical, and biological measurements into the data set.

Drilling reports are summarized into keywords using ChatGPT. Geologist remarks from the drilling report were given to ChatGPT to summarize. These remarks typically take the form of written notes and were taken per approximate meter of extracted core. An example:

microcrystalline carbonate visible on vein surfaces. clasts are 90\% angular and 10\% rounded. This indicates that the thickness of alluvium is less than few 10s cm and the bedrock is surfacing. angular fragments at 0 to 60 cm with mixed lithologies varying from serpentinised harzburgite to dunite. Serpentinization, oxidation, carbonation in veins.

Each set of remarks per depth unit (505 in total) were given to ChatGPT (gpt-turbo-3.5) with the prompt:

Please summarize the following text into ten keywords and explain why you picked each key word. The text to summarize: {text}

where {text} being replaced by the geologist's remarks. This produced hundreds of different keywords emerged from the process many of which were close duplicates or similar keywords. After filtering keywords for duplicates, similarity, and any keywords that were reported by ChatGPT less than 50 times (representing less than 10% of the BA1B total cored depth), 52 keywords remained. Those keywords were integrated in the dataset as binary variables. Using these keywords, we asked ChatGPT to group the different keywords into topics based on the type of information they convey, and we plotted the graph of keywords depending on depth to have preliminary information about the features of the core.

Ultimately this project presents a model that predicts accurately (>0.95 AUC) where alteration occurs in the borehole using this data. This internship project is being prepared for submission.

Production in highlight

Aiken, J. M., Sohn, R. A., Renard, F., Matter, J., Kelemen, P., Jamtveit, B. (2022) Gas migration episodes observed during peridotite alteration in the Samail ophiolite, Oman, Geophysical Research Letters, 49, e2022GL100395.

Fracture, friction, and the onset of geohazards

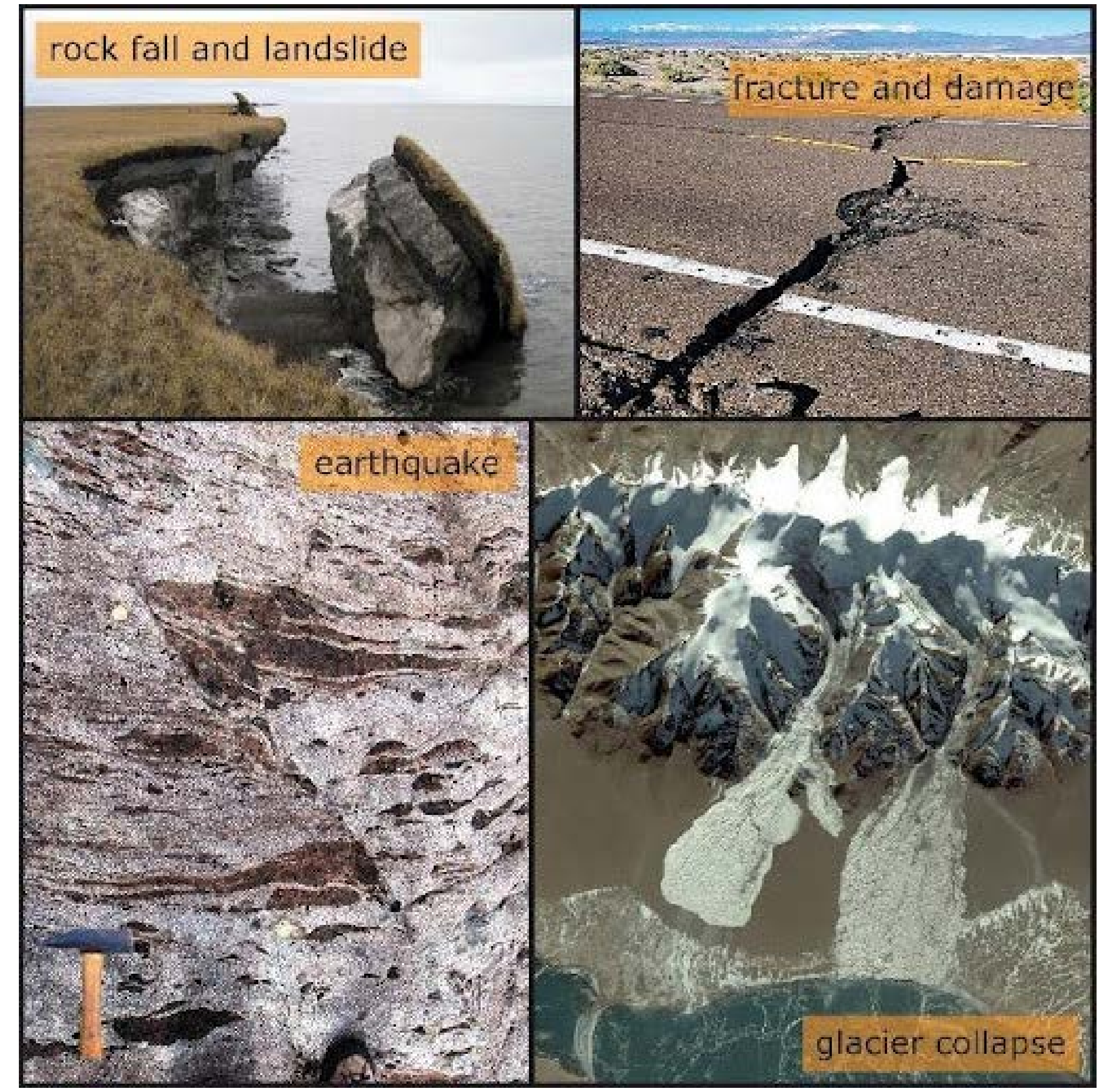
Funding
Center for Advanced Study at the Norwegian Academy of Science and Letters, project FricFrac

Participants
Francois Renard[1](PI), Anders Malthe-Sørenssen[1](Co-PI), Thomas V. Schuler[2], Wenlu Zhu[3], Åke Fagereng[4], Olivier Gagliardini[5], Luiza Angheluta[1], Luca Menegon[1], Erina Prastyani[1], Jessica Ann McBeck[1], Fabian Barras[1]

Affiliation
1) The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Norway
2) Department of Geosciences, University of Oslo, Norway
3) University of Maryland, USA
4) University of Cardiff, UK
5) IGE, University Grenoble Alpes, France

A group of eight researchers from the university of Oslo, and three researchers from the universities of Maryland (USA), Cardiff (UK) and Grenoble-Alpes (France) work together at the Center for Advanced Study over the academic year 2023-2024. The main research topic concerns the slow evolutions punctuated by burst like events localized onto interfaces or interface zones that control the evolution of a wide variety of geological systems, such as glaciers, earthquakes, rock falls, and landslides. In Earth's subsurface and cryosphere, the build-up of energy drives rocks and ice towards tipping points at which a small perturbation can trigger a rapid release of energy.

During this year at the Centre for Advanced Study, we develop a physics-based modelling approach to the development of a better theoretical understanding of the friction and fracture processes that control burst-like dynamics leading to these geohazards, and the construction of numerical models with potential predictive capability that utilize this advance in understanding. Our primary objective is to develop minimal models of fracture and friction in rock and ice to explain and predict how sliding instabilities initiate, grow, may develop into geohazards (earthquakes, landslides, glacier instabilities), and then arrest.



↑ Several geohazards are associated with fracture and frictional processes that lead to the creation of damage and catastrophic deformation events such as glaciers collapse, seismic faulting, rock falls, and landslides.

Production in highlight

Bouchayer, C., Nanni, U., Lefeuvre, P.-M., Hult, J., Schmidt, L. S., Kohler, J., Renard, F., Schuler, T. (2024) Multi-scale variations of subglacial hydro-mechanical conditions at Kongsvegen glacier, Svalbard, The Cryosphere, in revision.

McBeck, J., Cordonnier, B., Cooke, M., Fattaruso, L., Renard, F. (2023) Deformation evolves from shear to extensile in rocks due to energy optimization, Communications Earth and Environment, 4, 352.

McBeck, J., Cordonnier, B., Ben-Zion, Y., Renard, F. (2024) The relationship between deformation localization and catastrophic failure in fluid-saturated crystalline rocks in upper crustal conditions, Tectonophysics, 871, 230191.

Nanni, U., Bouchayer, C., Åkesson, H., Lefeuvre, P. M., Mannerfelt, E. K, Köhler, A., Schmidt, L. S., Hult, J., Renard, F., Schuler, T. V. (2024) Observed weakening of glacier ice-bed interface caused by climatic and hydro-mechanical feedbacks: towards glacier-wide acceleration? submitted.

The cyclic interplay of seismic and aseismic deformation in the lower continental crust

Funding
Deutsche Forschungsgemeinschaft, Walter Benjamin Program

Participants
Sascha Zertani[1], Luca Menegon[1], Bjørn Jamtveit[1]

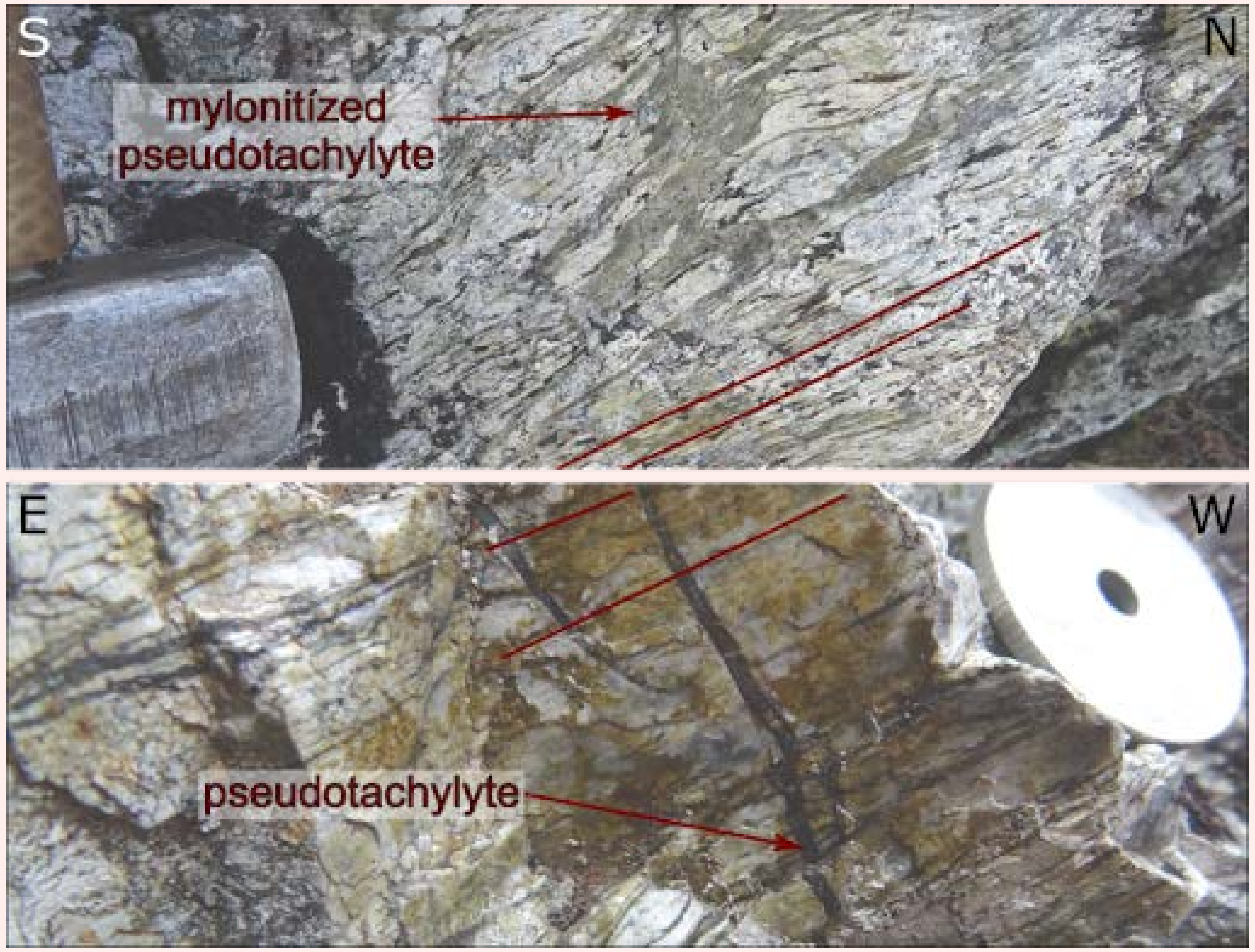
Affiliation
1) The Njord Centre, University of Oslo, Norway

During the formation of collisional mountain belts the deeply buried continental crust is modified by metamorphic reactions and deformed by brittle and/or ductile mechanisms. In this context, the dominant deformation mechanisms are not only dependent on the prevailing pressure-temperature conditions, but also the availability of fluids, and the interplay of deformation and metamorphic reequilibration across scales shapes the large-scale rheological behavior of the crust.

The Lofoten archipelago (northern Norway) preserves a block of lower continental crust that has been affected by localized deformation during the Caledonian orogeny and represents one of the prime examples to study the nucleation of earthquakes in the lower continental crust. Fossil earthquakes are exposed as pseudotachylytes (quenched frictional melts) and have occurred cyclically with ductile shear zones at amphibolite-facies conditions (see Figure).

The project aims to unravel the relative and absolute timing of deformation (brittle vs. ductile) and metamorphism (eclogite vs. amphibolite facies) to understand how the bulk rheological response of the continental crust varies through orogenic history. This is achieved by detailed field-based kinematic analysis of the deformation structures combined with microstructural and geochronological investigations.

We were able to show that eclogitization in the area occurred along corridors that localized metamorphism and deformation along pre-existing structures, related to the magmatic history of this lower-crustal section, and that eclogitization preceded amphibolite-facies metamorphism and occurred early in the orogenic history. Additionally, the project has succeeded in – for the first time – obtaining a robust age of lower crustal pseudotachylytes using a combination of electron backscatter diffraction and *in-situ* apatite U-Pb geochronology, publication of which is currently under review and expected in early 2024.

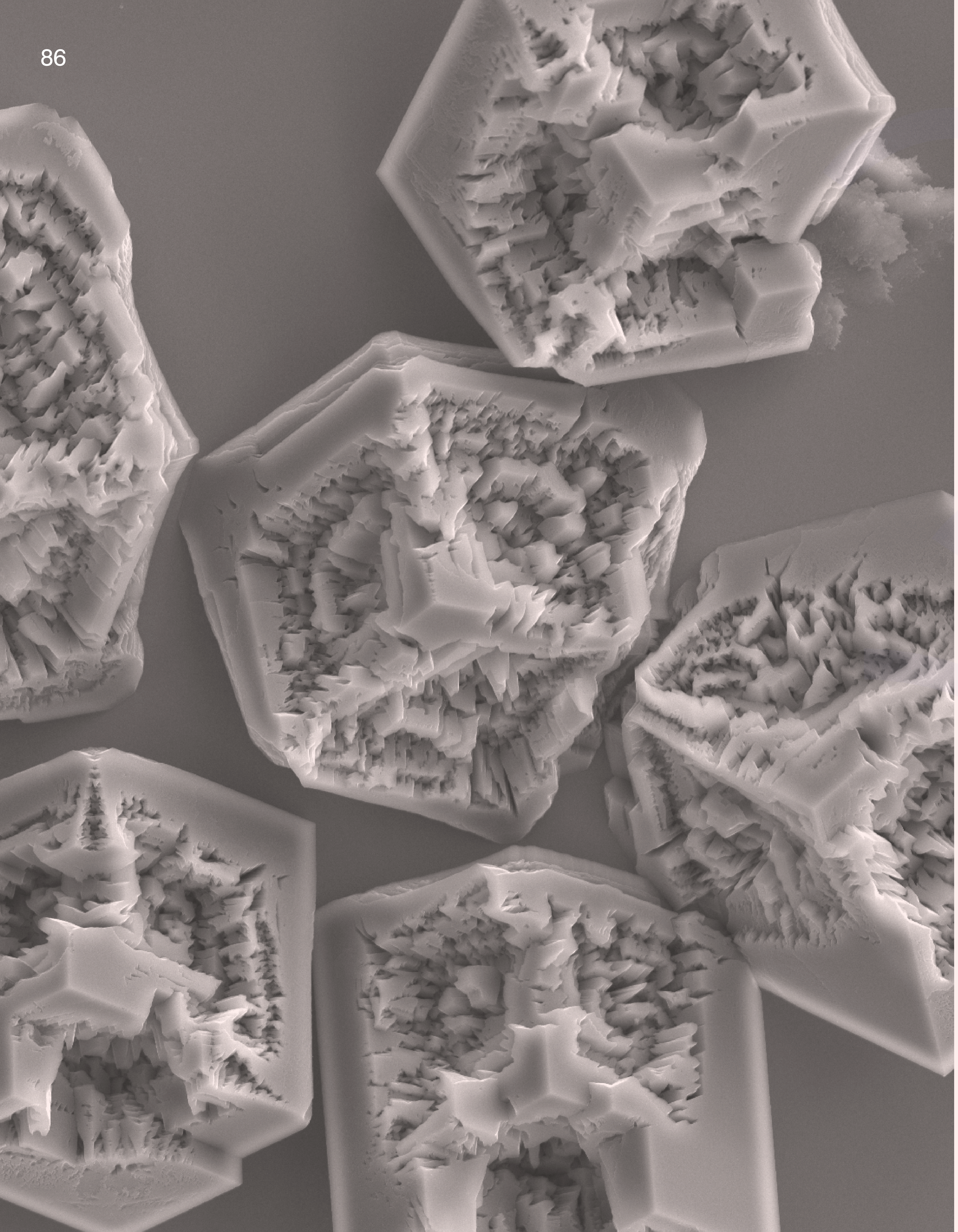


↑ Photographs (Lofoten) of a mylonitized pseudotachylyte **(top)** and a pristine pseudotachylyte that cuts through the ductile fabric **(bottom)**.

Production in highlight

Zertani, S., Menegon, L., Pennacchioni, G., Buisman, I., Corfu, F., & Jamtveit, B. (2023). Protracted localization of metamorphism and deformation in a heterogeneous lower-crustal shear zone. Journal of Structural Geology, 176, 104960.

Zertani, S., Menegon, L., Whitehouse, M. J., Jeon, H., & Jamtveit, B. (in review). Dating fossil lower-crustal earthquakes by in-situ apatite U-Pb geochronology. Earth and Planetary Science Letters.



3
Part 3

Couplings at the Nanoscale

1. Flow and mineral sequestration of carbon dioxide in basalts offshore Norway
2. Molecular dynamics simulations of nanoscale geological processes

Flow and mineral sequestration of carbon dioxide in basalts offshore Norway

Funding
The Faculty of Mathematics and Natural Sciences, University of Oslo, project CO2Basalt

Participants
Marija Plahter Rosenqvist[1], Yao Xu[1,2], Rakul Maria Johannesen[1,3], Marthe Grønlie Guren[1], François Renard[1,4], Luca Menegon[1], Kristina Dunkel[1], Olivier Galland[1], Knut Jørgen Måløy[1,2], Marcel Moura[1,2], Henrik Sveinsson[1], Anders Malthe-Sørenssen[1], Sverre Planke[5]

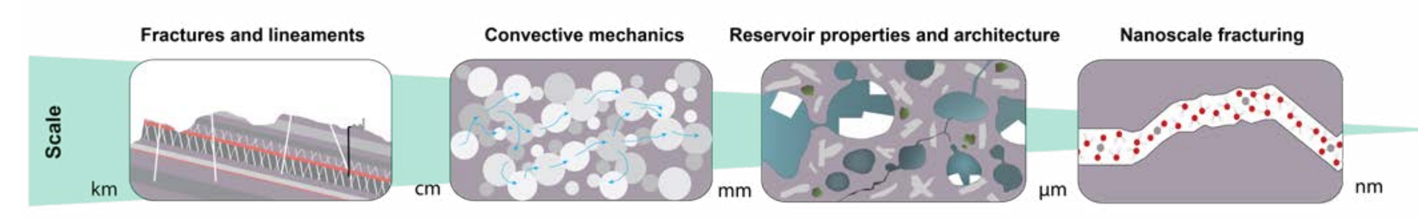
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Geological Survey of Faroe Islands, Denmark
4) ISTerre, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, Univ. Gustave Eiffel, CNRS, IRD, Grenoble, France
5) Volcanic Basin Petroleum Research AS, Oslo, Norway

Storing carbon in basalt comes with many benefits. The carbon dioxide will quickly react with the divalent cations (calcium, magnesium, iron) from dissolving minerals in the basalt and form carbonate minerals. In comparison, it might take several thousand years for significant amounts of carbon dioxide to mineralize in a sandstone reservoir. Once mineralized, the carbon will be immobilized over geological timescales. Storing carbon in basalt also provides large reservoir volumes worldwide. Estimates suggest that mid-ocean ridges worldwide can store up to 100,000 Gt of carbon dioxide. This is more than 2000 times the annual global emissions of carbon dioxide, and the possibilities of carbon storage in volcanic sequences are therefore important to study further. The main goal of the project CO2Basalt is to evaluate the hypothesis that the multiscale flow pathways in basalts can host voluminous flows of carbon dioxide mixed with water that will react with the host rock to produce carbonate minerals.

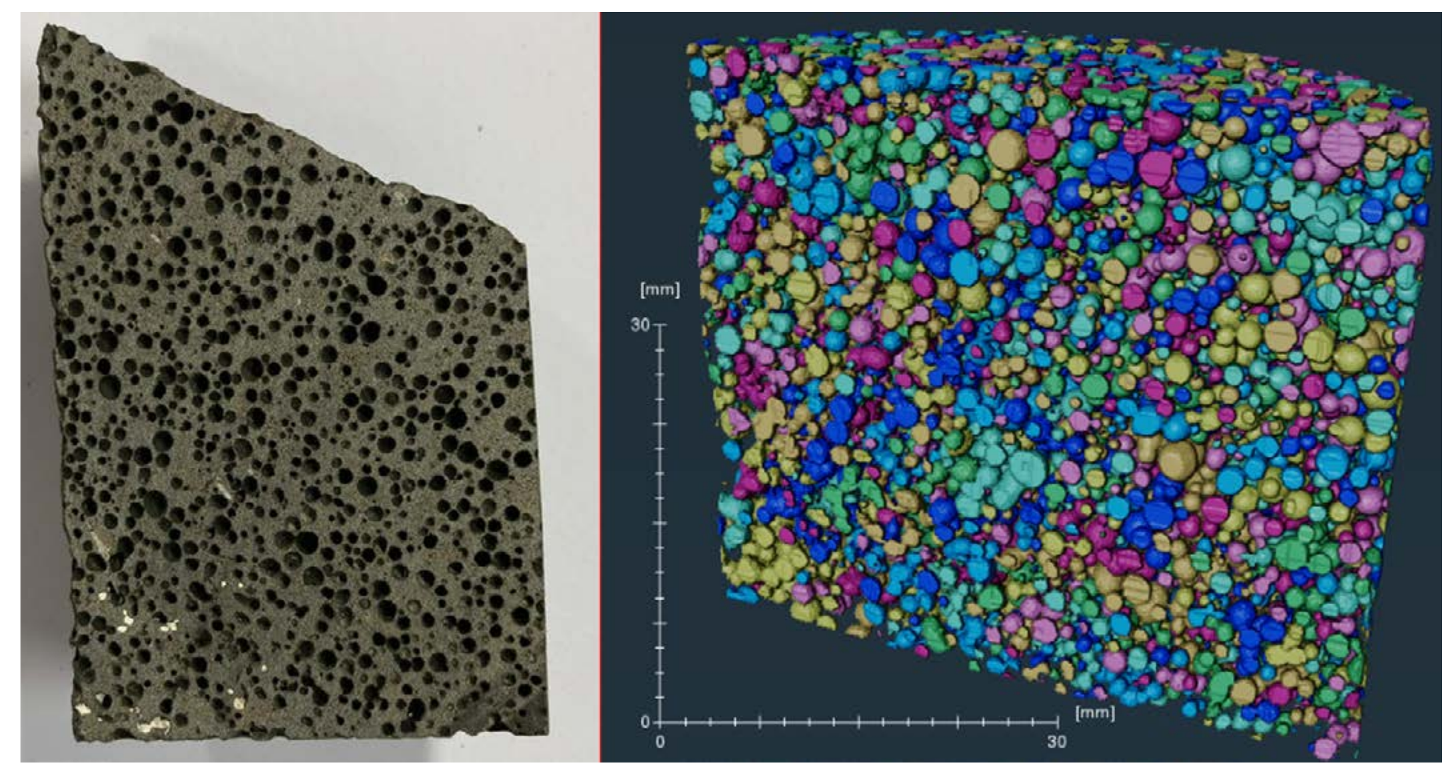
To answer this hypothesis, four early career researchers have been hired and we are working across scales using a broad variety of methods to study mapping of lineaments and fractures, convective mechanisms in porous and fractured media, reservoir properties and fracture propagation. The main scientific questions are:

What are the geological properties of the Faroe Islands Basalt Group and to what degree can they contribute towards permanent storage of CO_2?

1. How does CO_2 dissolve in water flow through porous and fractured media?
2. What are the petrophysical properties of the basalts and how will these affect fluid flow migration and reactivity in a CO_2 storage scenario?
3. How do dynamic fractures damage basaltic glass at the nanoscale and how does the water enter these fractures in the wake of the rupture?



↑ The CO2Basalt project is working across scales from km-scale mapping in the field to modelling fracture propagation at the nm-scale.



↑ CT-scan of a porous basalt showing the separated porespace (Rosenqvist et al., 2023).

PoreLab
NTNU-UiO Porous Media Laboratory

Guren, M. G., Sveinsson, H. A., Malthe-Sørenssen, A., & Renard, F. (2022). Nanoscale Damage Production by Dynamic Tensile Rupture in α-Quartz. Geophysical Research Letters, 49(20), e2022GL100468.

Johannesen, R. M. I., Ólavsdóttir, J., Boldreel, L. O., Eidesgaard, Ó., Senger, K, & Galland, O. Data integration across scales: 3D insights into the volcanostratigraphy and geometry of the Faroe Islands. *In preparation.*

Rosenqvist, M. P., Meakins, M. W. J., Planke, S., Millet, J. M., Kjøll, H. J., Voigt, M. J., & Jamtveit, B. (2023) Reservoir properties and reactivity of the Faroe Islands Basalt Group: Investigating the potential for CO_2 storage in the North Atlantic Igneous Province. *International Journal of Greenhouse Gas Control*, 123, 103838.

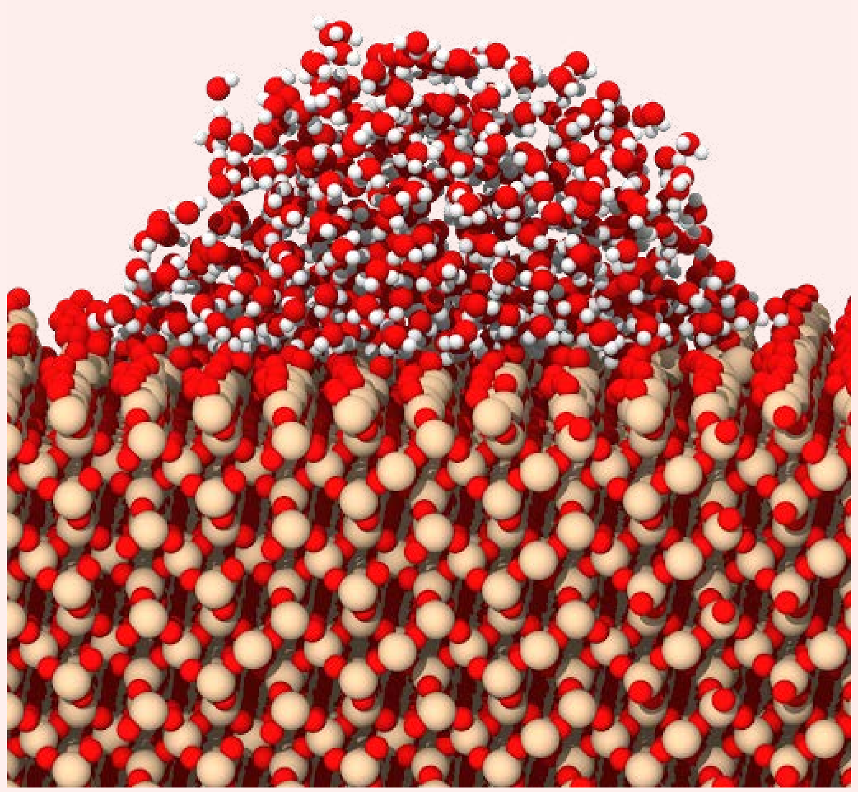
Rosenqvist, M. P., Millet, J. M., Planke, S., Johannesen, R. M., Passey, S. R., Sørensen, E. V., Vosgerau, H., & Jamtveit, B. (2024). The architecture of basalt reservoirs in the North Atlantic Igneous Province with implications for basalt carbon sequestration. *Geological Society, London, Special Publications*, *547*(1), SP547-2023.

Molecular dynamics simulations of nanoscale geological processes

Funding
University of Oslo
EU Horizon 2020 MSCA CoFund

Participants
Henrik Andersen Sveinsson[1], Marthe Grønlie Guren[1], Anthony Val Camposano[1], Ian Steegmayer[1], Even Marius Nordhagen[1], Bjørn Jamtveit[1], François Renard[1], Anders Malthe-Sørenssen[1]

Affiliation
1) The Njord Centre, University of Oslo, Norway



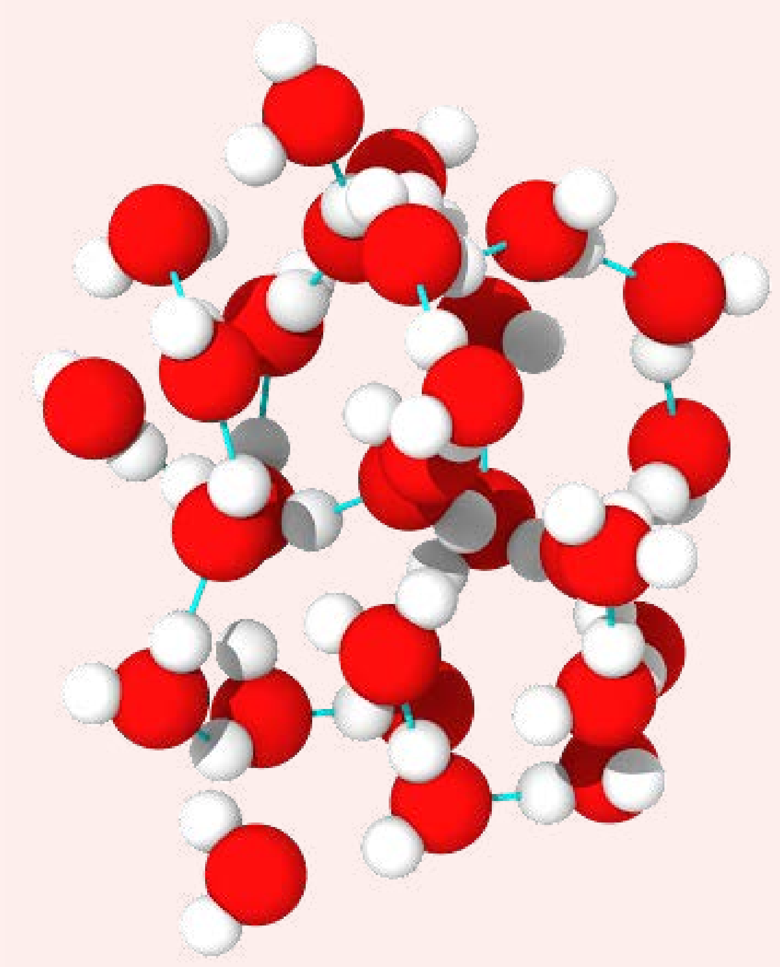
↑ A water droplet resting on a quartz silica using a single predefined functional form (Vashishta potential) to model atomic interactions of bulk water, water-silica, and silica. The water-silica interface system was used to calculate the contact angle of water.

Geological processes shape the earth, erect mountains and shatter the crust during Earthquakes. Many geological processes ultimately involve details at the nanoscale. For example, in reactions where rocks expand in the presence of water, atomic scale details may determine whether water can make it to the reaction site, or whether the reaction is shut off.

Molecular dynamics (MD) simulations can provide a deeper understanding of nanoscale processes that are not visible in experiments. The force fields used in molecular dynamics simulations are approximations, and by inspecting what physics may be coarsened out while retaining experimental behavior, one may also suggest what physics are important to produce a given behavior.

We have previously used molecular dynamics simulations to imply that the hydration of periclase into brucite is shut down because water films in pore throats are being shut off at a pressure of a few tens of megapascals, orders of magnitude lower than the force of crystallization. To enable direct simulation of reaction induced fracturing, stress-corrosion and the role of water in the fracture of rocks, we need a reactive rock–water force field. We are currently combining molecular dynamics and Monte Carlo simulations of water to develop a new silica–water force field. We have a particular emphasis on realistic transport properties of water to model dynamic failure processes in the Earth. The force field development will result in a computational pipeline that can create force fields tuned to geologically relevant conditions. We also train machine learning based force fields that provide close to ab-initio accuracy in molecular dynamics simulations, albeit at a higher computational cost than empirical force field MD. Using these force fields, we will study dynamics fracture and crack instabilities and processes such as water cavitation in the wake of a crack and the damage related to the collapse of nanobubbles.

We have also used molecular dynamics simulations with a slightly coarser model each water molecule is a single particle to investigate the failure and creep behavior of gas hydrates. We have established grain size and temperature dependencies and shown how the failure mechanisms change as the grain size increases in a high-stress regime. Current investigations are revealing that the power-law creep behavior of gas hydrates, which was determined two decades ago, emerges from molecular dynamics simulations using a coarse-grained water model.



→ A snapshot of a cluster (29 water molecules) obtained in an energy-biased-aggregation-volume- bias Monte Carlo (EB-AVBMC) simulation. This is used to obtain an estimate of the surface tension and gas density of the water model from the free energies of the system. To sample the phase space of the water model, the MC moves consist of the AVBMC swap moves and a single atom translation.

Production in highlight

Sveinsson, H. A., Cao P (2024). Distinct creep regimes of methane hydrates can be predicted by a monatomic water model. In review.

4

Appendices

List of staff

Senior Academic Staff

Last name	First name	E-mail	Position
Aharonov	Einat	einatah@mail.huji.ac.il	Adjunct professor (15%)
Angheluta-Bauer	Luiza	luiza.angheluta-bauer@fys.uio.no	Professor
Austrheim	Håkon	h.o.austrheim@geo.uio.no	Professor Emeritus
Dahlgren	Sven	sven.dahlgren@telemarkfylke.no	Guest Researcher
Dougal	Jerram	d.a.jerram@geo.uio.no	Adjunct Professor (10%)
Dunkel	Kristina	kristina.dunkel@geo.uio.no	Associate Professor
Dysthe	Dag Kristian	d.k.dysthe@fys.uio.no	Professor
Flekkøy	Eirik	e.g.flekkoy@fys.uio.no	Professor
Galland	Olivier	olivier.galland@geo.uio.no	Research Professor
Jamtveit	Bjørn	bjorn.jamtveit@geo.uio.no	Vice Dean
Le Borgne	Tanguy	tanguy.le-borgne@univ-rennes1.fr	Adjunct professor (20%)
Malthe-Sørenssen	Anders	anders.malthe-sorenssen@fys.uio.no	Professor
Mathiesen	Joachim	joachim.mathiesen@fys.uio.no	Adjunct professor (20%)
Menegon	Luca	luca.menegon@geo.uio.no	Professor
Måløy	Knut Jørgen	k.j.maloy@fys.uio.no	Professor
Renard	François	françois.renard@geo.uio.no	Director/Professor
Rikvold	Per Arne	p.a.rikvold@fys.uio.no	Professor Emeritus
Toussaint	Renaud	renaud.toussaint@fys.uio.no	Adjunct professor (20%)

Postdoctoral Fellows and Researchers

Last name	First name	E-mail	Function
Aiken	John	john.aiken@fys.uio.no	Researcher
Barras	Fabian	fabian.barras@mn.uio.no	Postdoctoral Fellow
Combriat	Thomas	t.m.d.combriat@fys.uio.no	Postdoctoral Fellow
Cordonnier	Benoît	Benoit.cordonnier@geo.uio.no	Researcher
Dziadkowiec	Joanna	joanna.dziadkowiec@fys.uio.no	Postdoctoral Fellow
Fu	Yuequn	yuequn.fu@fys.uio.no	Postdoctoral Fellow
Guren	Marthe	m.g.guren@geo.uio.no	Postdoctoral Fellow
Ho	Richard	richard.ho@mn.uio.no	Postdoctoral Fellow
Jacob	Jean-Baptiste	j.b.jacob@mn.uio.no	Postdoctoral Fellow
Khobaib	Khobaib	khobaibk@fys.uio.no	Postdoctoral Fellow
Lantman	Hugo	h.w.van.s.lantman@mn.uio.no	Postdoctoral Fellow
Linga	Gaute	gaute.linga@mn.uio.no	Researcher
McBeck	Jessica	j.a.mcbeck@geo.uio.no	Researcher
Mossige	Joachim	joachim.mossige@imv.uio.no	Postdoctoral Fellow
Moura	Marcel	marcel.moura@fys.uio.no	Researcher
Pierce	Kevin	kevin.pierce@mn.uio.no	Postdoctoral Fellow
Reis	Paula	paula.reis@mn.uio.no	Postdoctoral Fellow
Sinha	Santanu	santanu.sinha@ntnu.no	Researcher
Sveinsson	Henrik	h.a.sveinsson@fys.uio.no	Assistant Professor
Vincent-Dospital	Tom	tom.vincent-dospital@fys.uio.no	Postdoctoral Fellow
Zertani	Sascha	sascha.zertani@mn.uio.no	Postdoctoral Fellow

Doctoral Research Fellows

Last name	First name	E-mail	Function
Aspaas	Andreas	a.g.aspaas@geo.uio.no	Doctoral Research Fellow
Bierbaumer	Katharina	katharina.bierbaumer@mn.uio.no	Doctoral Research Fellow
Bouchayer	Coline	c.l.m.bouchayer@geo.uio.no	Doctoral Research Fellow
Brodin	Joachim	j.f.brodin@fys.uio.no	Doctoral Research Fellow
Camposano	Anthony	a.v.camposano@fys.uio.no	Doctoral Research Fellow
Demir	Ali	a.a.demir@mn.uio.no	Doctoral Research Fellow
Dhanapal	Syadhisy	syadhisy.dhanapal@geo.uio.no	Doctoral Research Fellow
Jain	Harish	harishpj@fys.uio.no	Doctoral Research Fellow
Johannesen	Rakul	r.m.johannesen@mn.uio.no	Doctoral Research Fellow
Låstad	Silja	s.b.lastad@mn.uio.no	Doctoral Research Fellow
Michalchuk	Stephen	stephen.michalchuk@geo.uio.no	Doctoral Research Fellow
Najafi	Fahimeh	fahimeh.najafi@fys.uio.no	Doctoral Research Fellow
Nordhagen	Even	evenmn@student.matnat.uio.no	Doctoral Research Fellow
Prastyani	Erina	erina.prastyani@mn.uio.no	Doctoral Research Fellow
Rosenqvist	Marija Plahter	m.p.rosenqvist@mn.uio.no	Doctoral Research Fellow
Rønning	Jonas	jonas.ronning@fys.uio.no	Doctoral Research Fellow
Shafabakhsh	Paiman	paiman.shafabakhsh@mn.uio.no	Doctoral Research Fellow
Schoeb	Franziska	franziska.schoeb@fys.uio.no	Doctoral Research Fellow
Skogvoll	Vidar	vidarsko@mn.uio.no	Doctoral Research Fellow
Xu	Yao	yaox@fys.uio.no	Doctoral Research Fellow

Supporting Staff

Last name	First name	E-mail	Function
Abbasova	Nigar	nigar.abbasova@fys.uio.no	Adm. support
Hoff	Janne	janne.k.hoff@mn.uio.no	Adm. coordinator
Hu	Yi	yi.hu@fys.uio.no	Senior engineer
Jankov	Mihailo	mihailo.jankov@fys.uio.no	Senior engineer

Visiting guests

Last name	First name	E-mail	Visiting from
Dansereau	Véronique	veronique.dansereau@univ-grenoble-alpes.fr	France
Dufournet	Elliot	elliot.dufournet@centrale-marseille.fr	France
Greiner	Sonja	shmgreiner@hi.is	Island
Rogowitz	Anna	anna.rogowitz@univie.ac.at	Austria
Scheid	Marie	marie.scheid11@gmail.com	France
Shrestha	Pranay	pranay.shrestha@mail.utoronto.ca	Canada
Birnir	Bjørn	birnirb@gmail.com	USA
Lorraine	Marratzu	marratzu.lorraine@gmail.com	France
Meakin	Paul	paulzmeakin@gmail.com	USA
Toffol	Giovanni	toffol-g@hotmail.com	Italy
Vinals	Jorge	vinals@umn.edu	USA
Wang	Jianfeng	jianfeng.wang@mn.uio.no	China

Master students

Last name	First name	E-mail	Supervisor(s)
Abbasova	Nigar	nigar.abbasova@fys.uio.no	Dag Kristian Dysthe, Luiza Angheluta-Bauer, Amin Doostmohammadi
Agadad	Laura Celin	l.c.agadad@geo.uio.no	Olivier Galland, Kristina Dunkel, Lars Eivind Augland
Blum	Cletus		Olivier Galland, Karen Mair, Amanda DiBaggio, Hans Petter Jostad, Håkon Heyerdahl
Bratsberg	Eldrid	eldribr@student.geo.uio.no	Olivier Galland
Cabrera	Gabriel	g.s.cabrera@fys.uio.no	Jessica McBeck, François Renard
Carlsen	Henrik	h.h.carlsen@fys.uio.no	Luiza Angheluta-Bauer
Christiansen	Vetle	vetlec@student.geo.uio.no	Nadége Langet, Valerie Marie Maupin, Volker Oye, François Renard
Dirdal	Theo Holm	theohd@student.geo.uio.no	Luca Menegon, Kristina Dunkel, Sascha Zertani
Falkeid	Silje	smfalkei@student.geo.uio.no	Karen Mair, François Renard
Due	Thor With	tgdue@student.geo.uio.no	Luke Griffiths, François Renard
Hansen	Fabian Sørsvang	fabiansh@student.geo.uio.no	Olivier Galland, Luc Girod, Andreas Aspaas
Kings	Jonathan	jonathan.kings@fys.uio.no	Eirik Flekkøy
Milos	Joksimovic	milos.joksimovic@fys.uio.no	Luiza Angheluta-Bauer
Payabyab	Ronald	rmpayaby@student.geo.uio.no	François Renard, Desiree Silvana Treichler
Sundsmoen	Kristoffer	krsundsm@student.geo.uio.no	Olivier Galland, François Renard, Andreas Grøvan Aspaas, Alvar Braathen
Valter	Oleksandra	oleksava@student.geo.uio.no	Luca Menegon, Kristina Dunkel, Sven Dahlgren, Olivier Galland
Våtevik Holm	Johan	johanvh@student.geo.uio.no	Luca Menegon, Lars Eivind Augland, Milena Farajewicz (Kuniko AS),
Øvereng	Vebjørn	vebjorn.overeng@fys.uio.no	Luiza Angheluta-Bauer

PhD and Postdoc projects

PhD projects

Candidate	Title/Topic	Supervisor(s)
Aspaas, Andreas	Creep bursts in rockslides – characterization and numerical simulation of transient deformations	François Renard, Bernd Etzelmüller
Bierbaumer, Katharina	Emplacement processes and evolution of Volcanic and Igneous Plumbing Systems: the Oslo Rift case study	Olivier Galland, Lars Eivind Augland, Kristina Dunkel
Baldelli, Beatrice	Gravity-stabilized flow on self-affine surfaces	Eirik Grude Flekkøy, Knut Jørgen Måløy, Gaute Linga
Bouchayer, Coline	Modelling transient velocity variations in glaciers	Thomas V. Schuler, François Renard, Kjetil Thøgersen, Andreas Kääb
Brodin, Joachim	Experimental studies on flow in porous media in 3D	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura
Camposano, Anthony	Machine-learning-based molecular modelling of nanoscale geological processes	Anders Malthe-Sørenssen, Henrik Andersen Sveinsson
Demir, Ali Aslan	Mesenchymal stem cell differentiation and mineralization in biomimetic hydrogels: microfluidics and modelling	Dag Kristian Dysthe, Hanna Tiainen
Dhanapal, Syadhisy	Development of machine learning techniques in experimental rock deformation studies with applications to geo-energy	François Renard, Benoit Cordonnier, Jessica McBeck
Johannesen, Rakul Maria	The potential for permanently storing CO_2 in basaltic lava flows. A multiscale, structural reservoir study of the Faroe Island Basalt Group	Olivier Galland, Jana Ólavsdóttir, Óluvá Eidesgaard, Hans Jørgen Kjøll, Sverre Planke
Jain, Harish	Collective emergent behaviour of active cellular systems	Luiza Angelutha-Bauer, Anders Malthe-Sørenssen
Låstad, Silja	Actin dynamics and cell motility	Dag Kristian Dysthe,), Xian (Edna) Hu, Anders Malthe- Sørenssen
Michalchuk, Stephen	Mechanisms and significance of transient brittle deformation in the ductile crust	Luca Menegon
Najafi, Fahimeh	Frictional properties of surface structures generated by machine-learning	Anders Malthe-Sørenssen, Henrik Andersen Sveinsson
Nordhagen, Even	History-dependent effects in atomic-scale friction	Anders Malthe-Sørenssen, Henrik Sveinsson, Kjetil Thøgersen, François Renard
Prastyani, Erina	Microphysical characterization of crack growth and the transition from brittle to semi-brittle deformation in crustal rocks	François Renard, Jess McBeck, Cordonnier, Benoit
Rosenqvist, Marija	Multi-scale flow pathways in basalts of the North Atlantic Igneous Province: implications for CO_2 storage.	Luca Menegon, Kristina Dunkel, Olivier Galland og Sverre Planke (VBER og Universitetet i Oslo/CEED).
Rønning, Jonas	Turbulence in Bose-Einstein condensates and active matter	Luiza Angheluta-Bauer, Eirik Grude Flekkøy
Schoeb, Franziska	Deep learning-based analysis of stem cell differentiation pathways	Dag Kristian Dysthe, Hanne Scholz (Faculty of Medicine/Hybrid Technology Hub)
Shafabakhsh, Paiman	Numerical Modelling and Imaging of Fluid Mixing in Rocks with Evolving Microstructure	François Renard, Gaute Linga, Tanguy Le Borgne
Skogvoll, Vidar	Multiple scales modelling of crystal plasticity	Luiza Angheluta, François Renard, Luca Menegon
Steegmayer, Ian	Investigation of nanoplastics and mineral interactions using machine learning	Anders Malthe-Sørenssen, Henrik Andersen Sveinsson
Xu, Yao	The Evolution of Spatial pH and Carbon Concentration in Density-Driven Convection of CO_2 in Water	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura

PhDs completed in 2023

Candidate	Title/Topic	Supervisor(s)
Bouchayer, Coline	Modelling transient velocity variations in glaciers	Thomas V. Schuler, François Renard, Kjetil Thøgersen, Andreas Kääb
Rønning, Jonas	Turbulence in Bose-Einstein condensates and active matter	Luiza Angheluta-Bauer, Eirik Grude Flekkøy
Skogvoll, Vidar	Multiple scales modelling of crystal plasticity	Luiza Angheluta-Bauer, François Renard, Luca Menegon

Postdoc and researcher projects

Candidate	Title/Topic	Supervisor(s)
Aiken, John	SerpRateAI: unravelling the rate of serpentinization using artificial intelligence	Francois Renard, Bjørn Jamtveit
Barras, Fabian	Modelling the interplay between earthquake rupture and fluid migration in the Earth's crust	François Renard, Bjørn Jamtveit
Cordonnier, Benoit	Neutron imaging of pollutant flow within geological samples	François Renard
Dziadkowiec, Joanna	Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivi-typrobing forces, electrochemical reactions, friction and reactivity	Anja Røyne, Dag Kristian Dysthe, Markus Valtiner
Guren, Marthe	Nanoscale modeling of reaction-induced fracturing	François Renard, Henrik Andersen Sveinsson, Anders Malthe-Sørenssen
Fu, Yuequn	Atomistic Insights into nano-scale cavitation on the silica surface	Eirik Grude Flekkøy, Knut Jørgen Måløy
Ho, Richard	Integrated technologies for tracking organoid morphogenesis	Luiza Angheluta
Jacob, Jean-Baptiste	Residual stress measurement in minerals using 3d X-Ray diffraction	François Renard
Khobaib, Khobaib	Experimental studies of slow drainage flows in a porous medium	Knut Jørgen Måløy
Lantmann, Hugo van Schrojenstein	Reconstructing the localized transient high stress state of seismogenic faults in the lower crust, Lofoten, Norway	Luca Menegon
Mossige, Joachim	How does artificial organs respond to sound and how rhythmic signals may affect their growth and development	Dag Kristian Dysthe, Alexander Refsum Jensenius
Linga, Gaute	Numerical modelling of the complexity of fluid flow in deforming porous media	François Renard, Eirik Grude Flekkøy
McBeck, Jessica	Emergent networks: Predicting strain localization and fracture network development	François Renard
Moura, Marcel	Intermittent burst dynamics on porous media two-phase flow	Eirik Grude Flekkøy, Knut Jørgen Måløy
Pierce, Kevin	Experiments and theory of multiphase flow and mixing phenomena in porous media	Linga, Gaute
Reis, Paula	The transport properties of thin liquid films left on the surface of grains during drainage	Moura, Marcel
Zertani, Sascha	The cyclic interplay of seismic and aseismic deformation in the lower continental crust	Luca Menegon, Bjørn Jamtveit

Guest talks, workshops and seminars

Date	Speaker and name of talk
January 20th	Internal Njord seminar: Joachim Mossige, NJORD and RITMO, UiO. "Culinary fluid mechanics and other currents in food science"
January 27th	Matej Pec, MIT. "Nanometric flow and the earthquake instability"
February 3rd	Vivek Prakash, University of Miami. "Fascinating flows and emergent mechanics in simple marine animals"
February 10th	Arnold Mathijssen, University of Pennsylvania. "Transport and delivery by living materials"
February 17th	Mattia Luca, Mazzucchelli. "Fluid-mineral equilibrium under stress: insight from molecular dynamics"
February 24th	Anne Imig, Technical University of Munich. "Transport and fate of herbicides in cropped lysimeters considering different model setups in the vadose zone"
March 3rd	Njord talks: Joanna Dziadkowiec, Njord " Mineral dissolution-replacement reactions under confinement." Paiman Shafabakhsh, Njord. "Neutron imaging of fluid mixing in rocks with carbonate precipitation"
March 10th	Alexis Cartwright-Taylor, Heriot Watt University. "Micromechanics of damage localisation and shear failure of a porous rock: sound and vision"
March 17th	Rellie Goddard , Woods Hole Oceanographic Institution. "Subgrain-size piezometry as a tool for measuring stress in polymineralic rocks"
March 24th	Sidney Nagel, Department of Physics at the The University of Chicago. "Disorder is different"
March 31st	Maciej Lisicki, Institute of Theoretical Physics, Faculty of Physics University of Warsaw. "Tales of tails: Elastohydrodynamics of microscale swimming"
April 14th	Giovanni Toffol, University of Padova, Department of Geosciences. "Understanding earthquakes from the study of pseudotachylytes: examples from the micrometric to the lithospheric scale."
April 21st	Njord talks: Harish Pruthviraj Jain; Njord. "Active reorganisation of tissues: Phase transition of ideas from physics to biology " Andreas Grøvan Aspaas, Njord. "What causes creep bursts in the Åknes landslide, Norway?"
May 5th	Anja Røyne, UiO. "How to share your science with the world"
May 12th	Andreas Carlson,UiO. "Quiescence induce fluidization and stress amplification in an epithelial layer"
June 14th and 15th	EarthFlows Meeting 2023. "Organizing committee: Vidar Skogvoll, Torstein Sæter, François Renard, Luiza Angheluta-Bauer, Janne Hoff"
September 15th	Åke Fagereng, Cardiff University. "What controls the range of aseismic to seismic behavior on subduction plate interfaces?"
September 22nd	Bjørn Birnir, University of California, Santa Barbara (UCSB). "The near integrability of the water wave equations."
September 29th	Njord talks by Richard Ho. "Minimal model of Gastruloid Elongation", Paula Reis. "A model for slow drainage with film-flow effects in porous media." Syadhisy Dhanapal. "Under Stress."
October 13th	Luca Menegon, Njord. "Transient high stresses during the earthquake cycle in the lower crust and their preservation in the geological record."
October 20th, 2PM	Alice Macente, University of Leeds. "Evolving porosity and permeability at the microscale: a case-study on reversing pore-filling mechanisms in basalts using X-Ray Computed Tomography."
October 27th	Federico Agliardi, University of Milano - Bicocca. "Modeling the processes underlying large creeping rock slope failures."
November 2nd and 3rd	Hackathon. Organizing committee: John Aiken, Kate Heerema, Nigar Abbasova, Janne Hoff
November 3rd	Thorsten Becker, University of Texas. "Cross-scale models of subduction and megathrust dynamics."
November 10th	J. S. Wettlaufer, Yale. "Films shape the world."
November 17th	David Marsan, ISTerre, CNRS, Université de Savoie. "Small earthquakes as indirect measures of slow slip."
November 24th	Mogens Jensen, Niels Bohr Institute, University of Copenhagen. "DNA repair, Droplet Formation and Chaos in Cells."
November 29th	The CO_2 Basalt seminar. Organizing committee: Marthe Grønlie Guren, Marija Plather Rosenqvist, Rakul Maria Johannsen
January - December	The PoreLab lecture series are organized alternating with the Porous Media Tea Time Talks (#PorousMediaTTT) usually on Wednesdays from 13:00 to 14:00. The series are held simultaneously in Oslo (UiO) and Trondheim (NTNU). The Porous Media Tea Time Talks is webinar series created and organized by a team of 5 young porous media researchers from 5 different groups: Marcel Moura (University of Oslo), Maja Rücker (Imperial College London, UK), Kamaljit Singh (Heriot-Watt University, UK), Tom Bultreys (Ghent University, Belgium) and Mohammad Nooraiepour, University of Oslo, Norway

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Published in 2023

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1. **Barras, Fabian**, and Nicolas Brantut (2023). *"Shear Localisation Controls the Dynamics of Earthquakes."* arXiv.Org. July 31. https://arxiv.org/abs/2307.16820.

2. **Bouchayer, C.**, Nanni, U., Lefeuvre, P.-M., Hult, J., Schmidt, L. S., Kohler, J., **Renard, F.**, Schuler, T. (2024) "*Multi-scale variations of subglacial hydro-mechanical conditions at Kongsvegen glacier, Svalbard.*" The Cryosphere, in revision.

3. **Combriat Thomas**; Olsen Petter Angell; **Lastad Silja Borring; Malthe-Sørenssen Anders;** Krauss Stefan and **Dysthe, Dag Kristian**. (2023). "*Acoustic wave-induced stroboscopic optical mechanotyping of adherent cells.*" bioRxiv.

4. **Dziadkowiec, J., Linga, G.**, Kalchgruber, L., Kavunga, S., Cheng, H-W., Nilsen O., Campsteijn, C., Pokroy, B., Valtiner M. (2024). *Electrochemically-assisted Growth of Hopper and Tabular Calcite under Confinement.* Crystal Growth and Design (under review).

5. **Galland O.**, Villar H. J., Mescua J., Jerram D. A., Messager G., Medialdea A., Midtkandal I., Palma J. O., Planke S., Augland L. E., Zanella A., in press. "*Structural control of igneous intrusions on fluid migration in sedimentary basins: the case study of large bitumen seeps at Cerro Alquitrán and Cerro La Paloma, northern Neuquén Basin, Argentina.*" Geological Society, London, Special Publications, v. 547

6. Giuntoli, F., **Menegon, L.**, Siron, G., Cognigni, F., Leroux, H., Compagnoni, R., Rossi, M., Vitale-Brovarone, A. (2024) "*Methane-hydrogen-rich fluid migration may trigger seismic failure in subduction zones at forearc depths.*" Nature Communications, in press

7. Lombardo, E. F., **Galland, O.**, Yagupsky, D., and Jerram, D. A., (2024) "*Characterization of a structural trap associated with an intrusive complex: the El Trapial Oil Field, Neuquén basin, Argentina.*" Geological Society, London, Special Publications, v. 547, no. 1, p. SP547-2023-2098.

8. Madathiparambil, A. M., Mirzaei, F., Tekseth, K. R., **Cordonnier, B.**, Agofack, N., Cerasi, P., **Renard, F.**, Chattopadhyay, B., Breiby, D. W. (2024) "*Mechanical response of cement and shale admixtures under cyclic triaxial loading monitored by in-situ synchrotron micro-computed tomography.*" Cement and Concrete Research, submitted.

9. **Mathiesen, J., McBeck, J., Cordonnier, B.**, Ben-Zion, Y., **Renard, F.** (2024) "*Deep-learning analysis of fracture networks leading to system-size failure in rocks.*" submitted.

10. **McBeck, J., Cordonnier, B.**, Ben-Zion, Y., **Renard, F.** (2024) "*The relationship between deformation localization and catastrophic failure in fluid-saturated crystalline rocks in upper crustal conditions.*" Tectonophysics, 871, 230191.

11. Nigardsøy, Bjørg Synnøve; Nilsen, Vegard; Karlsen, Tom Arild & **Mossige, Joachim** (2023). "*Characterization of particle removal in an airlift pump with a U-bend.*" arXiv.org. ISSN 2331-8422.

12. Palma J. O., Rabbel O., Spacapan J. B., Ruiz R., **Galland, O.** "*The Cara Cura intrusive complex, Neuquén Basin, Argentina: a field analogue of a whole igneous petroleum system.*" Geological Society, London, Special Publications, v. 547. In press.

13. Pomyalov, Anna, **Fabian Barras**, Thibault Roch, Efim A. Brener, and Eran Bouchbinder (2023). *"The Dynamics of Unsteady Frictional Slip Pulses."* arXiv.Org. August 23. https://arxiv.org/abs/2306.02311.

14. **Rosenqvist, M. P.**, Millet, J. M., Planke, S., **Johannesen, R. M.**, Passey, S. R., Sørensen, E. V., Vosgerau, H., & **Jamtveit, B.** (2024). "*The architecture of basalt reservoirs in the North Atlantic Igneous Province with implications for basalt carbon sequestration.*" Geological Society, London, Special Publications, 547(1), SP547-2023.

15. **Shafabakhsh, P., Cordonnier, B.**, Pluymakers, A., Le Borgne, T., **Mathiesen, J., Linga, G., Hu, Y.**, Kaestner, A., **Renard, F.** (2024) "*Dynamic neutron imaging of solute transport and fluid flow in sandstone before and after mineral precipitation.*" Water Resources Research. In press.

16. Toffol, G., Pennacchioni, G., **Menegon, L.**, Wallis, D., Faccenda, M., Camacho, A., Bestmann, M. (2024) "*On-fault earthquake energy density partitioning from shocked garnet in an exhumed seismic mid-crustal fault.*" In press.

17. Wang, J., **Dziadkowiec, J.**, Liu, Y., Jiang, W., Zheng, Y., Xiong, Y., Peng, P., **Renard, F.** (2024) "*Combining atomic force microscopy and nanoindentation helps characterizing in-situ mechanical properties of organic matter in shale.*" International Journal of Coal Geology, 104406.

18. Wang, L., Kwiatek, G., **Renard, F.**, Guérin-Marthe, S., Rybacky, E., Bohnhoff, M., Naumann, M., Dresen, G. (2024) "*Injection-induced seismicity controlled by fault roughness.*" PNAS, 121 (3), e2310039121

19. Xue, C., **McBeck, J.**, Lua H., Yan, C., Zhong J., Wue, J., **Renard, F.** (2024) "*Classification of shale lithofacies with minimal data: application to the Early Permian shales in the Ordos Basin, China.*" Journal of Asian Earth Sciences, 259, 105901.

20. Yin, Xueqing, **John M Aiken**, and Jonathan L Bamber (2023). *"Fdmr: A Comprehensive R Package for Spatio-Temporal Modelling."* University of Bristol. August 30. https://research-information.bris.ac.uk/en/publications/fdmr-a-comprehensive-r-package-for-spatio-temporal-modelling.

21. Yin, Xueqing, **John M. Aiken**, Richard Harris, and Jonathan L. Bamber (2023). *"Spatio-Temporal Spread of COVID-19 and Its Associations with Socioeconomic, Demographic and Environmental Factors in England: A Bayesian Hierarchical Spatio-Temporal Model."* arXiv.Org. August 18. https://arxiv.org/abs/2308.09404.

22. **Zertani, S., Menegon, L.**, Whitehouse, M.J., **Jamtveit, B.** (2024) "*Dating fossil lower-crustal earthquakes by in-situ apatite U-Pb geochronology.*" In press.

23. **Zertani, S.**, Morales, L.F.G., **Menegon, L.** (2024) "*Omphacite breakdown: nucleation and deformation of clinopyroxene-plagioclase symplectites.*" Submitted.

Invited talks

1. **Brodin J. F., Rikvold P. A., Moura M., Pierce K., Toussaint R., Måløy K. J.**, *"Experimental investigation of two-phase flow with a table-top optical scanner: the competition between viscous and gravitational effects under different boundary conditions"*, InterPore 15th International Conference on Porous Media & Annual Meeting, Edinburgh, Scotland (2023).

2. **Guren, M.G.** (2023). *CO_2 storage in basalt and nanoscale modelling of fracturing in silica and basalt.* Paris Institute of Planetary Physics, Paris, France 13 November 2023.

3. **Guren, M.G.** (2023). *Machine-learned interatomic potential for modelling nanoscale fracturing in silica and basalt.* CECAM Flagship School - Machine learning interatomic potentials: Theory and practice. Helsinki, Finland, 6-10 November 2023

4. **Le Borgne, T.**, Bouchez, C., **Mathiesen, J.**, Davy, P., & **Renard, F.** (2023). *Fracture networks as reactors.* American Geophysical Union, 11-15 December 2023, San Francisco, USA.

5. **McBeck, J., Renard, F., Ben-Zion, Y.** (2023). *Episodic delocalization in the upper crust: Implications for earthquake forecasting.* European Geosciences Union, 23-28 April 2023.

6. **Menegon, L.** (2023). *Brittle-viscous deformation cycles in the continental crust.* 6th EGU Summer School "Structural Analysis of Crystalline Rocks", 21-28 August 2023.

7. **Menegon, L.** (2023). *Earthquake nucleation and rheological transitions in the lower crust.* Congress of the Geological Society of Italy, Potenza, Italy, 20 September 2023

8. **Menegon, L.** (2023). *Earthquake nucleation and rheological transitions in the lower crust.* Ecole Normale Superieure, Paris, France, 24 January 2023.

9. **Menegon, L.** (2023). *Tectonic pressure variations drive fluid flow and brittle failure at the base of the seismogenic crust.* Institute for Energy Technology (IFE), Kjeller, Norway, 30 March 2023

10. **Menegon, L.** (2023). *Transient high stresses during the earthquake cycle in the lower crust and their preservation in the geological record.* Njord-CAS seminar, Oslo, Norway, 13 October 2023

11. **Michalchuk, S.P., Zertani, S., Renard, F.**, Plümper, O., Chogani, A., **Menegon, L.** (2023) *Dynamic evolution of porosity in lower crustal faults during the earthquake cycle.* European Geosciences Union General Assembly, 23-28 April 2023.

12. **Mossige, J.**: Invited speaker at the annual conference of the American Physical Society - Division of Fluid Dynamics (APS-DFD), November 2023, Washington D.C.

13. **Moura M.**, *"Experiments on the motion of liquids and gases through porous materials"*, META Forum Sci-Art Your Life!, Timisoara, Romania (2023)

14. **Moura M., Jankov M., Hansen A., Kjelstrup S., Bedeaux D., Flekkøy E. G. and Måløy K. J.**, *"Towards the measurement of entropy in porous media flows: our preliminary experimental attempts"*, Workshop on Upscaling of Immiscible Two-Phase Flow in Porous Media, Trondheim, Norway (2023).

15. **Moura M., Reis P., Schäfer G., Toussaint R., Flekkøy E. G., Rikvold P. A.** and **Måløy K. J.**, *"Thin film flow: fluid transport via thin liquid films in slow porous media flows"*, European Geosciences Union General Assembly, Vienna, Austria (2023).

16. **Reis, P.** (2023). *Numerical analysis of drainage in porous media using network models.* Department of Scientific Computing, Florida State University, USA, 25 October 2023.

17. **Renard, F.** (2023). *Anatomy of earthquakes in the lower continental crust,* Department of Geosciences, University of Copenhagen, Denmark, 12 April 2023.

18. **Renard, F.** (2023). *Pore-to-core scale processes involved during mineralization of carbon dioxide in basalts,* University of Minnesota, USA, 25 July 2023.

19. **Renard, F.** (2023). *The 2023 earthquake sequence in Turkey and how synchrotron imaging can help unravelling earthquake processes.* European Synchrotron Radiation Facility, Grenoble, France, 27 June 2023.

20. **Renard, F.** (2023). *The 2023 earthquake sequence in Turkey and Syria and why it is not possible to predict earthquakes (yet).* Niels Bohr Institute, University of Copenhagen, Denmark, 28 April 2023.

21. **Rikvold, P.A.**, Silva, D., Buendia, G.M., *"Multicritical Bifurcation and First-order Phase Transitions in a Three-dimensional Blume-Capel Antiferromagnet."* August 29, 2023: Invited Lunch Seminar, Center for Simulational Physics, University of Georgia, Athens, GA, USA. Via Zoom.

22. **Rosenqvist, M. P., Menegon, L., Dunkel, K., Planke, S., Johannesen, R. M., Guren, M.** (2023). *CO2Basalt: Flow and Mineral Sequestration of Carbon Dioxide in Basalts Offshore.* Royal Society of Chemistry Talks, Plymouth, 9 October

Conference talks

1. **Aspaas, A.**, Lacroix, P., Langet, N., Sena, C., Kristensen, L., Etzelmüller, B., and **Renard, F.** (2023). *What causes creep bursts in the Åknes landslide, Norway?* World Landslide Forum, 14-17. November 2023.

2. Bader, J., Nehring, A., Zhu,W., Montesi, L., Qi, C., **Cordonnier, B.**, **Renard, F.** & Kohlstedt, D. L. (2023). *Strain-dependent Melt Orientation, Melt Connectivity, and Permeability in Partially Molten Olivine-Basalt Aggregates.* American Geophysical Union, 11-15 December 2023, San Francisco, USA.

3. **Bouchayer, C.**, Nanni, U., Lefeuvre, P. M., Hulth, J., Schmidt, L. S., Kohler, J., **Renard, F.**, Schuler, T. V. (2023). *Multi-scale variations of hydro-mechanical conditions at the base of the surge-type glacier Kongsvegen, Svalbard,* European Geosciences Union, 23-28 April 2023.

4. **Dunkel, K. G.** and **Jamtveit, B.** (2023). *Formation and evolution of inversely-zoned "complex feldspar" in the lower crust.* EGU General Assembly, EGU23-4953.

5. **Dziadkowiec, J** (2023). *Confined Crystal Growth Experiments in Surface Forces Apparatus.* 8th International Crystallization in Porous Media Workshop, 13-15 June, Ghent, Belgium.

6. Filiberto, Lorena H., **Håkon Austrheim**, and Andrew Putnis (2023). "*Deformation And Fluid-Infiltration Influence In The Evolution Of The Krossøy Dyke-Swarm In The Northern Part Of The Bergen Arcs, Norway*". doi:10.5194/egusphere-egu23-5460.

7. **Guren, M. G., Sveinsson, H. A., Malthe-Sørenssen, A.,** Caracas, R., **Renard, F.** (2023). *Machine-learned interatomic potentials for modelling nanoscale fracturing in silica and basalt.* European Geosciences Union, 23-28 April 2023.

8. **Guren, M. G., Sveinsson, H. A., Malthe-Sørenssen, A.,** Caracas, R., **Renard, F.** (2023). *Nanoscale modelling of reaction-induced fracturing.* CO_2 Basalt workshop, Norges Geotekniske Insitutt (NGI), 14 February 2023

9. **Guren, M.G., Sveinsson, H. A., Malthe-Sørenssen, A.,** Caracas, R., **Renard, F.** (2023). *Machine-learned interatomic potentials for nanoscale fracturing of quartz and basalt,* Conference Flow and Deformation Across Scales, Porto de Galinhas, Brazil, 14-17 March 2023.

10. **Guren, M.G., Sveinsson, H. A., Malthe-Sørenssen, A.,** Caracas, R., **Renard, F.** (2023). *Molecular modelling of basalt surfaces,* CO2Basalt seminar, Oslo, Norway, November 2023

11. **Guren, M.G., Sveinsson, H. A., Malthe-Sørenssen, A.,** Caracas, R., **Renard, F.** (2023). *Nanoscale fracturing of silica and basaltic glass,* Earthflows, Oslo, Norway, June 2023

12. Heier, N. , Chakravarti, A. , **Røyne, A.** & Parrish, K (2023). "*Exploring How Lean Project Delivery Supports Carbon Capture, Utilization, and Storage for Industrial Retrofits.*" Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31) , 531-539. doi.org/10.24928/2023/0238

13. **Jain, Harish P**, Axel Voigt, and **Luiza Angheluta** (2023), *Energy profiles and statistics of spontaneous T1 transitions in confluent tissues* in American Physical Society March Meeting, Las Vegas, USA, March 2023

14. **Johannesen, R. M.** (2023) *Fractures in basalt as a reservoir for permanent CO_2 storage on the Faroe Islands.* Conference Flow and Deformation Across Scales, Porto de Galinhas, Brazil, 14-17 March 2023

15. **Johannesen, R. M.** (2023) *Multiscale structural mapping of volcanic sequences on the Faroe Islands - Implications for CO_2 sequestration in basalts.* CO2Basalt seminar, Oslo, Norway, November 2023

16. Noiriel, C., **Guren, M.G., Renard, F.** (2023). *Linking microscale to macroscale dissolution rates in carbonates with X-ray tomography imaging and stochastic modelling.* Goldschmidt Conference, 9-14 July 2023.

17. Olgiati, M; **Dziadkowiec, J;** Celebi, A; Mears, L; Valtiner M (2023). *Towards understanding interfacial thermodynamics: visualising and quantifying cation adsorption on muscovite mica with AFM.* AVS 69th International Symposium & Exhibition, 5-10 November, Oregon, USA.

18. **Pierce, K; Moura, M; Linga, G** (2023). *Hallmarks of chaotic mixing in two dimensional unsteady porous media flows.* Interpore Annual Conference, Edinburgh, Scotland, 22-25 May 2023.

19. **Pierce, K; Renard, F; Le Borgne, T; Linga, G** (2023). *Chaotic mixing in two-dimensional unsteady porous media flow.* Conference Flow and Deformation Across Scales, Porto de Galinhas, Brazil, 14-17 March 2023.

20. **Pierce, K; Renard, F; Le Borgne, T; Linga, G** (2023). *Progress in stochastic descriptions of fluid-driven sediment transport.* Earthflows, Oslo, Norway, June 2023.

21. **Pierce, K; Renard, F.; Le Borgne, T; Linga, G** (2023). *Impact of the solid structure on solute mixing in porous media flows,* Interpore Norway Annual Meeting, Oslo, Norway, Nov. 2023.

22. Pinel, V., **Galland, O.**, Furst, S., Métral, L., Camus, B., and Maccaferri, F.: *Surface displacement field induced by an ascending Weertman crack: numerical modeling versus analogue experiments.*, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-5645, https://doi.org/10.5194/egusphere-egu23-5645, 2023

23. **Renard, F.**, **Cordonnier, B.**, Doan, M.-L., Hollingsworth, J., **Barras, F.**, Fondriest, M., & **Prastyani, E.** (2023). *High-speed synchrotron imaging of rock granulation during dynamic rupture propagation.* American Geophysical Union, 11-15 December 2023, San Francisco, USA.

24. **Renard, F.**, **Cordonnier, B.**, Doan, M.L., Fondriest, M., Lukic, B., **Prastyani, E.** (2023). *Dynamic damage in dry and wet rocks monitored by ultra-fast synchrotron imaging,* European Geosciences Union, 23-28 April 2023.

25. **Renard, F.**, **Cordonnier, B.**, Lukic, B., Doan, M.-L-., **Barras, F., Guren, M., Combriat, T.** (2023). *Damage during dynamic rupture: insights from high-speed experiments on rocks,* Conference Flow and Deformation Across Scales, Porto de Galinhas, Brazil, 14-17 March 2023.

26. **Rosenqvist, M. P.** (2023). *Investigating the Potential for Basalt Carbon Sequestration in the North Atlantic Igneous Province.* CO2Basalt workshop, Norges Geotekniske Institutt (NGI), 14 February 2023

27. **Rosenqvist, M. P., Menegon, L., Dunkel, K.**, Laudone, G. M., Jones, K., Nogueira, L. P., Planke, S. (2023). *Characterization of micro-pore networks and variations in calcite precipitation in basalts offshore Norway.* CO2Basalt seminar, Oslo, Norway, November 2023

28. Valtiner, M., Ramach, U., Lee, J., Altmann, F., Schussek, M., Olgiati, M., **Dziadkowiec, J.**, Mears, L. L. E., Celebi, A. T., & Lee, D. W. (2023). *Real-time visualisation of ion exchange in molecularly confined spaces where electric double layers overlap.* Iontronics: from fundamentals to ion-controlled devices Faraday Discussion, 23 June, Edinburgh, United Kingdom

Posters and PICOs

1. **Aspaas, A.**, Lacroix, P., Langet, N., Sena, C., Kristensen, L., Etzelmüller, B., and **Renard, F. (2023).** *What causes creep bursts in the Åknes landslide, Norway?* Joint Technical Committee on Natural Slopes and Landslides (JTC1) Workshop on Impact of global changes on landslide hazard and risk. Oslo, Norway on 7th – 10th June 2023.

2. **Cordonnier, B.**, **Renard, F.** (2023). Poster. *Observe with a keen ear: Cracking the Earthquake Mechanisms with KORE and HADES Experimental Fleet.* American Geophysical Union, 11-15 December 2023, San Francisco, USA.

3. **Guren, M. G., Sveinsson, H. A., Malthe-Sørenssen, A., Renard, F.** (2023). *Modelling of nanoscale fracturing in basaltic glass.* Nordvulk summer school: Carbon capture, utilization and storage in the Nordic countries, 27 August - 1 september, Iceland.

4. **Jain, Harish P**, Axel Voigt, and **Luiza Angheluta**, *T1 transitions in Confluent Tissues*, The Geilo School 2023, The Physics of Evolving Matter Continued Connectivity, Communication and Growth

5. **Johannesen, R. M., Galland, O.**, Ólavsdóttir, J., Kjøll, H. J., Eidesgaard, Ó., Planke, S. (2023). *Fractured basalt as reservoirs for permanent CO_2 storage on the Faroe Islands.* Nordvulk summer school: Carbon capture, utilization and storage in the Nordic countries, 27 August - 1 september, Iceland.

6. **Johannesen, R. M., Galland, O.**, Ólavsdóttir, J., Kjøll, H. J., Eidesgaard, Ó., Planke, S. (2023). *Fractures in basalt as a reservoir for permanent CO_2 storage on the Faroe Islands.* Nordic Geological Winter Meeting, 4-6 January 2023, Trondheim, Norway

7. **Michalchuk, S. P., Dunkel, K.**, Ohl, M., and **Menegon, L.**: *Deformation and healing processes in the damage zone of a lower-crustal seismogenic fault,* EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-3414, https://doi.org/10.5194/egusphere-egu23-3414, 2023.

8. **Pierce, K; Moura, M; Linga, G** (2023). *Chaos in flatland: mixing in unsteady two dimensional porous media flow.* European Geosciences Union, 23-28 April 2023.

9. **Prastyani, E.**, **Cordonnier, B.**, **McBeck, J A.**, **Renard, F.** (2023). Crack growth in Westerly granite core with pre-existing notches under triaxial compression. 15th Euroconference on Rock Physics and Rock Mechanics, Woudschoten, The Netherlands, 23-26 October 2023.

10. **Prastyani, E.**, **Cordonnier, B.**, **McBeck, J A.**, Wang, L., Rybacki, E., Dresen, G., **Renard, F.** (2023). *Microphysical characterization of crack growth and the transition from brittle to semi-brittle deformation in crustal rocks.* UGCT course: X-ray tomography image processing with deep learning, Ghent, Belgium, 06-08 February 2023.

11. **Rosenqvist, M. P.**, **Dunkel, K. G.**, Galerne, C., Planke, S., **Menegon, L.**, and the Expedition 396 Scientists (2023). Mechanisms of Natural Carbon Sequestration by Calcite Precipitation in Basalts of the Mic-Norwegian Magmatic Margin. Nordvulk summer school: Carbon capture, utilization and storage in the Nordic countries, 27 August - 1 september, Iceland.

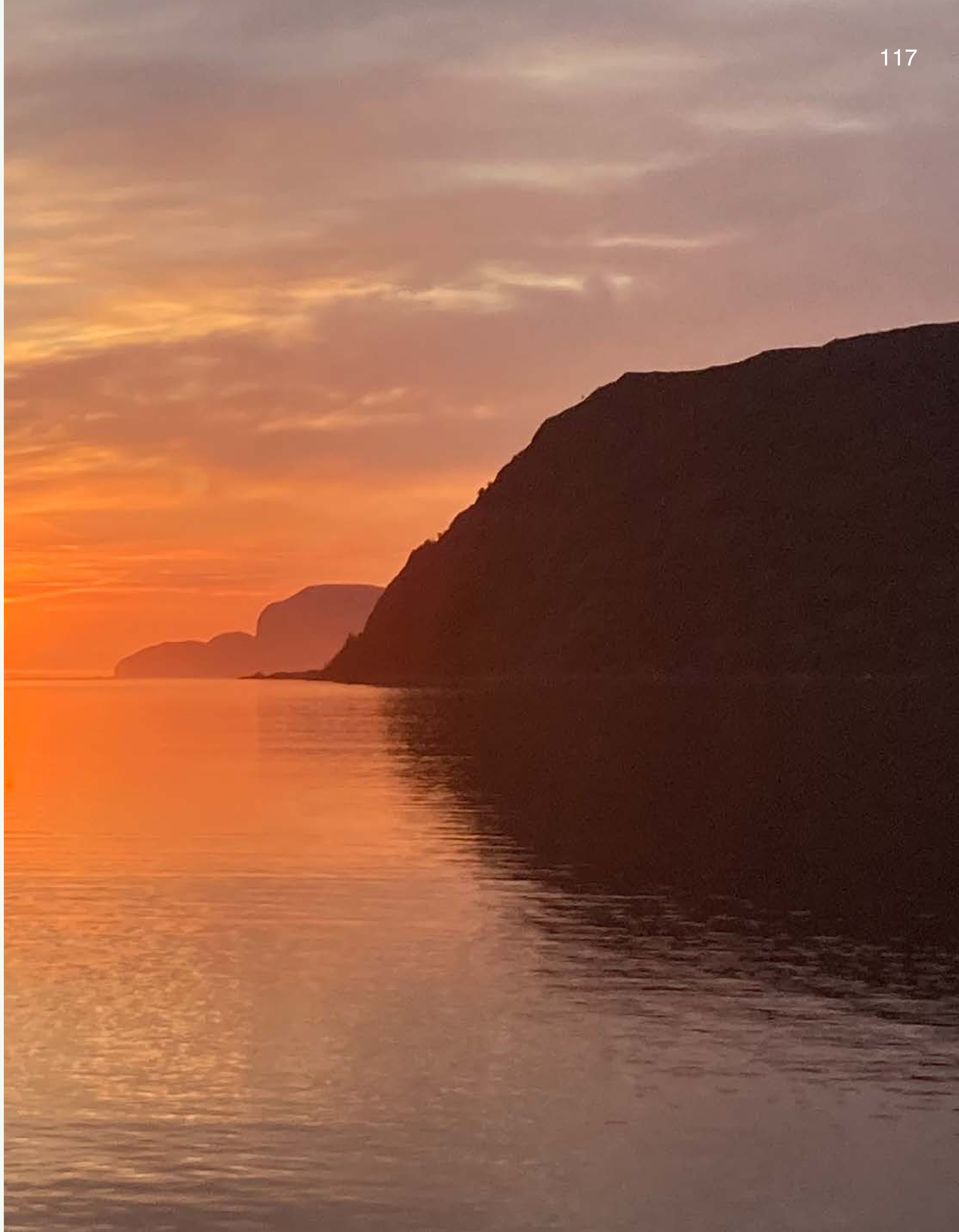
12. **Rosenqvist, M. P.**, Planke, S., **Dunkel, K.**, **Galland, O.**, **Menegon, L.** (2023). *Multi-scale flow pathways in basalts of the North Atlantic Igneous Province: Implications for CO_2 storage.* DEEP Summer School 2023: Magmatiske prosesser og avsetninger i Nordøst-Atlanteren, 25 June - 3 July 2023, Iceland

13. **Shafabakhsh, P.**, **Le Borgne, T.**, **Mathiesen, J.**, **Linga, G.**, **Cordonnier, B.**, Pluymakers, A., Kaestner, A., **Renard, F.** (2023). *Dynamic neutron and x-ray three-dimensional imaging of fluid flow and mixing during mineral precipitation in porous rocks,* European Geosciences Union, 23-28 April 2023.

14. **van Schrojenstein Lantman, H.** and **Menegon, L.**: *Reconstructing the localized transient high stress state of seismogenic faults in the lower crust,* Lofoten, Norway, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-9750, https://doi.org/10.5194/egusphere-egu23-9750, 2023.

Media and outreach

1. Bjørnar Sandnes, **Knut Jørgen Måløy** and **Eirik Grude Flekkøy**. (2023) "*Granular Labyrinth*" Album of Porous Media, doi: 10.1007978-3-031-23800-0_55.
2. **Brodin, Joachim Falck, Knut Jørgen Måløy, Marcel Moura,** and **Per Arne Rikvold** (2023). "*Rising Invader*". Album Of Porous Media, 55-55. doi:10.1007/978-3-031-23800-0_41.
3. **Brodin, Joachim Falck, Per Arne Rikvold, Marcel Moura,** and **Knut Jørgen Måløy.** (2023). "*Invasion Pattern*". Album of Porous Media, 59–59. doi:10.1007/978-3-031-23800-0_45.
4. **Dunkel, K. G.** (2023). GeoOnsdag: *Mineralreaksjoner under lupen - Vitner fra fortiden og løsninger for fremtiden.* (Popular science talk about mineral reaction at UiO's science library.)
5. Einevold, Gaute & **Mossige, Joachim** (2023). *Vett og Vitenskap med Gaute Einevold: Om kjøkkenfysikk - med Joachim Mossige.* https://vettogviten-skap.no og som Apple podcast.
6. **Galland O.** *Interview for article in Dagbladet about Iceland eruption* (19.12.2023)(https://www.dagbladet.no/nyheter/kan-bli-krise/80699389)
7. **Galland O.** *Interview for Nettavisen about submarine eruption in Japan* (29.11.2023) (https://www.nettavisen.no/nyheter/se-det-spektakulare-vulka-nutbruddet-veldig-sp-esielt/v/5-95-1487926)
8. **Galland O.** *Interview for VGTV on Iceland eruption* (19.12.2023)
9. **Galland O.** *Invitations for studio interviews at NRK TV Morgen Nyheter and TV2 God Morgen Norge* (19.12.2023)(declined)
10. **Galland O.** *Lab visit for 8th grade from French school* (18.01.2023)
11. **Galland O.** *Studio interview NRK TV Morgen Nyheter about volcanotectonic crisis in Iceland* (06.11.2023)
12. **Kristian Stølevik Olsen, Eirik Grude Flekkøy, Knut Jørgen Måløy** and James Campbell. (2023). "*Frictional Finger Labyrinth*" Album of Porous Media, 72-72. doi: 10.1007978-3-031-23800-0_56
13. Le Xu, **Knut Jørgen Måløy, Renaud Toussaint, Eirik Grude Flekkøy** and Benjy Marks. (2023). "*Dispersion patterns with tracer flow in fractures*" Album of Porous Media, 51-51, doi: 10.1007978-3-031-23800-0_37
14. **Linga, G., Mathiesen, J., Renard, F., Le Borgne, T.** (2023). *"Fingerprints of Chaos in a Two-Phase Porous Media Flow."* In: Médici, E.F., Otero, A.D. (eds) Album of Porous Media. Springer, Cham. https://doi.org/10.1007/978-3-031-23800-0_64.
15. **Mossige, Joachim** (2023). *Felleskollokvium ved fysisk institutt* (Felleskollokvium at the Dept. Physics)
16. **Mossige, Joachim** (2023). *NRK P2 Abels tårn paneldeltaker på Realfags-biblioteket* 17.10.2023 (NRK P2 Abels tårn panelist at UiO's science library)
17. **Moura, Marcel,** and **Knut Jørgen Måløy.** (2023). "*Viscous Fingering Fractal in a Porous Medium*". Album of Porous Media, 53–53. doi:10.1007/978-3-031-23800-0_39.
18. **Renard, F.** (2023). *"Imaging the Path to Failure in Rocks."* In: Médici, E.F., Otero, A.D. (eds) Album of Porous Media. Springer, Cham. https://doi.org/10.1007/978-3-031-23800-0_96.
19. Vogt, Yngve; Krauss, Stefan Johannes Karl; **Mossige, Joachim; Dysthe, Dag Kristian; Angheluta, Luiza** & Jenseni-us, Alexander Refsum (2023). *Bereder grunnen for kunstige organer.* [Busi-ness/trade/industry journal]. Apollon.



Project portfolio

Active projects in 2023

Project leader	Project title	Host	Funding Source	Project Start Date	Project End Date	Total Funding (NOK in 1000)
Aiken, John	The rate and mechanisms of active serpentinization of peridotites from the Semail ophiolite, Oman (SerpRateAI)	The Njord Centre	RCN	01.08.2023	31.07.2026	4 300
Angheluta, Luiza & Renard, François	EarthFlows	The Njord Centre	UiO	01.01.2019	31.12.2023	9 440
Dysthe, Dag & Angelutha, Luiza	Integrated technologies for tracking organoid morphogenesis (ITOM)	The Njord Centre	UiO	01.04.2022	30.03.2026	2 565
Dziadkowiec, Joanna	Surface Forces Apparatus studies of mineral growth in confinement	The Njord Centre	UiO	01.01.2023	31.12.2023	135
Flekkøy, Eirik & Måløy, Knut Jørgen	Porous Media Laboratory (PoreLab)	Dept. of Physics	RCN	01.07.2017	30.06.2027	66 400
Galland, Olivier	How inelastic properties of crustal rocks control the propagation of dykes and sills in volcanic plumbing systems (BEYOND ELASTICITY)	The Njord Centre	RCN	01.07.2023	30.06.2026	12 000
Galland, Olivier	The geology of supercritical geothermal systems	The Njord Centre	UiO	01.01.2023	31.12.2024	400
Linga, Gaute	Mixing in multiphase flows through microporous media (M4)	The Njord Centre	RCN	01.12.2021	30.11.2025	8 000
Malthe-Sørenssen, Anders	Training in computational science: CompSci	The Faculty of Mathematics and Natural Sciences	EU, CoFund	01.10.2021	31.10.2025	15 390
Malthe-Sørenssen, Anders	History-dependent friction	The Njord Centre	RCN	01.07.2019	31.01.2024	9 229
McBeck, Jessica	Emergent networks: Predicting strain localization and fracture network	The Njord Centre	RCN	01.09.2020	28.02.2025	6 852
Menegon, Luca	Conditions for earthquake nucleation in the lower crust (CONTINENT)	The Njord Centre	RCN	08.01.2023	31.07.2027	12 000
Michalchuk, Stephen	ToF-SIMS trace-element geospeedometry and mapping fluid infiltration pathways in lower-crustal earthquakes	The Njord Centre	UiO Unifor	01.01.2023	31.12.2023	107
Moura, Marcel	Connectivity enhancement due to thin liquid films in porous media flows (FlowConn)	The Njord Centre	RCN	01.09.2021	31.08.2025	8 000
Renard, François & Knut-Jørgen Måløy	Collaboration on flow across scales, Norway, Brazil, France, USA (COLOSSAL)	The Njord Centre	RCN	01.12.2020	31.05.2025	4 490
Renard, François	Visualizing multiphase flow in porous media with neutron imaging (PoreFlow)	NTNU (UiO partner)	RCN	01.12.2020	30.06.2024	900
Renard, François	Break-through rocks (BREAK)	The Njord Centre	EU, ERC	01.01.2022	31.12.2026	35 000
Renard, François	CO_2 Basalts	The Njord Centre	UiO	01.04.2022	31.03.2025	7 695
Renard, François	Friction and fracture and the onset of geohazards (FricFrac)	CAS/ The Njord Centre	CAS	01.08.2023	01.06.2024	3 500

Projects starting in 2024

Project leader	Project title	Host	Funding Source	Project Start Date	Project End Date	Total Funding (NOK in 1000)
Barras, Fabian	UNLOC	The Njord Centre	RCN	01.03.2024	28.02.2027	8 000
Dziadkowiec, Joanna	REACT	The Njord Centre	RCN	07.01.2024	06.01.2027	8 000
Linga, Gaute	Mixing by interfaces	CAS/ The Njord Centre	CAS	01.01.2024	31.12.2024	700
Bierbaumer, Katharina	Unraveling the magmatic evolution of the Larvik Plutonic Complex using U-Pb dating of zircon	The Njord Centre	UiO Unifor	01.01.2024	31.12.2024	100

UiO: University of Oslo
EU: European Union
ERC. European Research Council
RCN: Research Council of Norway
CAS: Centre for Advanced Study at the Norwegian Academy of Science and Letters

Contact

njord-post@mn.uio.no
www.mn.uio.no/njord/ english

Postal Address

Njord
P.O. 1048 Blindern
0316 Oslo, Norway

Visiting Address

3rd floor, west wing, Physics Building
Sem Sælands vei 24
Blindern, University of Oslo, Norway