UNIVERSITETET
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NJORD

Annual report 2022

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

Preface

“Real breakthroughs are not found because you want to develop some new technology, but because you are curious and want to find out how the world is.”

– Anton Zeilinger

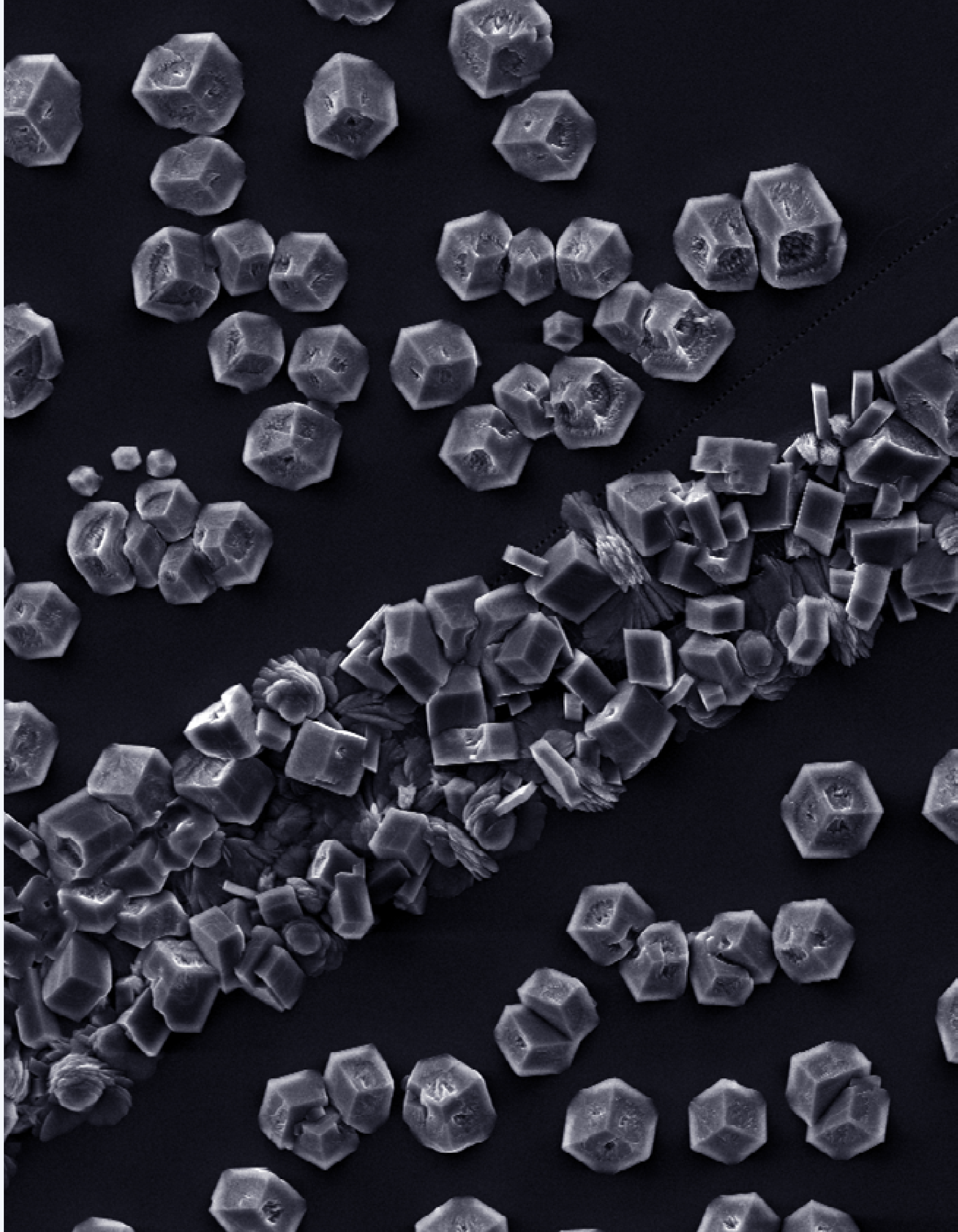
In 2022, the Njord Centre has grown and has come back to normal activities after two years of pandemics. We have maintained a high level of publications, around sixty five this year; we have organized and contributed to several conferences in Norway and abroad; we have hosted international researchers; we have visited research groups abroad; and we have submitted and obtained highly competitive research proposals. Several research projects have started this year and seventeen early career researchers, coming from a dozen of countries all over the world, arrived in Njord. I would like to welcome all of them: the diversity they bring is an asset our research builds on. This diversity ensures that new ideas, ways of thinking, and cultures will nurture the group and that our cross-disciplinary research will have an impact that contributes building a society of knowledge.

At the Njord Centre, we perform mainly basic research with the objective to push the frontiers of knowledge through our curiosity-driven approach. We also perform applied research because outstanding scientific questions may arise from specific problems. For example, our project CO2-Basalt, funded by the Sustainability call organized by the Faculty of Mathematics and Natural Sciences, is driven by the idea that volcanic rocks in the North Sea may store huge amounts of carbon dioxide, and provide a mitigation solution to reduce the effect of climate change. This project involves geological applications and basic research on the flow in porous media and fluid-rock interactions where geologists and physicists of Njord work in concert. This is a great example where our research is both knowledge-driven and solution-driven, breaking the artificial boundary sometimes created between basic and applied research.

In 2023, the geology and physics components of Njord will be reviewed by international panels in the framework of the evaluation organized by the Research Council of Norway. This evaluation will critically assess our research performance in an international context. The Njord Centre will thus be able and willing to draw conclusions based on the outcome of this evaluation to maintain the high level of basic research we promote. Doing so, our goal is to improve our scientific impact to contribute making the departments of Physics and Geosciences, the Faculty of Mathematics and Natural Sciences, and the University of Oslo successful and relevant to the society in Norway, in Europe, and beyond.

Blesle, December 30th, 2022

François Renard
Director of the Njord Centre



About Njord

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).

In 2022, the Njord Centre has defined a research strategy for the period 2023-2027 that the departments of Geosciences and Physics has approved. In the coming years, the Njord Centre will perform studies in three research directions: 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:

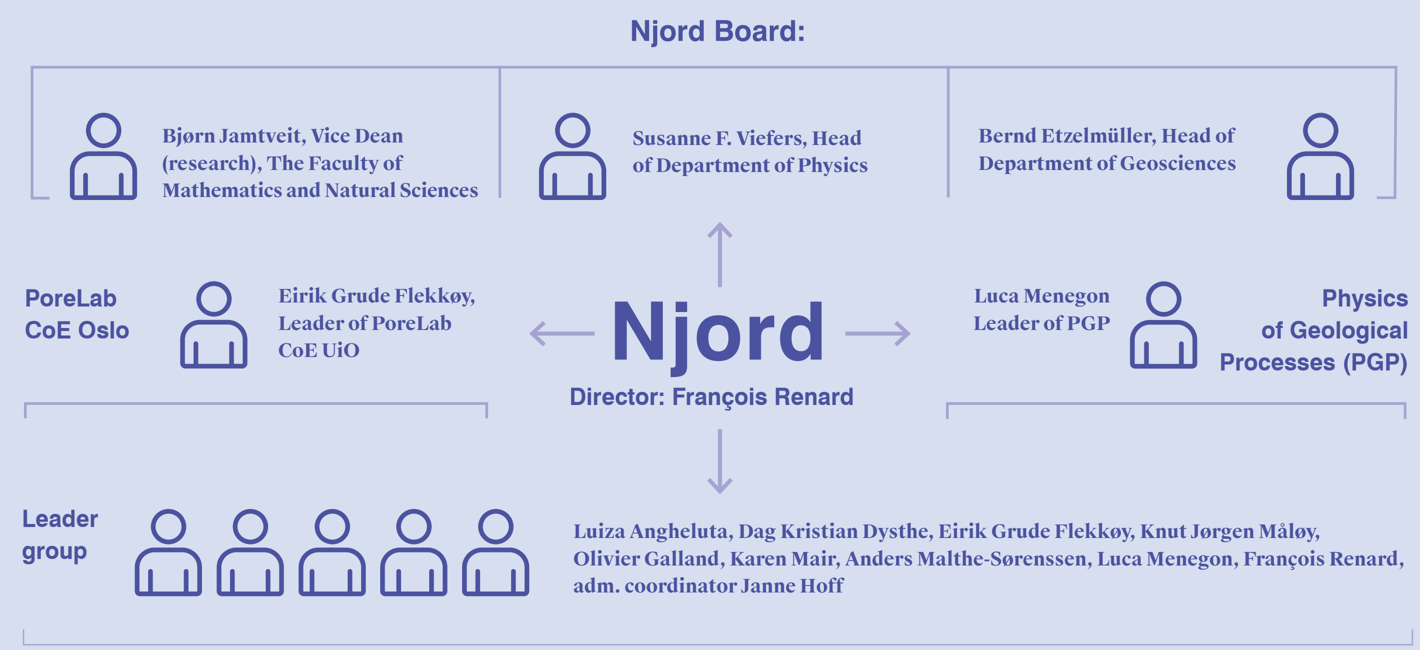
- Create an interactive co-localized organization of geoscientists and physicists conducting field geology, theory, numerical modelling and experiments in concert.
- Be an active, and often leading partner in international projects and collaborations.
- Participate in international projects (International 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 educational 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.

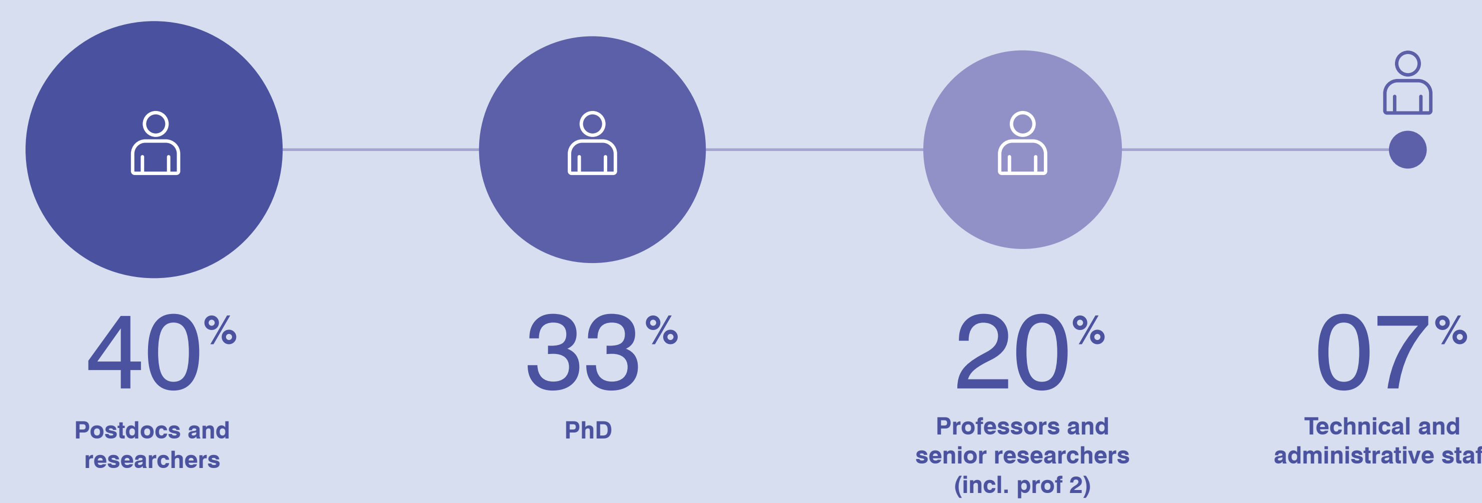
Organization

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.

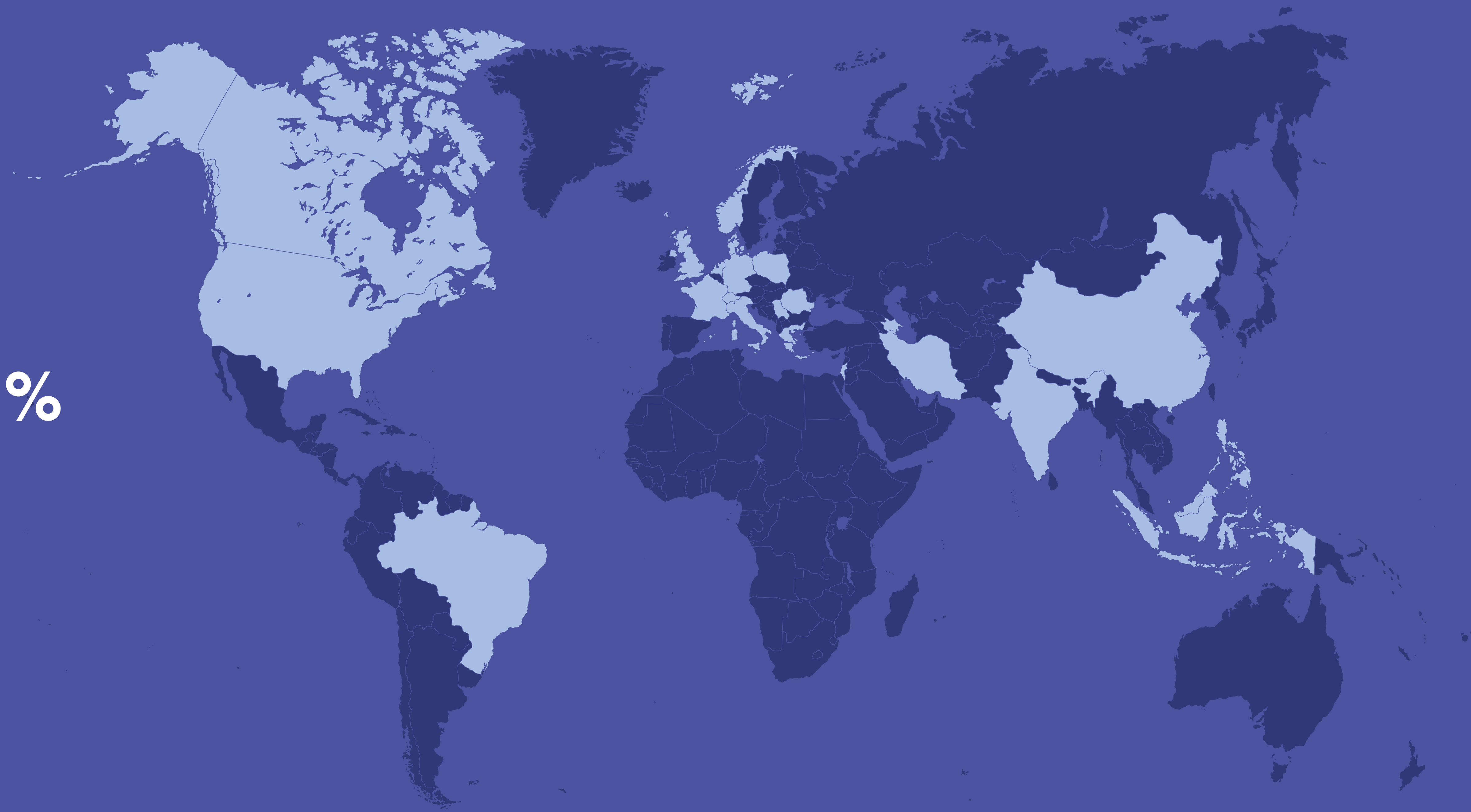
In the first years of the center (2018-2020), Njord was directed by Professor Bjørn Jamtveit. From January 1st 2021, Professor François Renard has been director of Njord. The director, assisted by the administrative coordinator, Janne Hoff, who is responsible for project management, administration, as well as technical and financial delivery. The director reports to the board. The Njord leader group includes the nine senior scientists. In total, Njord comprises about 60 members, 32 % of which are women. There are members are employed by the Department of Physics, the Department of Geosciences and directly by the Njord Centre.



Staff



Geographical origins of Njord employees



Norway

33 %

Geographical origin by percentage

11 % France

5 % Germany

4 % Canada

4 % India

3 % Brazil

3 % China

3 % Iran

3 % Italy

3 % Switzerland

3 % UK

3 % USA

2 % Azerbaijan

2 % Indonesia

2 % Poland

2 % Romania

2 % Serbia

2 % Denmark

2 % Faroe Island

2 % Greece

2 % Israel

2 % Netherlands

2 % Phillipines

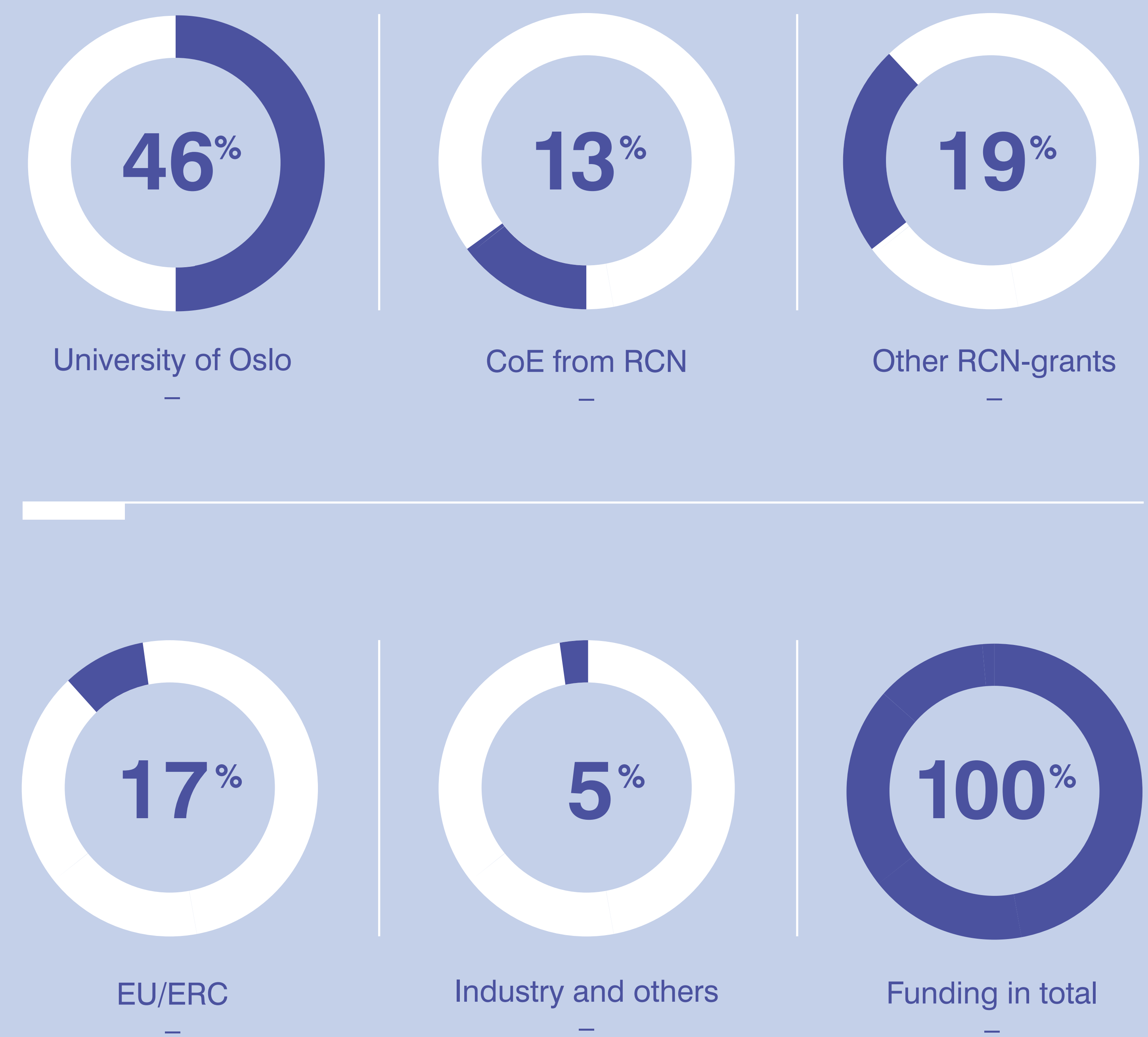
Finances and Funding

48 MNOK Funding in total in 2022

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.

Distribution of funding



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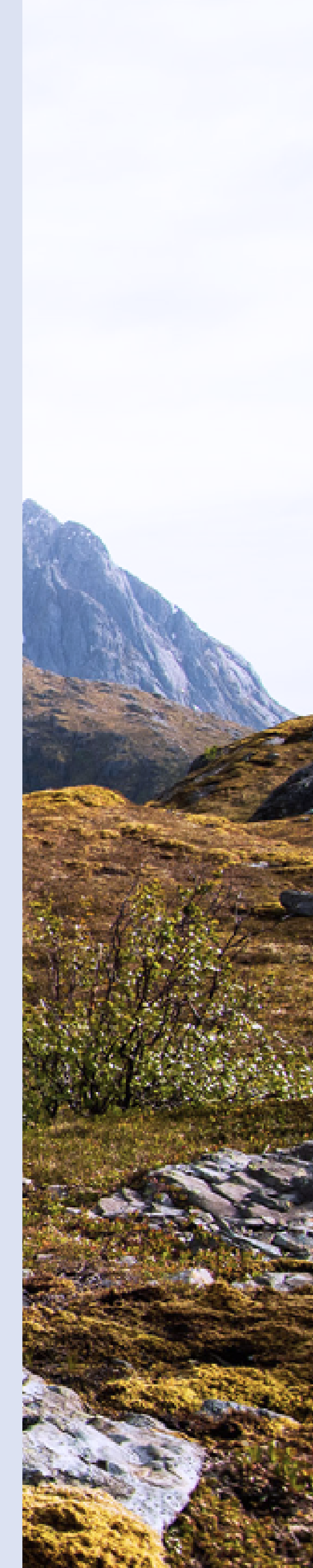
Activities at Njord



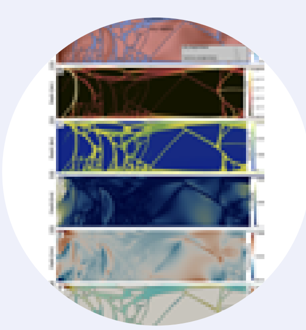
Highlights of 2022

January

The Strategy of the Njord Centre 2023-2027 is approved by the board and sets the course for the years to come.

February

Moulas, E., Kaus, B., and Jamtveit, B., Dynamic pressure variations in the lower crust caused by localized fluid-induced weakening. Communications Earth and Environment, 3, 157.

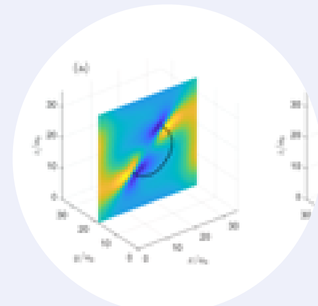


March

Marthe Guren defended her PhD "Imaging and modelling nanoscale dynamics of mineral-mineral and mineral-fluid interfaces during mechano-chemical transformations".

April

The Centre for Advanced Study selects Njord's project FricFrac for 2023/24. The project is led by Njord's professors François Renard and Anders Malthe-Sørenssen.

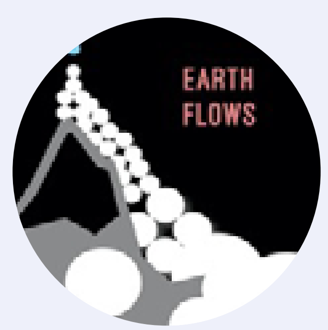


May

Skogvoll, V., Angheluta, L., Skaugen, A., Salvalaglio, M., & Viñals, J. (2022). A phase field crystal theory of the kinematics of dislocation lines. Journal of the Mechanics and Physics of Solids, 104932.

June

The 8th annual EarthFlows Seminar sets new record of 75 attendees. International guest speakers and internal speakers from the departments of Geosciences, Physics and Mathematics of UiO gave exciting talks and there were many fruitful discussions.

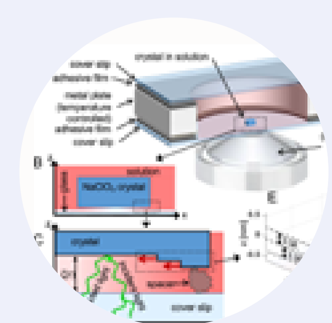


July

Best poster awards to Paula Reis and Gauta Linga during the 2022 Gordon Research Conference on Flow and Transport in Permeable Media.

August

Kohler, F., Pierre-Louis, O. & Dysthe, D.K. (2022) Crystal growth in confinement. Nature Communications, 13, 6990.

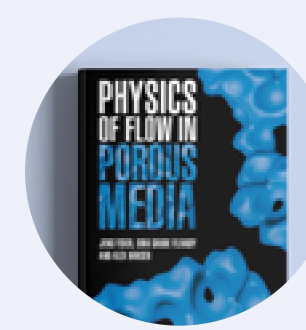


September

Luca Menegon, John Aiken and Olivier Galland receive funding from the FriPro programme of the Research Council of Norway.

October

Book release: Physics of Flow in Porous Media by Jens Feder, Eirik Flekkøy and Alex Hansen.



November

Research Professor Olivier Galland is awarded the Best Keynote presentation on "Magmatism and Petroleum Systems" at the CON-EXPLO conference in Argentina.

December

Jessica McBeck receives the Arne Richter Award from the European Geosciences Union and the Else-Ragnhild Neumann Award for Women in Geosciences 2022.

Interview

Name
Hugo van Schrojenstein Lantman

Current position:
Postdoctoral researcher

Been at UiO since:
May 2022

Hugo van Schrojenstein Lantman

"My research relies heavily on the residual stress within crystals that is caused by internal defects, so there is a lot that I can learn from the researchers at Njord who approach this topic by numerical simulations."

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

Short version: I really like rocks. Long version: Since I was a kid, I've been fascinated by geology. No matter if it was the gravel in my grandparents' driveway or the mountains we hiked up during holidays, I could never keep my eyes off the rocks, so studying Earth Sciences was a logical choice. As it turns out, almost all facets of Earth Sciences are fascinating, but I ended up with a particularly strong interest in how rocks deform, react, and transform in response to changes in their surroundings. Perhaps some kind of metaphor for how we ourselves must also adapt as the world around us continuously changes, at least for a big part by our own doing. It also fascinates me how we can unravel processes on gigantic length- and timescales by looking at the tiniest of crystals and microstructures. These factors together have led me down the path I've taken to end up working at Njord.

What are your current research projects?

My work focuses on earthquakes in the lower crust that occurred a long time ago, in what is now the Lofoten archipelago. Since these rocks are dry and incredibly strong, the stress required to fracture the rocks must have been immense. I'm building on previous and ongoing work by other researchers in Njord, adding to a working model of these earthquakes. Using a new application of electron microscopy, I am establishing spatial data sets of the stress that is preserved in crystals within and next to the fault planes, as a proxy for the stress state leading up to and during the earthquakes. I will also be performing deformation experiments to determine physical properties and deformation behavior of these crystals.

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

Not necessarily a specific publication or scientist, but research that combines several different disciplines to a greater whole has always amazed me. This is exactly the kind of work that I aim for, although we must not lose sight of the importance of fundamentals of individual disciplines.

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

My work is of course strongly related to that of many of the other geologists in Njord, particularly when it comes to earthquakes and fracturing from a variety of perspectives and scales. At the same time, my research relies heavily on the residual stress within crystals that is caused by internal defects, so there is a lot that I can learn from the researchers at Njord who approach this topic by numerical simulations.

Where do we usually find you?

I'm all over the place! When I'm not hidden away in the corner office, you can probably find me in a lab: examining samples in the microscope lab; taking that work a step further with electron microscopy in the basement of the geosciences building; processing the results in the computer lab; or performing deformation experiments with the nano-indenter in the friction lab.

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

It's an eye opener! Previously I was surrounded by other rock nerds like me, usually with similar research topics. Now being among physicists, biologists, engineers and apparently even a social scientist, is very refreshing and opens up a whole lot of new and interesting perspectives. It's also helpful in getting a better grasp on explaining my work to researchers with a different background.

Interview

Name
Paula Reis

Current position:
Postdoctoral Fellow

Been at UiO since:
April 2022

Paula Reis

"The exchange of information between people from diverse backgrounds has so far showed me how to look at the same problem from very different perspectives and led to find new applications to old tools I developed in the past."

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

I have always been interested in making tools that can bring practicality to our lives. During my undergrad in engineering, this interest was channeled into developing mathematical models that can help us understand the behavior of complex materials and phenomena taking place in nature. This had led me to engage in projects related to the investigation of unusual processes, such as the recovery of large deformation upon heating in shape memory allows in my master's, and the mechanisms of gas flow obstruction in porous media during condensing flows, in my PhD. In 2021 when I saw the job posting related to modeling an unexpected drainage mechanism in porous media, beautifully captured by the group in PoreLab/Njord with experiments, I thought that that would be a perfect opportunity for the next step in my career. I am really glad it worked out!

What are your current research projects?

I am currently working in a project named FlowConn. The project is related to two-phase flow of gases and liquids in granular porous media, and aims to investigate, more specifically, the transport properties of thin liquid films left on the surface of grains during drainage. This type of flow is very common in both natural (vadose zone in soil) and industrial processes (PEM fuel cells, CO_2 geological storage), and this line of research can help bring answers to many relevant questions related to these systems, as "What is the availability of water and nutrients for plants in soil after irrigation?" or "How much CO_2 can be safely stored after its injection in an aquifer?".

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

As an engineer coming from more homogeneous groups of research, I believe that being immerse in Njord's geosciences-physics center allowed me to have more awareness of the current challenges and relevant topics of study for scientists in fields directly related to transport in porous media. We can easily focus too much on solving a specific problem and lose track of how science is evolving beyond our narrow scope without this direct network different disciplines. Besides that, the exchange of information between people from diverse backgrounds has so far showed me how to look at the same problem from very different perspectives and led to find new applications to old tools I developed in the past.

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

The knowledge generated with the conjunction of numerical modeling and experiments in FlowConn can improve our understanding of physical processes related to several practical problems we face today. Research related to how fluids percolate porous media can help us predict the behavior of natural materials such as soil, snow, and biological tissues, engineer construction materials like cement and ceramics, and manage geological water and hydrocarbon reservoirs. Therefore, I really believe that our results can contribute to the areas far beyond academia.

Where do we usually find you?

Most of the time I am in the office v312 in the third floor, focused on my simulations. On occasion I can also be found in the laboratories underground fascinated by what other researchers in our group can achieve with flow experiments, for a change of scenario.

Interview

Name
Jonas Rønning

Current position:
Doctoral research fellow

Been at UiO since:
2018

Jonas Rønning

"In both the active system and in Bose-Einstein condensates the creation and annihilation of these defects are driving chaotic states, which are termed active- and quantum turbulence. I think it is very interesting that very similar models can be used to describe so different types of fluids."

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

When I started at UiO I chose to do my master project with Luiza Angheluta because her proposed project on quantum turbulence in Bose-Einstein condensation was interesting and was a combination of quantum and statistical physics, which was my favorite courses during the bachelors. After I finished my master, I got the opportunity to continue with a PhD on the same topic. During the first semester, we stated to use the same formalism to study defects in biological active matter.

What are your current research projects?

Currently I have been studying the dynamics and nucleation of topological defects in Bose-Einstein condensates, and in hydrodynamic models for active matter. Active matter are materials that consists of particles that takes energy from the environment and turns it into motion. This is typically biological systems like bacterial solutions. Topological defects are defects that cannot be removed by continuous deformations of the system because they are protected by the topology. The defect is localized, but it effects the entire material. In both the active system and in Bose-Einstein condensates the creation and annihilation of these defects are driving chaotic states, which are termed active- and quantum turbulence. I think it is very interesting that very similar models can be used to describe so different types of fluids.

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

There have been many. The reason I went into physics in the first place is largely due to popular science literature like "a brief history of time" by Stephen Hawking and "a short history of nearly everything" by Bill Bryson. In addition, I started high school right after the detection of the Higgs Boson, and the excitement that followed made physics seem like the place to be. More relevant to my research is the documentary "Liquid helium II: the super fluid" from 1963 which introduced me to the fascinating properties of quantum fluids.

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

Both my projects lie within the fluid dynamics part of Njord's research. The project on flow in active matter is a classical fluid dynamics problem where we consider a fluid that is made of many swimming rods, while in the project on quantum turbulence we use concepts from and draws parallels to turbulence in classical fluids.

Where do we usually find you?

I am usually at my desk working on the computer, doing some calculations, or reading. Since I do theory I could work from anywhere, but I prefer to work at the office both to have a designated workspace and to be able to discuss with others. If you don't find me at the desk, then I am most likely at or near the coffee machine.

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

My work has mostly been theoretical, and I don't think it will have any immediate applications outside of academia. We are made of biological matter and a better understanding of its mechanical properties might have medical applications in the future, and it would also be cool if my research could be used in making synthetic biological systems with nanorobotics.

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

I find it hard to answer this question because I haven't experienced any research environment outside of Njord. My general experience is that it is very nice to hear all the different perspectives and methods to get insight into a problem that are discussed at the lunch table and at the internal seminars. One also gets to see a lot of cool rocks.

Interview

Name
Silja Borring Låstad

Current position:
Doctoral Research Fellow

Been at UiO since:
August 2022

Silja Borring Låstad

"Mechanical forces are important both for rock deformation and cell behavior, though cells are not only acted upon by these forces, but also actively generate forces themselves."

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

It is a bit random that I ended up doing what I do at Njord. During my bachelor's in physics I got fascinated with complex systems and the numerous systems one can study with a background from physics. I wrote my master's thesis on population dynamics of bacteria. This in turn made me intrigued by the rich diversity even the smallest living systems possess, which made me curious to know more about living systems, such as cells. After mostly doing theoretical and numerical work, I also wanted to get more knowledge about what it means to do experimental science, since I find it a bit meaningless to work on theories that might never be tested experimentally.

What are your current research projects?

At the moment I am working on many smaller projects going in many different directions. I'm trying to simulate the behavior of the cytoskeleton and its interaction with the surrounding cell membrane during a phenomenon known as "cell drinking" (or macropinocytosis). In parallel I am culturing cells and learning experimental techniques so I can start to observe and to collect data on how the cytoskeleton moves in real cells. In the long run the plan is to focus more on the role of the cytoskeleton in cell migration.

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

It sounds cheesy, but I think I am more inspired by the scientific community as a whole, rather than by individual scientists. I find the community to be very open minded and inclusive, and I think it is great that one can get involved with research already on the bachelor's level.

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

My project is quite different from most projects at Njord, though the number of biophysics projects is increasing. Still, I think my projects have some similarities with other works at Njord. Mechanical forces are important both for rock deformation and cell behavior, though cells are not only acted upon by these forces, but also actively generate forces themselves. Flows will also be important for my project, as cell migration is driven by a retrograde flow of actin (one of the building blocks of the cytoskeleton) inside the cell.

Where do we usually find you?

I spend most of my time in my office, but I can also be found in the cell lab. And sometimes I might even be found at Department of Biosciences, among the actual biologists.

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

This is a hard question. Cell migration is important for many medically important phenomena, such as morphogenesis, the immune system and cancer metastasis. Hopefully, my research can serve as a tiny contribution in some of these fields.

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

It means that I can learn from many fields I am not actively working on myself, which might provide unexpected inspiration for my own project. It is a reminder that diversity and universality goes hand in hand across many physical systems, which I think is one of the most interesting and beautiful aspects of our world. It also means that I get to see pictures of many beautiful landscapes and envy colleagues that get to do field work in the outdoors!

Interview

Name
Rakul Maria Johannsen

Current position:
PhD fellow

Been at UiO since:
January 2022

Rakul Maria Johannsen

"I am born and raised on the basaltic rocks in the North Atlantic Ocean, and my curiosity for their origin has always been there."

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

I am born and raised on the basaltic rocks in the North Atlantic Ocean, and my curiosity for their origin has always been there. In my master I developed a 3D model of the Faroese Geology, integrating a broad specter of data. And when I graduated, I wanted to continue with this work and see if it was possible to use the model for some specific challenges. This, together with more focus on Carbon Capture and Storage (CCS), led to me designing a project on the possibilities of CCS on the Faroe Islands.

What are your current research projects?

The overall topic of the PhD is CO_2 storage in the Faroese basalt sequences, where I am mainly focusing on porosity and permeability based on fractures. Now I am trying to predict what the fracture network looks like on 600-800m depth at a specific study site. This is done with a great mixture between fieldwork, photogrammetry, and interpretations of existing data.

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

Even though I am trying hard to be an independent researcher, my great granddad Jóannes Rasmussen has inspired me a lot. He was the first geologist on the Faroe Islands and did an extensive work on the Faroese geology. As I am getting more knowledge, the respect for his work is increasing and I can see how much he has done with way less data and tools compared to what I have access to today. His work and his structured way of working is an inspiration, but also his eager of communicating the knowledge to the public inspire me. He used to say that his research did not have any value if the people did not understand it.

Where do we usually find you?

I would love to say in the field, but I am mostly sitting in front of my computer at the CO2Basalt office. However, I cannot complain as I am often working with photogrammetric models from the Faroe Islands, so it is not that far from being in the field. Since the research is in a collaboration with the Faroese Geological Survey I am working there from time to time.

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

Compared to other topics I have been working on, my current project has an applied approach. The project is aiming towards a goal of actual storing CO_2 in the subsurface, so the research hopefully leads to actual injection within the next years. This can open for our goal of the Faroe Islands being the first country with zero emission or even negative emission. This is not what I think of every day, but it is nice to have in mind those days- when your motivation is not on top.

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

It is inspiring to work in an environment where people work on different topics and approaching the challenges with different methods. It is also motivating for me to work in such a large campus as UiO and meet other PhD students working on similar topics, compared to the office on the Faroe Islands with 15 employees.

Interview

Name
Stephen Michalchuk

Current position:
PhD Researcher

Been at UiO since:
November 2020

Stephen Michalchuk

"Sometimes, gaining various experiences, utilizing your skills, figuring out exactly your interests, and waiting patiently for the right project to come along, is the correct approach."

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

Back in 2013 as I was finishing up my MSc in Sweden, there was a PhD position that caught my eye that involved examining lower crustal earthquakes. Probably for the best, I was not ready for that PhD at the time. Over the next 7 years, I gained various experiences from working in both the oil & gas and in the mining industries; from the technical to the soft skills. Throughout this time, I always paid attention to new PhD openings, in particular to ones involving faults, shear zones, and microstructures. Often out of my own curiosity, I would keep somewhat up-to-date with on-going research (open-access publications is a thing of beauty!). In mid-January 2020, before COVID was making the headlines, I was operating an induced-polarization exploration geophysics project at 5500 moh, with limited internet access (i.e. barely email!) in the High Atacama Desert of Chile-Argentina when I saw the Njord PhD position that I'm currently in. Sometimes, gaining various experiences, utilizing your skills, figuring out exactly your interests, and waiting patiently for the right project to come along, is the correct approach.

What are your current research projects?

I'm in the midst of writing up my first paper of my PhD on porosity generating mechanisms during the earthquake cycle, using rocks from Lofoten as my natural laboratory. This project addresses two objectives: at lower crustal conditions (>20 km deep), (1) where do we find primary and secondary porosity after an earthquake + how does it form, and (2) how does this porosity help facilitate and localize strain in the development of ductile shear zones. I'm fortunate enough to integrate quantified porosity data from an exceptionally clean synchrotron x-ray microtomography dataset with SEM-cathodoluminescence (SEM-CL), electron backscatter diffraction (EBSD), and focused ion beam (FIB-SEM) nanotomography to establish a model in which porosity is generated during the initial faulting and mineral growth phase, and subsequently this porosity is consumed by precipitation of new material into the pore cavities during viscous creep.

A second project that I've begun just a month ago is to examine at the nanoscale the healed fractures in the damaged wall-rock of these lower crustal earthquakes mentioned above. This work involves SEM-CL, EBSD, scanning transmission electron microscopy (STEM), transmission Kikuchi diffraction (TKD), and NanoSIMS (secondary ion mass spectrometry) analyses to determine the cause of a core-rim zonation we find in the plagioclase crystals, and to determine the origins of the nanoparticles found healing the fractures.

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

All of my projects fit inside the "Fracture, Friction and Creep" topic of the EarthFlows research group within Njord. This entails that I'm concerned at examining the geological mechanisms for porosity generated by fractures, metamorphic reactions generating porosity, nanoscale deformation leading to coseismic slip, fluid-rock interactions that alter the rheology, and the evolution of porosity as strain is localized on these fault rocks and undergoes ductile deformation.

Where do we usually find you?

Not unlike all the other interviewees, I'm also most often found in my office either processing data, keeping up-to-date with a mountain of literature, designing figures, re-processing data, sometimes actual science writing, or chatting with my Dutch office-mate. Although as a field-based geologist, I would be remiss if I didn't romanticize a short sentence or two of the rugged field localities in Lofoten, Canadian Rockies, Utah, or the not so rugged and pretty "meh" vegetated Swedish west coast! Indeed, understanding the mechanisms for earth processes often begins with getting your nose up to the rock.

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

As someone that has worked in the oil & gas industry and the mining industry, the characterization of geological material is of high importance. Therefore, the workflow and the electron microscopy techniques that academics use are often employed in industry to further understand the geological environments they're exploring in. My work lends itself as in-depth studies for how and where fluids might be expected to flow in crystalline rocks for, as an example, understanding ore deposits.

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), 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 2022, Njord staff have been responsible for or contributed to the following courses at the Department of Physics:

Mechanics
FYS MEK1110

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.

Electromagnetism
FYS1120

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

Thermodynamics and Statistical Physics
FYS2160

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

Mathematical Methods in Physics
FYS3140

This course covers a number of 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.

Computational Physics
FYS3150/FYS4150

This course gives an introduction to 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.

Statistical Mechanics
FYS4130

This course gives a thorough introduction to thermodynamics and statistical physics, with an emphasis on the fundamental properties of gases, liquids and solids.

Experimental Techniques in Porous and Complex Systems
FYS4420/FYS9420

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.

Condensed Matter Physics II
FYS4430/FYS9430

This course presents an overview of some functional materials and their properties, mainly seen from an experimental viewpoint. Topics that are covered include dielectric materials, magnetic materials, and superconductors as well as selected topics within soft materials and micro/nanostructured materials.

Disordered Systems and Percolation
FYS4460

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.

Dynamics of Complex Media
FYS4465/FYS9465

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.

Biological Physics
FYS4715

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

Cross-Disciplinary Thematic Focus for Honours Students
HON1000

The course gives perspectives from multiple disciplines on the current interdisciplinary topic. The intention is to give an introduction to a topic known via the Honours Programme and to inspire to further work on this topic.

Education

In 2022, Njord staff have been responsible for or contributed to the following courses at the Department of Geosciences:

Mineralogy
GEO2110

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

Petrology and Geochemistry
GEO2150

This course provides an introduction to 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.

Geomorphology
GEO2210

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).

Glaciology
GEO4420

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.

Geomechanics
GEO3131/GEO4131

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).

Tectonics
GEO4840/GEO9840

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.

Petrography and Microstructures
GEO4810

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.

Earthquake and Volcanic Processes
GEO4151

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

Fieldwork

A number of the projects carried out at Njord rely on geological fieldwork. This involves geological mapping, sampling, and monitoring programs on a wide range of scales. Fieldwork both constrains and inspires experimental and modelling approaches to our studies of geological processes.

The participants in the machine learning workshop on a glacier. Foto: Ben Robson, UiO

In April and August, a team of geoscientists conducted fieldwork on Svalbard to monitor the Kongsvegen surging glacier. The team consisted of Coline Bouchayer (Njord), Thomas Schuler (UiO), Jon Hulth (UiO), Wenxue Cao (UiO), Ugo Nanni (UiO), Urs Fischer (Nagra, Switzerland). The team drilled a borehole and instrumented it with borehole seismometers, water pressure and thermistor sensors, and a ploughmeter at the bottom to study the properties of the subglacial environment when the glacier is sliding. The team did also the maintenance of existing borehole and standalone geophone stations installed in 2021.

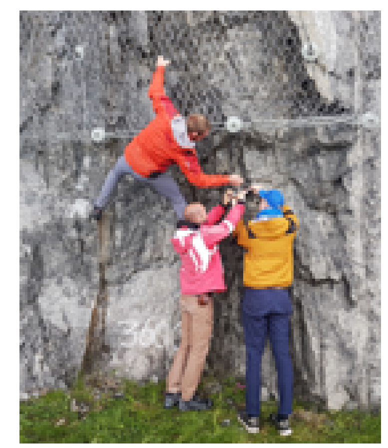
In May, Olivier Galland and Dougal Jerram (CEED, UiO) conducted fieldwork in the Neuquén Basin, Argentina. The aim was to map eroded Miocene volcanic systems to understand their structure and evolution, and they structural impact on the sedimentary formations through which the magma was emplaced. In particular, a focus was on understanding the impact volcanic activity had on the petroleum systems in the study area.

In spring and autumn, Luca Menegon and master student Oleksandra Valter visited the Fen Carbonatite Complex in Telemark together with the Geological Advisor of Buskerud, Telemark and Vestfold counties, Sven Dahlgren. The Fen Complex contains one of the largest concentrations of rare-earth elements (REE) and niobium in Europe. The fieldwork aimed to investigate the origin of deformation structures such as shear zones and folds in the carbonatites, and their potential role in the segregation of REE and niobium in specific domains.

In June, François Renard, Luca Menegon, Steven Michalchuk, Sasha Zertani, Hugo van Lantman, Jean-Baptiste Jacob, and Kristina Dunkel, together with Nicolas Brantut (University College London), Marcel Thielmann (University Bayreuth), and Benoît Cordonnier (European Synchrotron Radiation Facility) went to the Lofoten archipelago for two weeks to study lower-crustal earthquakes in the framework of the project Break-Through Rocks. The Lofoten archipelago has a high density of lower crustal rocks that have recorded fossil earthquakes. These rocks, called pseudotachylytes, correspond to frozen frictional melts produced by the seismic activity in this region some 400 million years ago. The origin of such deep earthquakes, as well as their influence on the further developments of their host rocks, is currently an important topic of research.

In August, Rakul Johannesen, Marija Rosenqvist, Marthe Guren, from the team of the project CO2Basalt went to the Faroe Islands for geological mapping of fractured basalt layers using drones. The main idea is to estimate how fluids circulate in basalt reservoirs and if carbon dioxide could be stored permanently in these formations.

Dealing with the forces of nature is part of the fieldwork



What it takes to get good samples.

Drill core from the Faroe Islands with basalt flows, some with open pores and some filled with secondary minerals

Drone picture from Faroe Islands

In September, John Aiken organized a week-long workshop on machine learning applied broadly across glaciology. In collaboration with University of Bergen, University of Utrecht, University of California Berkeley, and the Finse Alpine Research Station, fourteen participants focused on topics related to the physical evolution of glaciers, automatic processing of remotely sensed data of glaciers, and data processing related to global modelling of glaciers. The workshop included an excursion to Midtalsbreen, the closest glacier to Finse, where traditional data gathering methods such as mass balance poles were contrasted with modern methods using drones.

In November, Olivier Galland and Dougal Jerram (CEED, UiO) conducted short fieldwork in the northern Neuquén Basin, Argentina. The first aim of the trip was to collect structural information of the Andean frontal thrust in the study area to assess its seismogenic properties. This fieldwork is a collaboration with Grégoire Messager (University of Pau, France). The second objective was to produce a video to be published in Youtube to describe the outstanding geology of Cerro Alquitrán, a volcanic intrusion at the rim of which large volumes of bitumen natural seep out at the earth's surface.

We at Njord consider fieldwork is highly valuable for us in solving questions and in the processes of merging our cross-disciplinary expertise. In 2023, we plan to involve the physicists of Njord more in the field activities.

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 use five 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 4MP images at 1000fps. 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. Micro-scale 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.

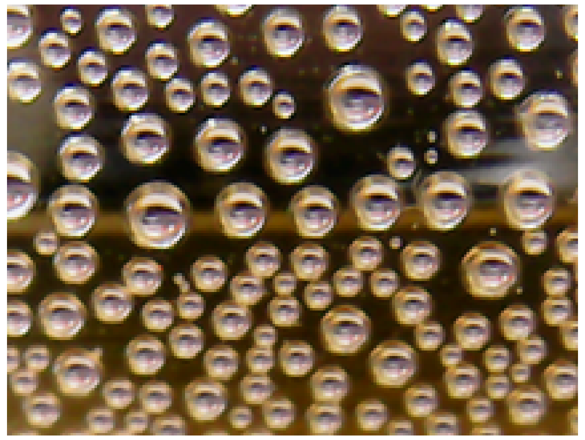
PoreLab have recently bought a Krüss DSA25 drop shape analyzer to perform direct measurements of surface tension, wetting properties and surface free energy.

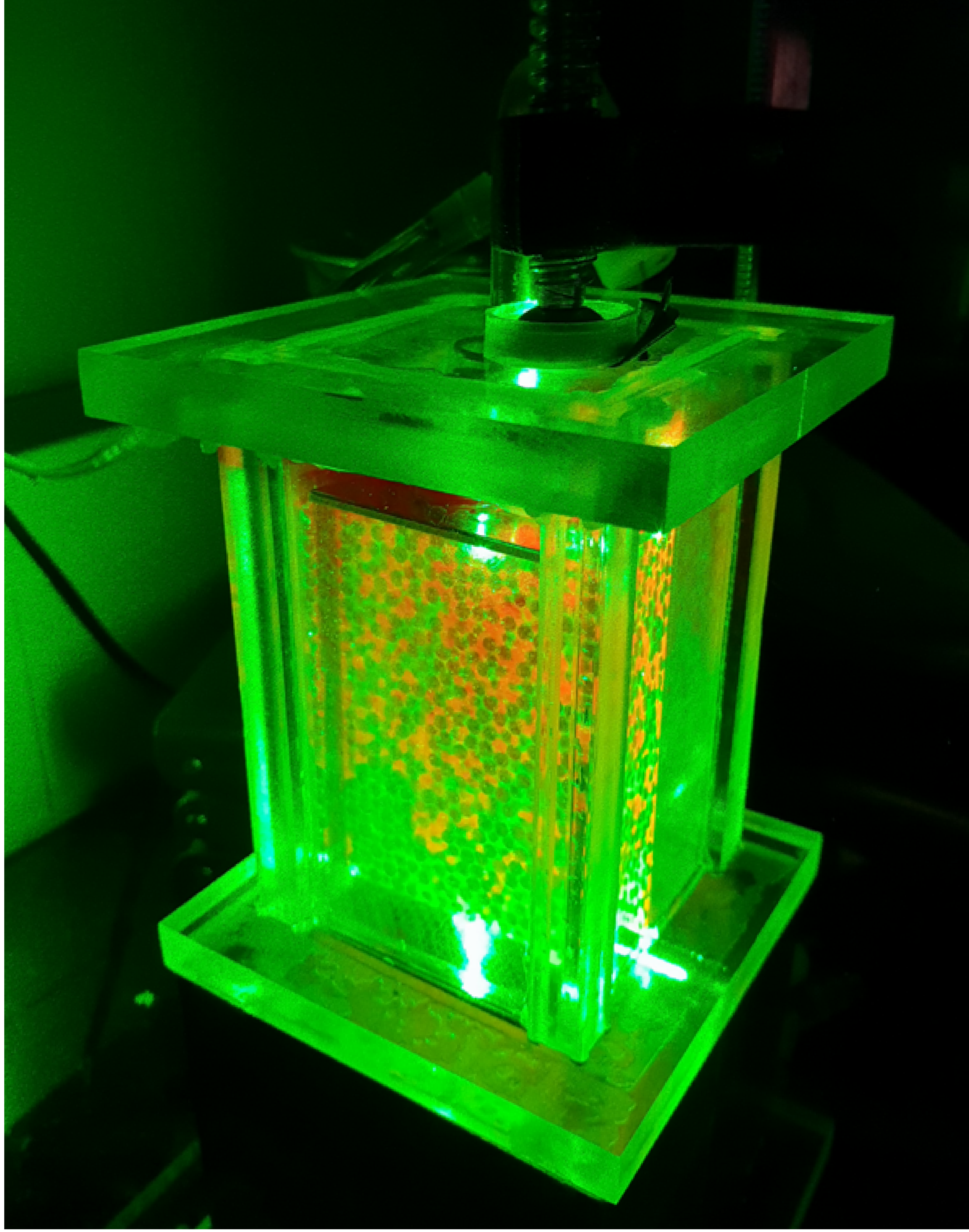
The laboratories are equipped with Formlabs Form3 family of 3D printers that are based on the Low Force Stereolithography (LFS) technology. Our 3D printing cluster consists of two smaller capacity Form 3 and two larger volume Form 3L printers. This setup meets our ever increasing need for the printing 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.

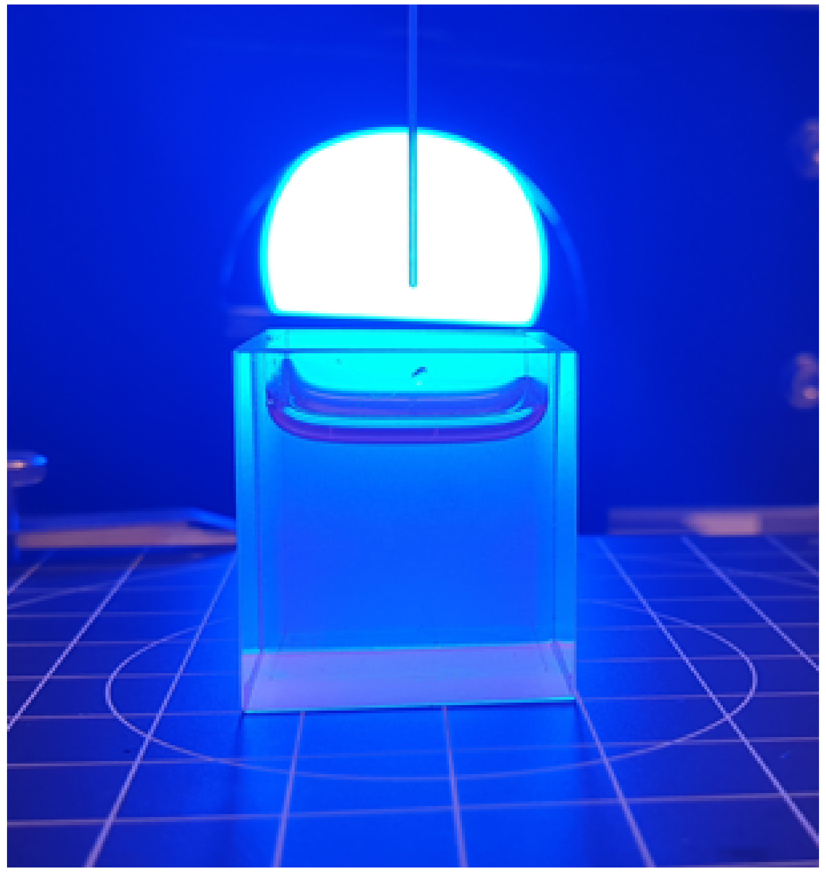
The labs are well equipped to perform homodyne correlation spectroscopy for the measurement of particle velocity fluctuations in fluids, diffusion constants and viscosities. PoreLab has have developed a 3D optical scanner which makes it possible to measure 3D fluid structures in refraction index matched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

The newest equipment in PoreLab's laboratories are two torque and force gauges, Mark-10 ESM303HE and Mark-10 TSA750H. These test stands are an excellent tool for quick-action compression, tension and torsion testing.

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







"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."

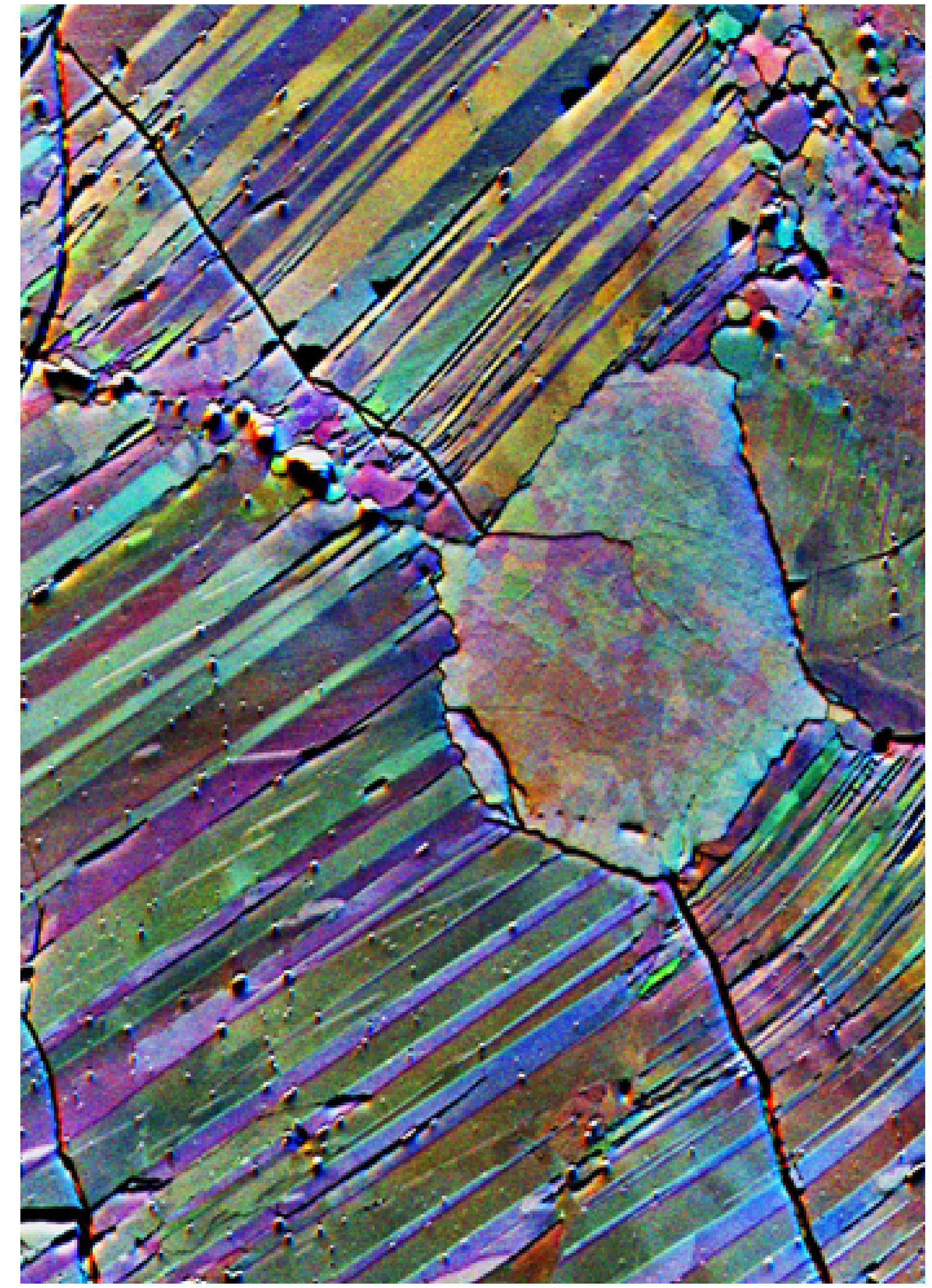
deformation. We have developed triaxial rock deformation apparatus, the HADES rig and KORE rig, which are installed at the beamline ID19 at the European Synchrotron Radiation Facility. These rigs allow imaging rocks during deformation using dynamic X-ray microtomography. We have also developed three 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.

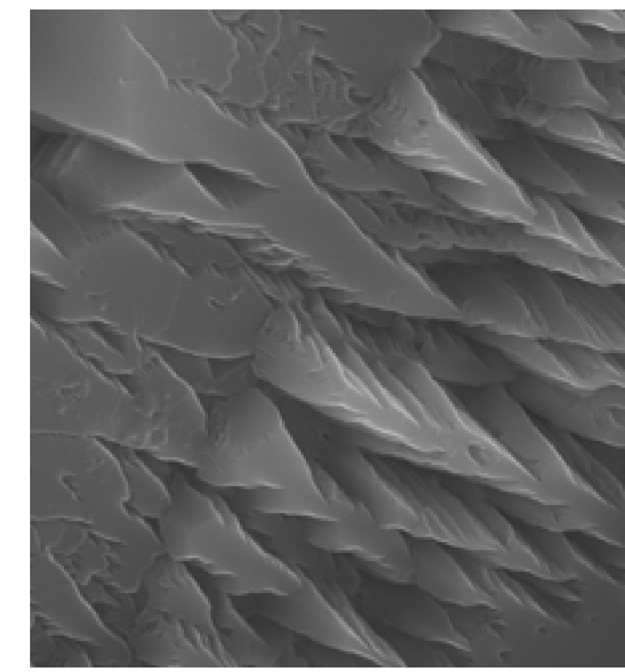
Within the Frictionlab, the NI-Earth lab hosts a G200x Nanoindenter from KLA, which is capable of measuring Young's modulus, hardness and creep of geological materials at room temperature and at up to 500 °C using a laser heating system.

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 (SPIM) system to view 3D biological samples.

The new established **LagLivLab** is partially in the Njord laboratories, and supported by both the physics department and a hybrid technology hub. The laboratory is equipped to build lab-on-a-chip and study cell biology. We have a clean room which is dedicated for cell culture and contains a MARS Class II biological safety cabinet and a PHCBi CO_2 incubator which is used to grow 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.



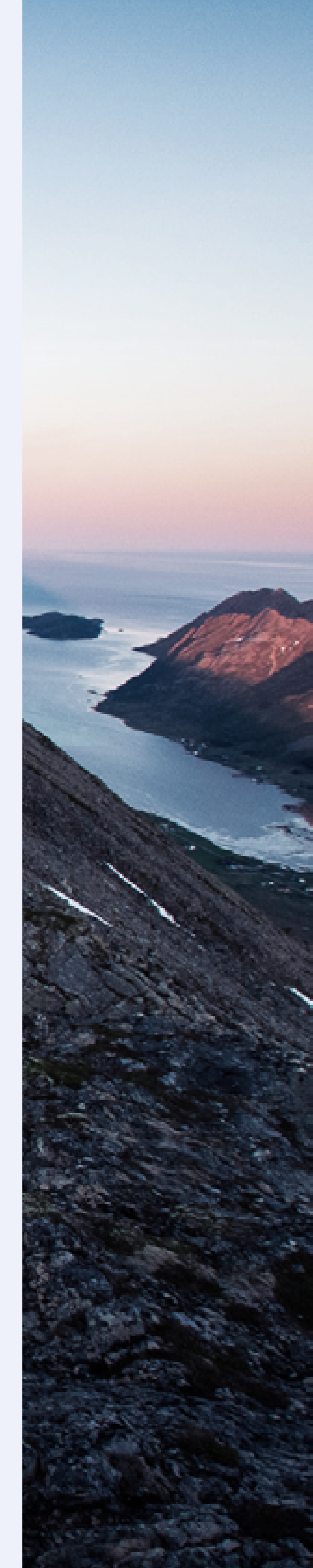


In 2020 the University of Oslo received 20.3 million of NOK from the Research Council of Norway based on the 2018 call for National Research Infrastructures. This funding has established the geochronology part of the **Goldschmidt Laboratory**, a national infrastructure for geochemical, microstructural, 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 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 aims at establishing a European expert community in electron and X-ray microscopy for structural and chemical imaging techniques for Earth materials.

03

Research projects



About Chapter 3

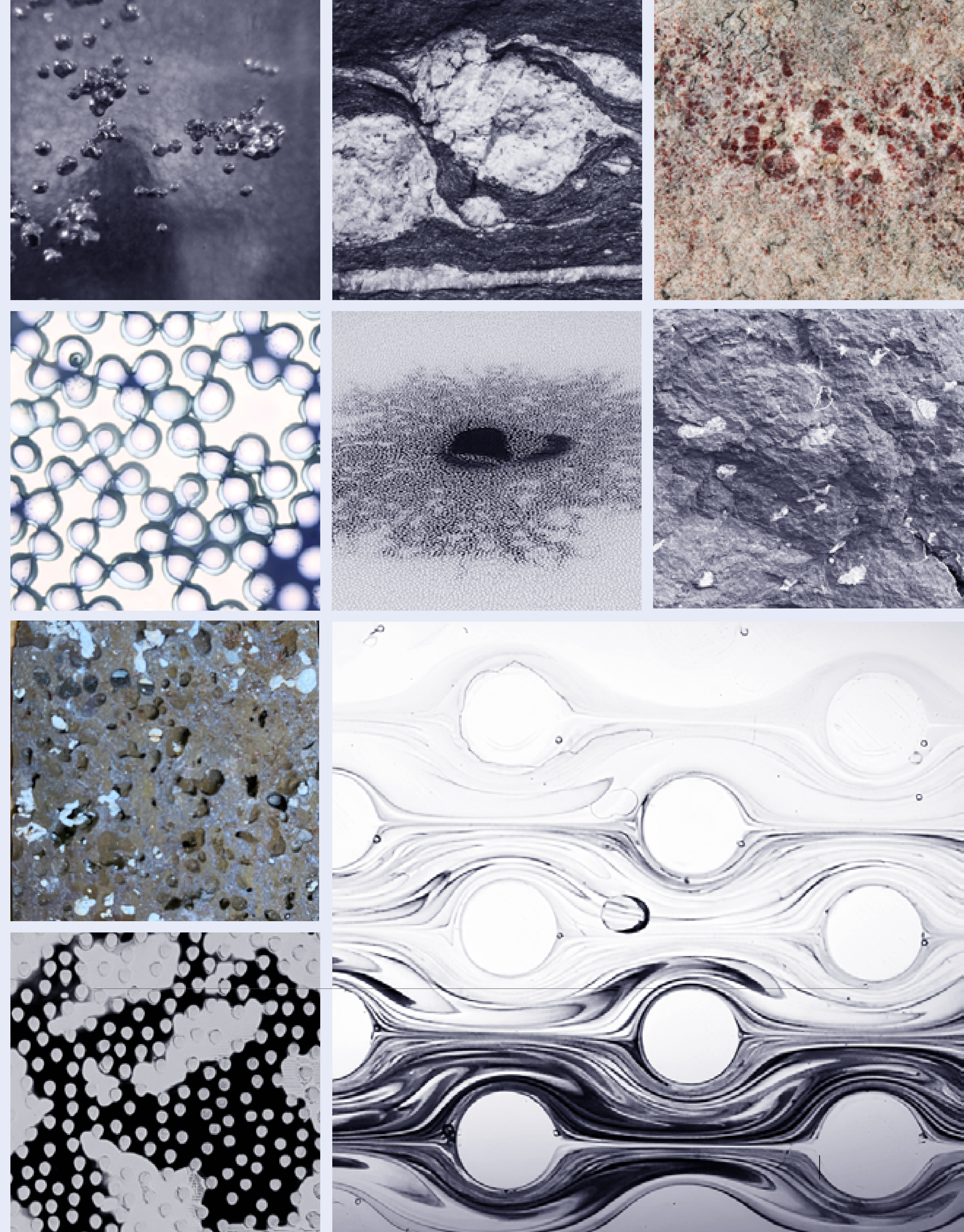
The research at the Njord Centre is organized around three main topics: 1) Fluid flows in complex media, 2) Fracture, friction and creep, and 3) Couplings at the nanoscale. These topics represent the core of the research strategy the centre has defined for the period 2023-2027.

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. In other situations, the solid confinement is deformable and changes shape as a response to the forces imposed by fluid pressure gradients or to external forces.

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. The paradigm of driven, dissipative systems can also be extended to biological matter such as cellular tissues, where the interplay between scales and energy fluxes are even more complex due to the active matter constituents that consume energy from the environment and convert it into mechanical forces and work.

Finally, most of the systems studied at Njord 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 particularly relevant in geoscience, where the only sources of information to understand ancient processes are the patterns left in rocks. It is also relevant for porous materials where emergent structures are often observed to arise as numerous processes act in concert.



Chapter 3 | Part 1

Fluid Flows in Complex Media

Funding
PoreLab, Centre of Excellence funding scheme with project number #262644

Participants
Joachim Falck Brodin[1,2], Knut Jørgen Måløy[1,2], Per Arne Rikvold[1,2], Marcel Moura[1,2], Mihailo Jankovi[1,2], Renaud Toussaint[1,2,3]

Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] PoreLab, The Njord Centre, University of Oslo, Norway
[3] Universite de Strasbourg, CNRS, IPGS UMR 7516, F-67000 Strasbourg, France

3D experiments on multi-phase flow in porous media

We utilize our in-house developed 3D scanner, based on optical index matching, to investigate the fundamental dynamics of two-phase flow in porous media, from pore-scale, via meso-scale up to macro-scale. Currently we are pursuing different approaches where the transitions between flow regimes can be captured by a dimensionless fluctuation number [1,2].

We are continuing our 3D investigations with the aim to derive a meaningful dimensionless Bond number to quantify the balance of viscous, capillary and gravitational forces. We believe that such a dimensionless number could figure in a function describing geometric parameters of the flow structures [3].

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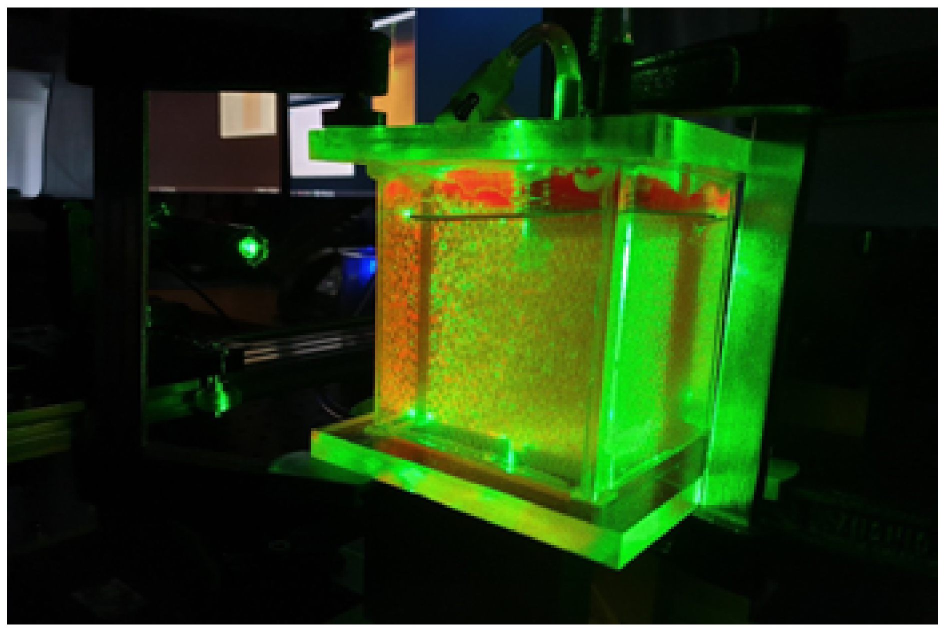
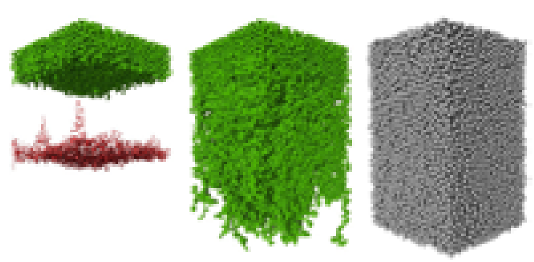
[3] Brodin, J. F., Moura, M., Toussaint, R., Måløy, K. J., & Rikvold, P. A. (2020). Visualization by optical fluorescence of two-phase flow in a three-dimensional porous medium. *arXiv preprint* arXiv:2008.02118.



Picture of the 3D-scanner in action during a flow experiment.



3D rendering of a scanner image, from an experiment on 2-phase flow in a synthetic medium made of glass beads. The defending fluid is removed. On the left we se a stable front, segmented out and suspended under in red, in the middle the invading structure has evolved over an unstable front, on the right we see a rendering of the porous medium – randomly packed glass spheres.

Production in highlight

Brodin, J. F., Moura, M., Toussaint, R., Måløy, K. J., & Rikvold, P. A. (2022, March). Visualization by optical fluorescence of two-phase flow in a three-dimensional porous medium. In *Journal of Physics: Conference Series* (Vol. 2241, No. 1, p. 012004). IOP Publishing.

Brodin, J., Rikvold, P., Moura, M., Toussaint, R., & Måløy, K. (2022). Competing Gravitational and Viscous Effects in 3D Two-Phase Flow Investigated With a Table-Top Optical Scanner. *Frontiers In Physics*, 10. doi: 10.3389/fphy.2022.936915

Funding
The Research Council of Norway, SFF PoreLab

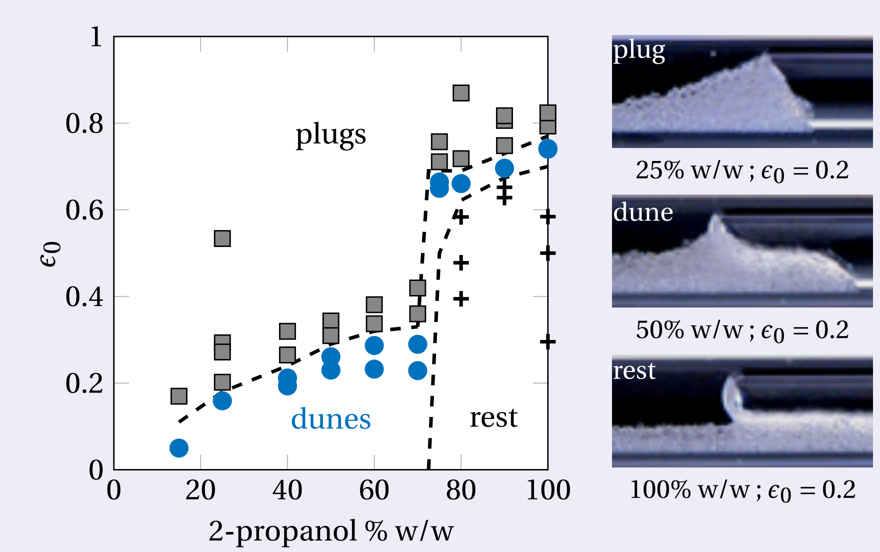
Participants
Louison Thorens[1,2], Guillaume Dumazer[1], Monem Ayaz[1], Knut Jørgen Måløy[1], Eirik Grude Flekkøy[1], Bjørnar Sandnes[3], Mickael Bourgoin[2], Stephan Santucci[2]

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

Capillary washboarding, plug formation, and fluidization during slow drainage of a frictional fluid

We study the slow drainage of a frictional fluid in a confining structure, analyzing specifically the displacement of particles by a liquid/air meniscus, within an immersed granular bed in a horizontal capillary tube. Modifying systematically the wettability and surface tension of the draining liquid, as well as the initial height of the granular bed, we could identify the necessary conditions for the emergence of a bulldozing process, leading to different drainage instabilities with the formation of ripples and plugs. Indeed, we reveal a new unstable regime of the drainage with the periodic formation of dunes, analogous to the road washboarding instability. A 2D theoretical analysis, based on the competitive role of friction and capillarity, and quantitatively supported by 2D numerical simulations of a meniscus bulldozing a front of particles, captures all the qualitative features of the various drainage dynamics observed experimentally.

Further by increasing the injection rate, the complex interplay between capillary forces and frictional and viscous dissipation is responsible for the development of several displacement regimes. The effect of the viscous forces in flow conditions dominated by viscous dissipation is the gradual fluidization of the entire granular material.



Phase diagram of the final drainage patterns observed ("plugs", "dunes" or undisturbed granular beds at "rest") as a function of the experimental controlling parameters, the initial height of the granular layer ϵ_0 and the isopropanol concentration. We also provide snapshots of the corresponding shape of the meniscus during the slow drainage of various frictional fluids.

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, submitted *Phys. Rev. Letter.* (2022)

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. Letter*, 117, 028002 (2016)

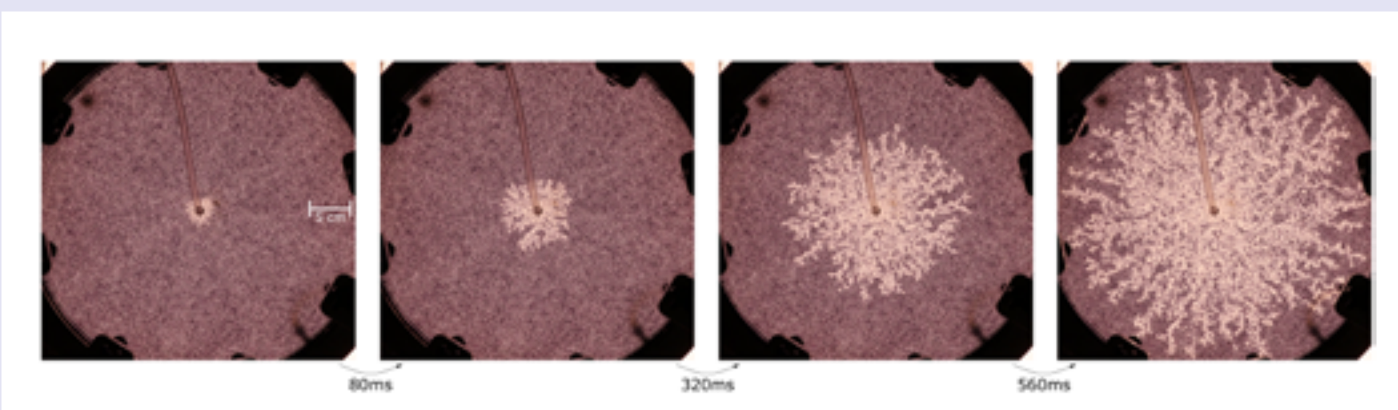
Funding
The Research Council of Norway, SFF PoreLab

Participants
Fredrik Kvalheim Eriksen[1], Marcel Moura[1], Mihailo Jankov[1], Antoine Turquet[1,2], Knut Jørgen Måløy[1], Eirik Grude Flekkøy[1]

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

The transition from viscous fingers to compact displacement during unstable drainage in porous media

A fractal viscous fingering structure is observed when a low viscosity fluid displaces a fluid with a much higher viscosity at high injection rates in a porous medium. However, when the viscosity ratio M between the invading and defending fluids exceeds a given threshold, a notably different invasion pattern is observed with a more compact displacement structure around the injection point followed by viscous fingers around its perimeter. By means of experimental, numerical and theoretical approaches, this project aims to characterize and explain the processes leading to the cross-over from unstable viscous fingers to the more stable and dense compact displacement patterns. The research is based on a series of drainage experiments in a radial porous Hele-Shaw cell in which we systematically vary the viscosity ratio of the defending (wetting) fluid and the overpressure of the invading (non-wetting) fluid to map out the resulting invasion structures as a function of viscosity ratio and injection pressure. We show that above a certain injection pressure and viscosity ratio threshold, a more stable and compact invasion structure emerges within the viscous fingering patterns, resulting in a roughly circular displacement with viscous fingers on the outside. The onset of the stable displacement is found to begin at a rather low viscosity ratio M. We find that the ratio between the length of the outer fingers and the size of the compact invasion scales with the viscosity ratio and approaches a roughly constant value during growth, resulting in structures with proportionate growth and larger compact invasions for higher viscosity ratios. As opposed to the viscous fingering instability, we describe rich ganglion dynamics within the compact invasion structures and show that the pressure gradient is not screened by the outer fingers.



Four snapshots illustrating the temporal evolution of a typical experiment in which the defending fluid was a water- glycerol mixture with glycerol concentration Cg = 20 % (by mass) and the air pressure was 50 cmH_2O. The time delay between consecutive snapshots is shown in the figure.

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Production in highlight

Fredrik Kvalheim Eriksen, Marcel Moura, Mihailo Jankov, Antoine Leo Turquet, and Knut Jørgen Måløy. (2021). The transition from viscous fingers to compact displacement during unstable drainage in porous media. *Phys. Rev. Fluids* 7, 013901 (2022).

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

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

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

Flow and mineral sequestration of carbon dioxide in basalts offshore Norway

Storing carbon dioxide 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 CO2-Basalt 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.

In 2022, we started this project by hiring three early career researchers who joined the field in the Faroe Islands to start integrating studies from the nanoscale of fluid-rock interactions in basalt to the core scale of porosity of fractured basalt and then to the reservoir scale of carbon dioxide storage. The main scientific questions are:

1. What are the geological and fracture properties of the Faroe Islands Basalt Group and to what degree can they contribute towards permanent storage of carbon dioxide (see figure below)?

2. What are the petrophysical properties of the basalts off-shore in the North Sea and how will these affect fluid flow migration and reactivity in a carbon dioxide storage scenario?

3. How does dynamic fractures damage basaltic glass at the nanoscale and how does the water enter these fractures in the wake of the rupture?

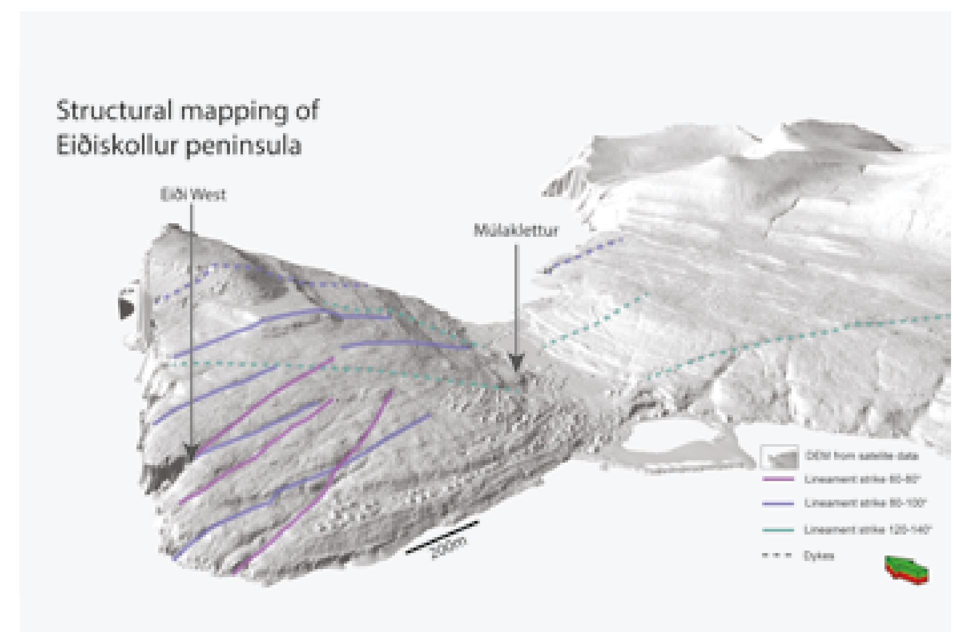

Figure. Digital elevation model of Eidiskollur site in Faroe Islands, showing the same stratigraphic unit as where potentially CO_2 will be stored in. Lineaments and dykes are mapped across the island and colored by strike.

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Production in highlight

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.

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

Funding
The Research Council of Norway (project GoT)

Participants
John M. Aiken[1,2], Robert A. Sohn[3], Francois Renard[1], Bjørn Jamtveit[1], Peter B. Kelemen[4], Oliver Plümper[5]

Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] Expert Analytics, Oslo, Norway
[3] Woods Hole Oceanographic Institution
[4] Lamont-Doherty Earth Observatory
[5] Utrecht University

The rate and mechanisms of active serpentinization of peridotites from the Semail ophiolite, Oman

Vision: Develop an integrated model of active serpentinization based on an ensemble of machine learning models applied to geological and geophysical data from the Oman Drilling Project.

A link between seismicity and peridotite alteration at mid-ocean ridges has been hypothesized (Grevemeyer et al., 2013; Horning et al., 2018), and there is ample evidence that earthquakes caused by tectonic stress or thermal contraction may allow fluid percolation into peridotite to trigger serpentinization (Roumejon and Cannat, 2014; Aupart et al., 2021). However, a definitive observation of reaction-driven seismicity associated with the volume changes involved in serpentinization has never been made. Furthermore, the in-situ rate of this cracking process is poorly constrained. Estimating this rate will require an interdisciplinary approach including seismology, geology, petrology, and physics. One of the primary goals of the Oman Drilling Project's Multi-Borehole Observatory has been to constrain the extent to which reaction driven cracking enables peridotite alteration.

The peridotites collected during the Oman Drilling Project have experienced serpentinization at several different stages, from the initial oceanic alteration (Aupart et al., 2021) to the still ongoing near-surface hydration and carbonation. We will describe two aspects of the system: 1) the Active Serpentinization System, and 2) The Geological Record. The Active Serpentinization system represents the ongoing time-evolution (hours, days, weeks) of peridotite alteration in Oman. The Geological Record represents the changes that have occurred over geological timescales (up to millions of years) to arrive at the current state of the Oman peridotites.

The overarching goal of this project is to produce an ensemble of machine learning models that both explains and constrains the natural serpentinization rate of peridotite in Oman. Machine learning is used across this project to detect events in waveform data, analyse X-ray computing tomography scans of rock cores, and to combine the large body of data to estimate serpentinization rates. Machine learning will accelerate our understanding of reaction driving cracking and provide us with a strong quantitative link between the geological record of serpentinization processes and the active serpentinization processes in Oman. Overall, this project aims to answer the following three research questions (RQ):

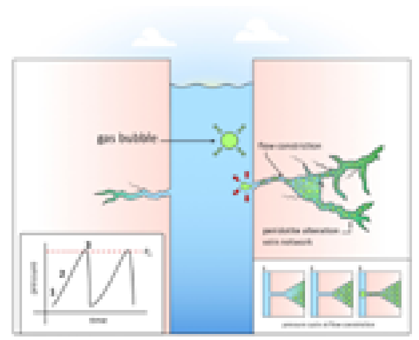
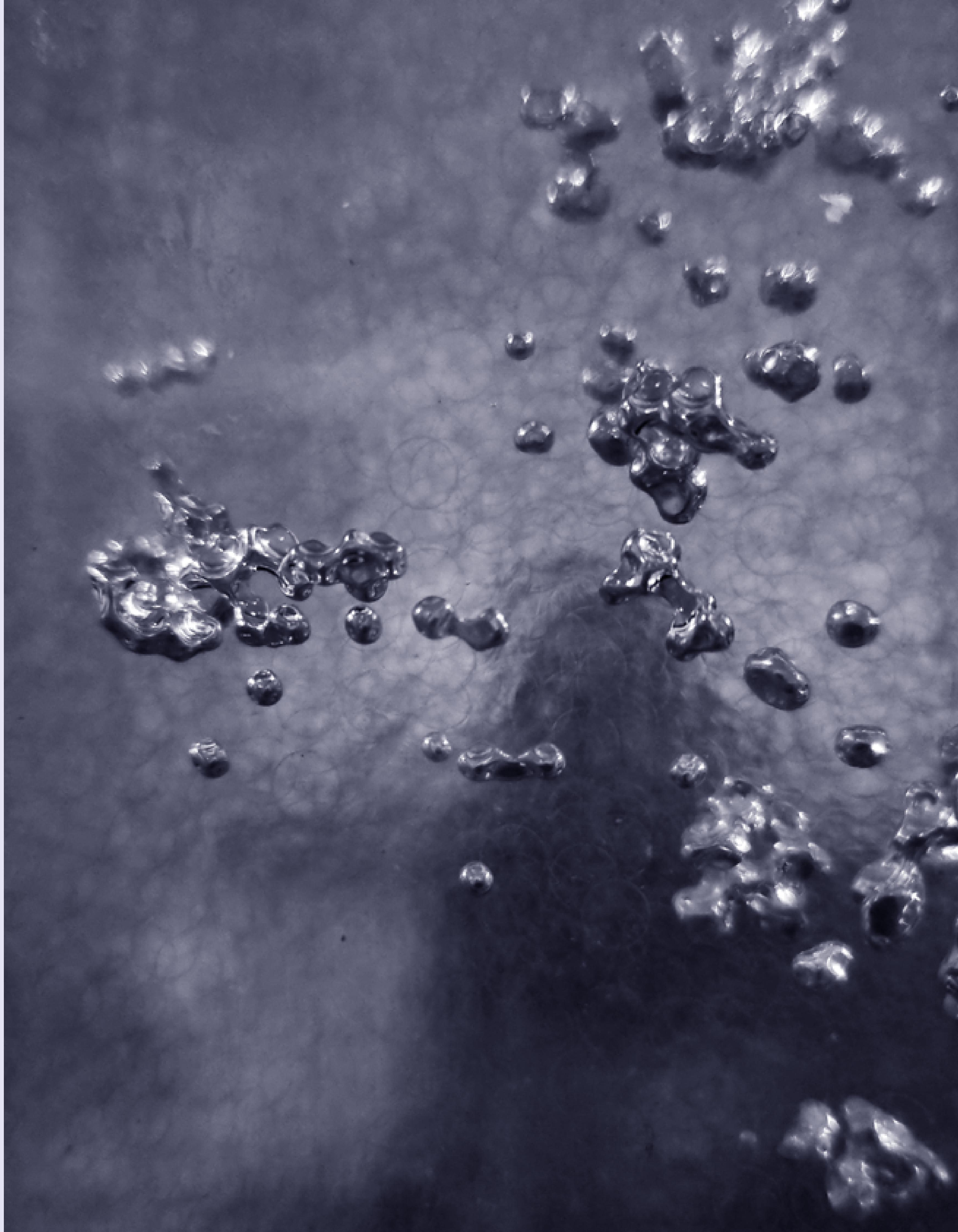


Fig: A schematic diagram of the gas/fluid/rock system in the oman multiborehole observatory

- **RQ1:** How can we use microearthquakes and borehole degassing data to constrain the rate and mechanism of active serpentinization of the Oman peridotite?
- **RQ2:** How can fracture networks present in the geological record be used to constrain fluid flow and serpentinization rates in the ultramafic formation surrounding the boreholes?
- **RQ3:** How can we produce an integrated model of serpentinization through time and space by combining degassing events, microseismicity, borehole fluid level changes, and geological observations?

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. https://doi.org/10.1029/2022GL100395



Funding
University of Oslo,
Strategic Research Initiative

Participants
Luiza Anghelutha[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]

Interface dynamics in geophysical flows: EarthFlows

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 can also behave like fluids on geological timescales. A great example of this is ice. The relaxation timescales differentiate between solid and fluid-like matter, which often coexist through highly complex and dynamical interfaces. Nonlinear physical processes like friction, fracture and plasticity in complex materials are example of processes that occur along interfaces, grain boundaries or mediated by defects.

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) has 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

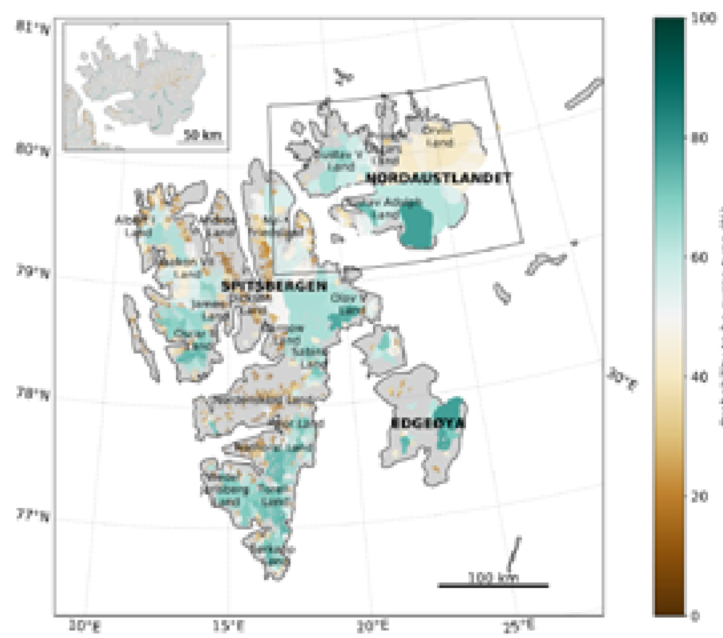


Figure A: Averaged probability map for each glacier to be classified as surge-type using a machine-learning approach. The zoom in the Nordaustlandet ice cap shows how the average probability has been computed. First, a probability is calculated at every point along the centerline of every glacier. Then, we average the probabilities to surge of every point along the centerline to obtain an average surging probability for a given glacier (Bouchayer et al., 2022).

Affiliation
1) The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway

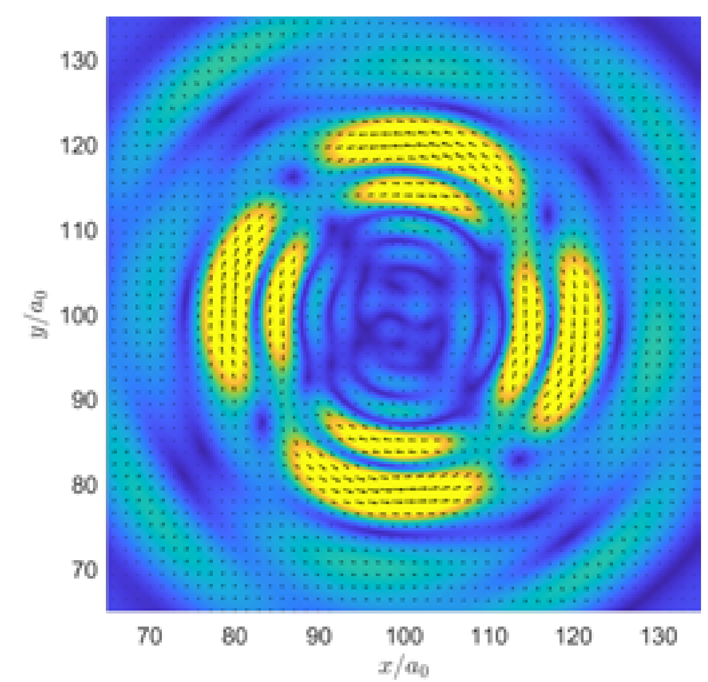


Figure B: In continuum mechanics, the divergence of the stress tensor is assumed to be zero since elastic waves in the medium relax on a much shorter time scale than the motion of dislocations. However, an explicit coupling between these two time scales is needed during fast events, like the annihilation of oppositely charged edge dislocations. The figure shows the divergence of the stress tensor (as a vector field) immediately after the annihilation of a dislocation dipole as the elastic waves are relaxing, simulated using the hydrodynamic phase-field crystal model.

and similar theoretical approaches based on non-equilibrium phase transitions and critical phenomena.

Project highlight 1: Machine-learning unravels glacier instabilities (Bouchayer et al., 2022). 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 below). 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 and their dynamics become increasingly important. The dominant type of defects in single crystals are dislocations, which are topological line defects, the motion of which describes the plastic strain under load. Using a minimalistic symmetry-conserving model, namely the phase-field crystal (PFC), we have shown from these symmetry principles that the motion of these lines is indeed driven by a Peach-Koehler force and found the explicit, model-dependent mobility (Skogvoll et al., 2022a). An open question in the PFC literature has been the connection between macroscopic stresses and the motion of dislocations, which we have answered by connecting the microscopic evolution of the defects with a hydrodynamic framework (Skogvoll et al., 2022b).

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Production in highlight

Bouchayer, C., Aiken, J. M., Thøgersen, K., Renard, F., Schuler, T. V. (2022) A machine learning framework to automate the classification of surge-type glaciers in Svalbard. *Journal of Geophysical Research: Earth Surface*, 127, e2022JF006597

Skogvoll, V., Angheluta, L., Skaugen, A., Salvalaglio, M., & Viñals, J. (2022a). A phase field crystal theory of the kinematics of dislocation lines. *Journal of the Mechanics and Physics of Solids*, 104932.

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Funding

The Research Council of Norway (project INTPART COLOSSAL)

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, Departments of Geosciences and Physics, 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

Collaboration on flows across scales (Brazil, France, Norway, USA)

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.

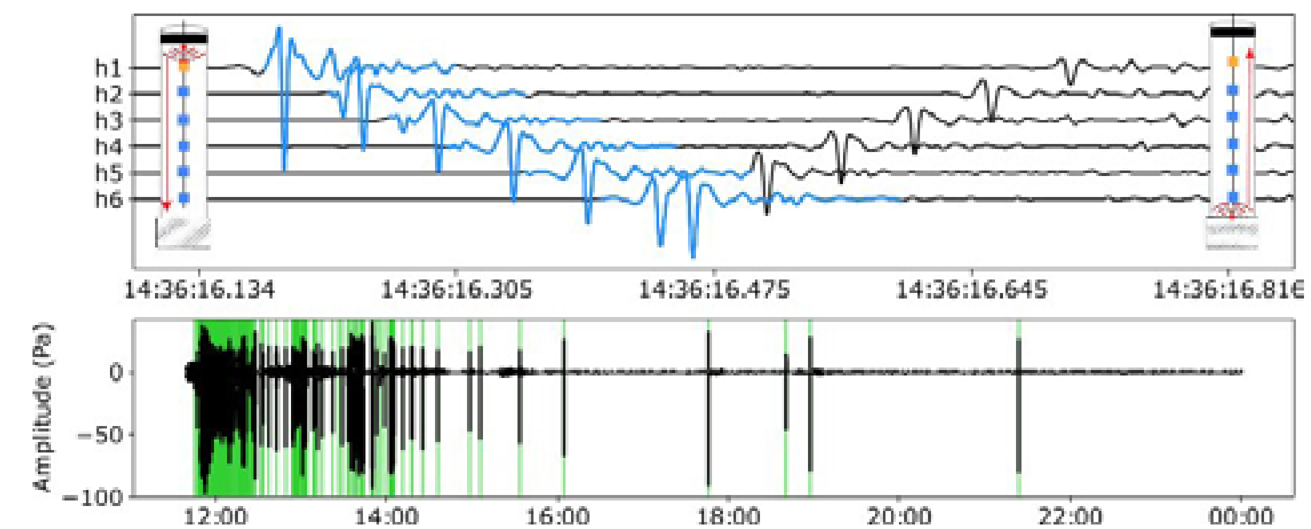
The research and education has relevant societal implications in the domains of geohazards (earthquakes, landslides, glacier collapse), groundwater resource (production and protection of aquifers, reactivity and transport of contaminants in the subsurface), and georesources (geothermal energy, carbon dioxide sequestration, solution mining).

In 2022, two researchers from Oslo spent research internships abroad. Dr. Galland stayed at ISTerre, Grenoble where he contributed to set up photogrammetric system to monitor surface deformation of analog models laboratory, to be implemented in dike-emplacement experiments (collaboration with Dr. Pinel), and tectonic experiments (collaboration with Dr. Martinod). This collaboration led to the application to an Aurora grant. Dr. Moura visited Peter Kang's group at the University of Minnesota to collaborate with a 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. Larose from ISTerre, Grenoble, came for one month to Oslo and evaluated the potential of using ambient seismic noise to monitor the possible failure of unstable clay mass (including quick-clays) and also to monitor permafrost rock slopes. To perform such preliminary evaluation, he organized different meetings with potential partners like NTNU, NGI, NGU and NORSAR. Seismic waves collected from ambient noise seem to be a good technique to track damage development and failure in various natural geomaterials and the goal is to write a research proposal.

A writing workshop with early career and senior researchers from Norway and France was held in Blesle in June 2022. During this workshop a PhD student progressed on an article on the nanoscale simulations of fracture propagation in quartz (Guren et al., 2022). Another early career researcher worked on a manuscript on fluid flow in the serpentine body of Oman (Aiken et al., 2022).

Finally, the highlight of this year was the international EarthFlows conference in June 2022, with more than 70 participants from Norway and abroad.



Bubble signals of a degassing events in the Oman ophiolite (Aiken et al., 2022). Top: An example of a single bubble signal, high-pass filtered at 40 Hz, observed on all hydrophones. The pressure signal propagates down the borehole as a tube wave, reflects off the bottom, and propagates back up again (inset schematic). The blue wave-form indicates the template used to detect bubbles in the hydrophone data. Bottom: Raw data from hydrophone h1 for the May 18, 2019 bubble swarm episode. The green bars indicate bubble detections using the matched filter technique.

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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.

Guren, M., G., Sveinsson, H., Malthe-Sørenssen, A., Renard, F. (2022) Nanoscale modelling of dynamic rupture and damage production in a-quartz, *Geophysical Research Letters*, 49, e2022GL100468.

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

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

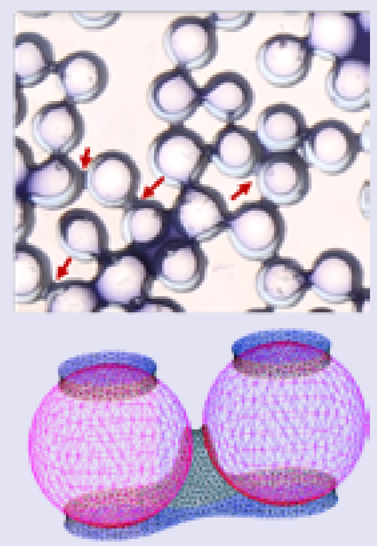
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) PoreLab, Norwegian University of Science and Technology, Norway

Connectivity enhancement due to thin liquid films in porous media flows

The flow of liquids and gases inside porous networks is a rather common process. It happens for example when rain falls on a 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 the thin liquid film network. In the FlowConn project we investigate film flow effects 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 map the whole thin film network. The ability to map the film network will serve as an input for a new theoretical investigation of the problem, based on solid concepts from network theory (graph theory). This approach, coupled with network simulations, will allow us to have a full understanding of the physics of the problem. A crucial step for the simulations is the understanding of the shapes of the liquid films and their respective hydraulic conductivities. We are studying the properties of these shapes using an algorithm based on energy minimization principles (Surface Evolver).



Top: Thin liquid films and capillary bridges (as those marked by the red arrows in the figure) can create new pathways for the transport of fluids in a porous medium, effectively enhancing the overall fluid connectivity of a sample. In the FlowConn project we will study the basic physical mechanisms responsible for the transport of fluids through such films.
Bottom: The shape of thin liquid films is important to determine their hydraulic conductivities. Here we show the result of a simulation to study such shapes using the Surface Evolver software package.

Production in highlight

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).

Moura M., Måløy K. J., Flekkøy E. G. and Toussaint R., "Verification of a dynamic scaling for the pair correlation function during the slow drainage of a porous medium," *Phys. Rev. Lett.* 119, 154503 (2017).

Flekkøy E. G., Schmittbuhl J., Løvholt F., Oxaal U., Måløy K. J. and Aagaard P., "Flow paths in wetting unsaturated flow: Experiments and simulations," *Phys. Rev.* E 65, 036312 (2002).

Kenneth A. Brakke., "The surface evolver," Experiment. *Math.* 1 (2) 141 - 165, (1992).

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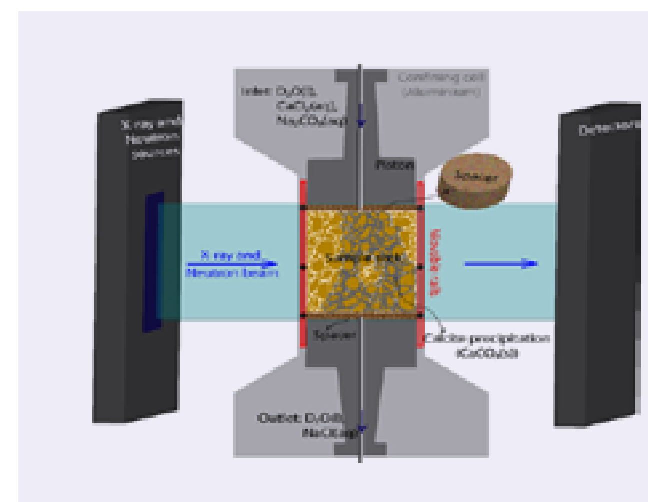
Funding
The Research Council of Norway (PoreFlow #301132)

Participants
Benoit Cordonnier[1], Paiman Shafabakhsh[1], Jessica McBeck[1], Anne Pluymakers[2], Alessandro Tengattini[3], Anders Kaestner[4], Dag Breiby[5], Francois Renard[1]

Affiliation
1) The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Norway
2) Faculty of Civil Engineering and Geosciences, Department of Geoscience and Engineering, TU Delft, The Netherlands
3) Univ. Grenoble Alpes, 3SR, F-38000 Grenoble, France
4) Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland
5) Institute of Physics, PoreLab, NTNU, Trondheim, Norway
6) University Grenoble Alpes, University Savoie Mont Blanc, CNRS, IRD, ISTerre, 38000, Grenoble, France

Neutron imaging of fluid flows in rocks

Flow through porous rocks is a common but highly complex process with applications in various domains such as the transport of solutes and pollutants in the subsurface, the storage of carbon dioxide in geological reservoirs, and the durability of cements in boreholes. The PoreFlow project is a collaboration with the group of Dag Breiby at NTNU in Trondheim. In the framework of this project, the Njord Centre is investigating the potential of neutrons and X-rays for imaging such processes at high time and spatial resolutions. To reach this goal, we rely on highly competitive applications to obtain beamtime in large neutron facilities such as the Institut Laue Langevin (ILL, beamline NeXT) and the Paul Scherrer Institute (PSI/SINQ, beamline ICON. In 2022, we obtained 4 days at PSI/SINQ where we could image fluid flow in rock samples by coupling neutrons and X-ray microtomography. To perform the experiments, we have developed a series of core holders.



Core holder developed at the Njord Centre to image fluid flow in rocks using large instruments. This core holder was used in 2022 by Paiman Shafabakhsh, PhD student, to image flow in a rock where mineral precipitation occurred.

We have also analyzed fracture networks imaged using synchrotron radiations during rock deformation experiments. We have demonstrated how the geometrical properties of the fracture network may control fluid flow in crystalline rocks (McBeck and Renard, 2022).

We performed experiments of two-phase mixing and the effect of precipitation of calcite in porous rocks on the flow properties. We are presently bringing together a strong community of scientists focused on fluid flow in porous media to push even further the imaging capabilities and its scientific application. Our goal is also to build competences to use the European Spallation Source (ESS), a large international facility built in Lund, Sweden, where Norway is a partner. This facility will open to users in 2025.

Production in highlight

Renard, F. (2022). Neutron imaging of fluid flow in rocks and applications to subsurface processes, *Conference on the Nordic perspectives on advanced neutron imaging*, Lyngby, Denmark, 24 November 2022.

Renard, F. (2022). Invited talk. Using Large Instruments to Image Flow and Deformation Processes in Rocks, *Gordon Research Conference on Flow and Transport in Permeable Media*, 17-22 July 2022, Les Diablerets, Switzerland.

McBeck, J., Renard, F. (2022) Deriving three-dimensional properties of fracture networks that control fluid flow from two-dimensional observations in rocks approaching failure under triaxial compression, *Water Resources Research*, https://doi.org/10.1029/2022WR032783.

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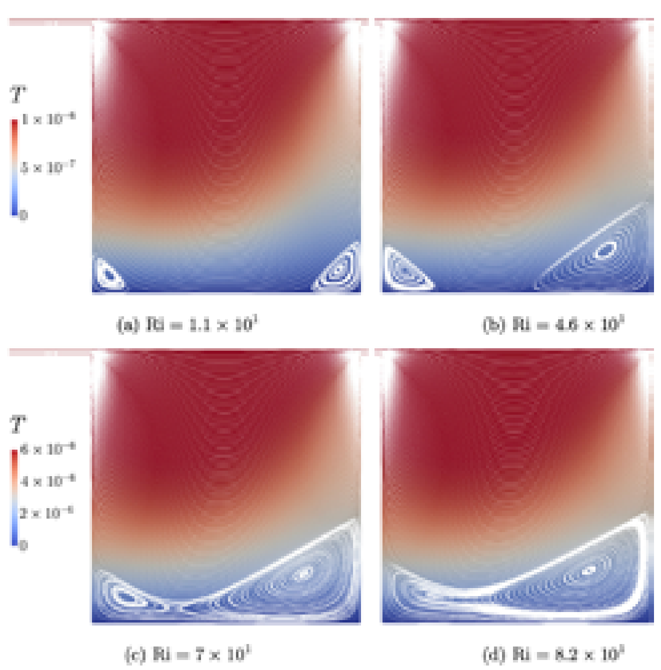
Support from the Research Council of Norway through the Center of Excellence funding scheme, Project No. 262644 (PoreLab)

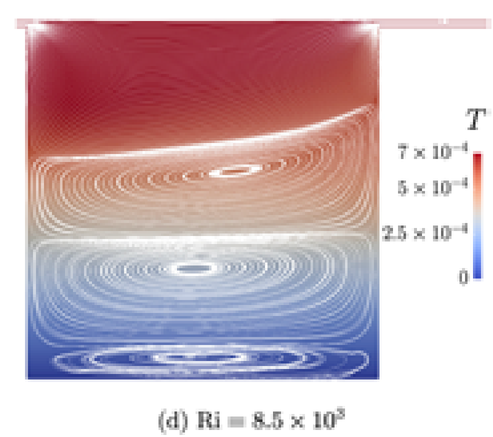
Participants
Beatrice Baldelli, Gaute Linga, Eirik G. Flekkøy

Affiliation
[1] PoreLab, The Njord Centre, University of Oslo, Norway

Thermal conduction through a cool well

Understanding the heat exchange between a moving fluid and solid walls is of interest in contexts that range from those of biology to engineering and geology. This heat is generally affected by the surface roughness. In this study the surface roughness is represented by a single square well over which the fluid is flowing between two narrow channel openings. When there is a temperature difference between the top and the bottom of the well, the resulting flow field in the well is governed both by fluid inertia and buoyancy forces. The ratio of the latter to the former is known as the Richardson number Ri. Contrary to most studies of thermal convection, where the buoyancy enhances the flow (for instance, when solar heating forms cumulus clouds) this study focuses on the case where the flow is suppressed by buoyancy as the bottom of the well is colder than the top. This reduces the vertical transport of thermal energy and hence has an insulating effect as the advective part of the transport is reduced with increasing temperature differences: As the value of Ri increases the cavity becomes filled by vortices that grow out of the bottom corners, see Fig. A. As this happens the average fluid velocity decreases, so that the fluid in the cavity approaches the state where diffusion becomes the dominant factor in the heat transport, as is the case in Fig. B where the slow system spanning vortices hardly advects any energy at all, leaving the energy transport to thermal diffusion. The main result of the study is the measurement of the effective thermal conductivity through the well, which changes by a factor 3 or more as Ri and Reynolds number is varied.





The streamlines and temperature field (red is warm, blue is cold) at different values of the top-to-bottom temperature difference. The dimensionless Ri is the ratio of buoyancy forces to inertial forces in the fluid.

Production in highlight

Baldelli, B., Linga G., Flekkøy, E.G., (2022). Thermal conduction through a cool well. *Physical Review Fluids* 7, 103503.

Funding
The Research Council of Norway

Participants
Olivier Galland[1], Kim Senger[2], Hans Jørgen Kjøll[3], Anna Sartell[4]

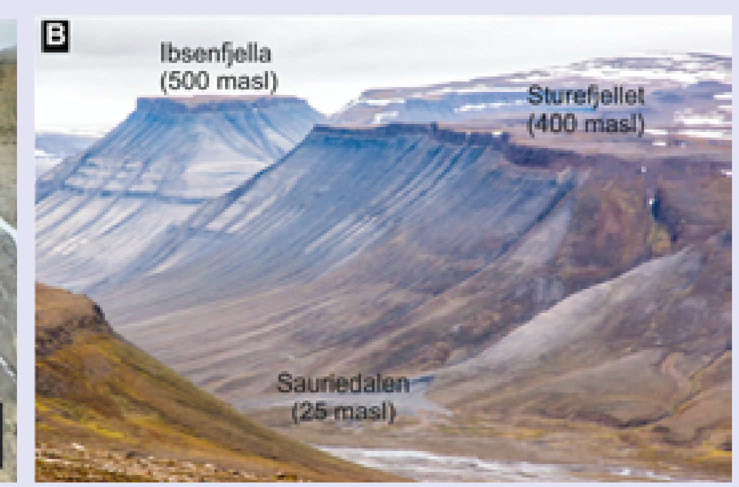
Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] UNIS, Svalbard
[3] Department of Geosciences, University of Oslo, Norway
[4] University of Helsinki, Finland
[5] University Grenoble Alpes, University Savoie Mont Blanc, CNRS, IRD, ISTerre, 38000, Grenoble, France

Lower Cretaceous magmatism in Svalbard

The high Arctic hosts a major tectono-magmatic element, the so-called High Arctic Large Igneous Province (HALIP). It comprises large volumes of mafic rocks emplaced across the pan-Arctic in the Early Cretaceous. Magmatic rocks related to the HALIP occur as sills, dykes, lavas and pyroclastic material in Svalbard, Franz Josef Land, the New Siberian Islands, Sverdrup Basin of Arctic Canada, northern Greenland and the offshore Alpha-Mendeleev Ridge – the most accessible of these are emplaced in heterogeneous rocks with excellent outcrop quality in Svalbard. However, the overall lack of data from this generally remote and poorly accessible part of the world leaves first-order scientific questions open, such as those that address the tectonic and paleo-climatic evolution of the Arctic. In particular, the following key question remains unsolved: is the HALIP actually a Large Igneous Province, and did it have a similar global impact on the Earth's history as other LIPs?

To address these questions, we reviewed the available geological, geophysical, geochemical and geochronological data available on the Lower Cretaceous magmatism Svalbard (Senger and Galland, 2022). In addition, we conducted several field expeditions in in Isfjorden, central Svalbard to (1) constrain the shapes and volumes of exposed magmatic intrusions (Galland et al., in preparation), (2) constrain the thermal impacts of igneous intrusions on their sedimentary host rocks, and (3) constrain the age of the magmatism through precise geochronological dating (Sartell et al., in preparation).

Core holder developed at the Njord Centre to image fluid flow in rocks using large instruments. This core holder was used in 2022 by Paiman Shafabakhsh, PhD student, to image flow in a rock where mineral precipitation occurred.



Production in highlight

Senger, K., and Galland, O., 2022, Stratigraphic and Spatial Extent of HALIP Magmatism in Central Spitsbergen: Geochemistry, Geophysics, Geosystems, v. 23, no. 11, p. e2021GC010300.

Galland, O., Kjøll, H.J., Horota, R., Runge, J., Sartell, A., Senger, K., in preparation, The 3-dimensional structure of a large mafic sill emplaced in sedimentary basins: the case study of Dicksonland, central Spitsbergen, Svalbard

Sartell, A., Senger, K., Söderlund, U., Kjøll, H.J., Galland, O., in preparation, Geochronological constraints of HALIP magmatism in Central Spitsbergen, Svalbard.

Funding
The Research Council of Norway (project M4)

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

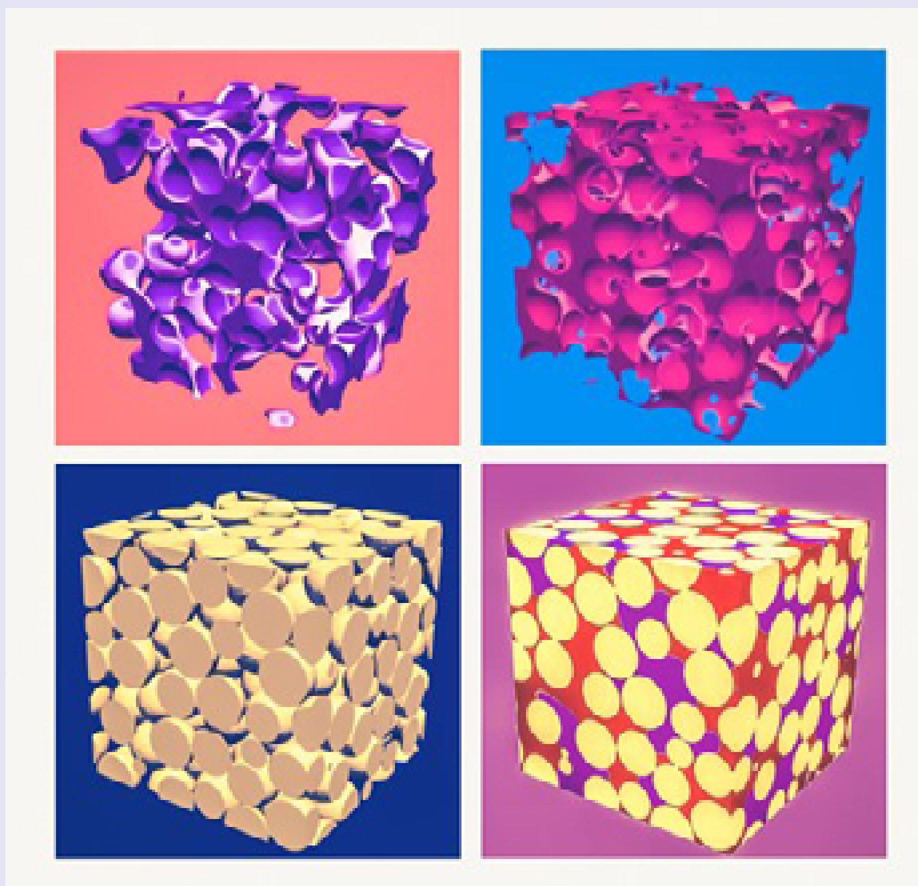
Affiliation
[1] The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Norway
[2] PoreLab, The Njord Centre, University of Oslo, Norway
[3] Geosciences Rennes, University of Rennes, France
[4] SINTEF Digital, Oslo

Mixing in multiphase flow through microporous media

Solute mixing is a key ingredient in a wide range of geophysical, industrial and biological processes, especially in porous media where concentration gradients are known to be significant at the pore scale. Hence it controls effective reaction rates, pollutant transport, as well as growth conditions for microbial life. Despite its ubiquity, little is currently known about solute mixing in multiphase flows, i.e. when two or more phases are flowing together in a porous medium.

The ambition of the project M4 is to establish the laws of mixing in multiphase porous media flows, and thereby to theoretically explain and predict mixing in time-dependent, multiphase flows in a wide class of porous materials. To achieve this, we develop numerical methods for highly accurate simulation of mixing in multiphase flows, and we design and execute novel experiments imaging solute mixing in porous media.

In the first year of M4, we have developed a numerical suite of open-source software for highly resolved simulation of mixing in 2D and 3D. Using these tools, we have made extensive computational investigations into mixing and dispersion (see also project Modiflow) dynamics in time-dependent flows through porous media. We have devised a first model to predict (the rate of) chaotic mixing as a function of flow characteristics. On the experimental side, we have made use of 3D printing technology to design quasi-2D porous geometries, and started to experimentally quantify fluid stretching as a function of porous media disorder.



Numerical simulations of two-phase flow through a periodic bead pack. The flow is driven upwards by an average pressure gradient. From left to right, top to bottom: (i) Non-wetting fluid phase, (ii) wetting fluid phase, (iii) solid phase, (iv) all phases together.

Production in highlight

G. Linga, Chaotic mixing in intermittent two-phase flow. Gordon Research Seminar, invited talk (2022).

G. Linga, L. Angheluta, J. Mathiesen, Onset of turbulence in channel flows with scale-invariant roughness, Physical Review Research 4, 033086 (2022)

I. S. Haugerud, G. Linga, E. G. Flekkøy, Solute dispersion in channels with periodic square boundary roughness, Journal of Fluid Mechanics, 944 (2022).

Funding
The Research Council of Norway, SFF PoreLab

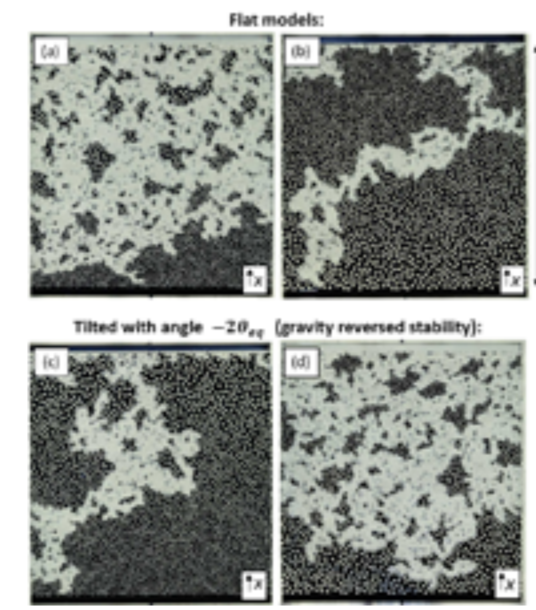
Participants
Tom Vincent-Dospital[1], Marcel Moura[1], Renaud Toussaint[1,2], and Knut Jørgen Måløy[1]

Affiliation
[1] PoreLab, The Njord Centre, University of Oslo, Norway
[2] University of Strasbourg

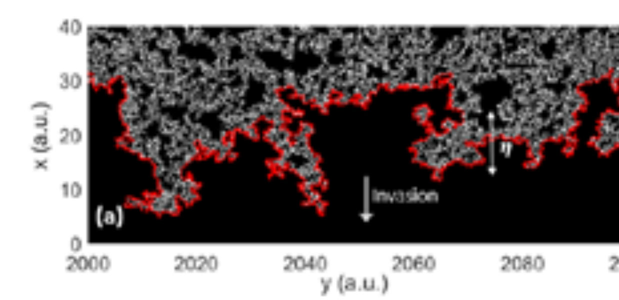
Stable and unstable capillary fingering in porous media with a gradient in grains size

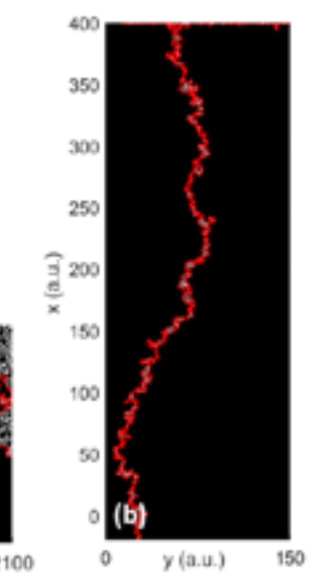
Porous media that display a gradient in the structure of their networks are common in nature, but the understanding of the drainage patterns in such media is still limited. We propose a theoretical framework that allows to better quantify these patterns, and we validate it both with experiments in 3D printed models and with numerical simulations.

In this work we present a theoretical and experimental investigation of slow drainage in porous media with a gradient in the grain size (and hence in the typical pores' throats), in an external gravitational field. We mathematically show that such structural gradient and gravitational field have a similar effect on the obtained drainage patterns, when they stabilize the invasion front. With the help of a newly introduced experimental set-up, based on the 3D printing of transparent porous matrices, we illustrate this equivalence, and extend it to the case where the front is unstable. We thus show that gravity can either enhance or reverse the drainage pattern of a graded porous media. We also present invasion percolation simulations of the same phenomena, which are in line with our theoretical and experimental results. In particular, we show that the width of stable drainage front scales with the spatial gradient of the average pore invasion threshold and with the local distribution of this (disordered) threshold. Overall, we propose a unifying theory for the up-scaling of dual immiscible fluid flows covering most classical scenario.



Drainage experiments in a 3D printed quasi two- dimensional model. Air invaded from the top of the pictures into a water-glycerol solution coloured with nigrosin. **(a)** A decrease in 'permeability' as the flow progresses (the air invades from the big pores to the small ones). The invasion is stable. **(b)** An increase in 'permeability' with the flow progression and an unstable processes. In both cases, the model is horizontal (G = 0). **(c)** and **(d)** show the same experiments in a chosen destabilising or stabilising gravity field (respectively) with tilt angle −2θeq The stability of the flow is thus reversed.





a) Invasion percolation simulations, that have stabilizing gradient in invasion threshold.
b) Invasion percolation simulations denoted that have destabilizing gradient in invasion threshold.

Production in highlight

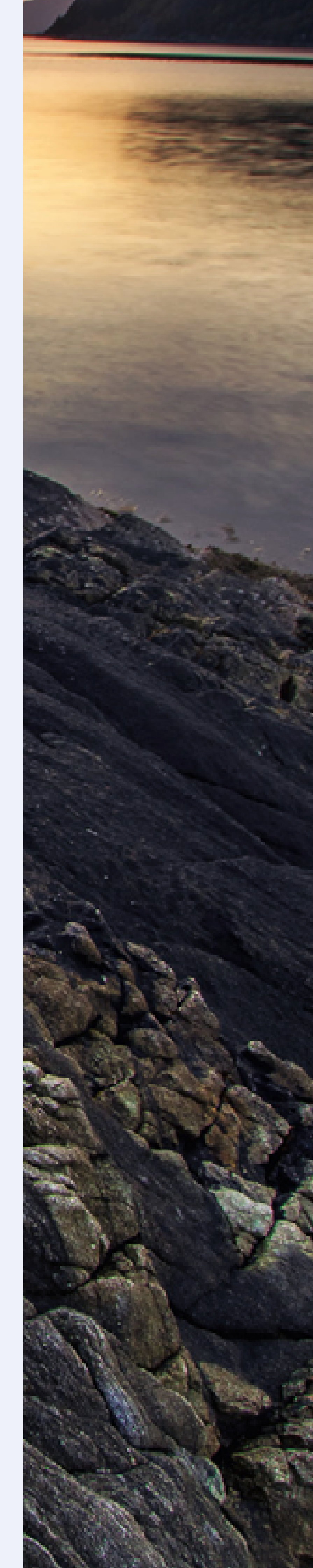
Tom Vincent-Dospital, Marcel Moura, Renaud Toussaint, and Knut Jørgen Måløy, Stable and unstable capillary fingering in porous media with a gradient in grain size. Commun Phys 5, 306 (2022). https://doi.org/10.1038/s42005-022-01072-1

Knut Jørgen Måløy, Marcel Moura, Alex Hansen, Eirik Grude Flekkøy, and Renaud Toussaint. Burst Dynamics, Upscaling and Dissipation of Slow Drainage in Porous Media. Front. Phys. 9:796019. doi: 10.3389/fphy.2021.796019 (2021)

Chapter 3 | Part 2

Fracture, Friction and Creep

1. Structural and metamorphic transformation processes in the lower continental crust and upper mantle
2. History-dependent friction
3. Emergent networks: predicting strain localization and fracture network
4. Break-through rocks
5. Conditions for earthquake nucleation in the lower crust
6. Collisional orogeny in the Scandinavian Caledonides
7. Maturation and fracturing of organic-rich shale during primary migration
8. Volcanic plumbing systems
9. The impact of volcanism on petroleum systems



Funding
European Research Council Advanced Grant DIME

Participants
Bjørn Jamtveit, John Aiken, Marija Rosenqvist, Francois Renard, and numerous international collaborators.

Affiliation
[1] The Njord Center, University of Oslo, Norway
[2] Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel

Structural and metamorphic transformation processes in the lower continental crust and upper mantle

The focus of DIME in 2022 were dived in two subprojects. One part was focused on the evolution of the lower continental crust, the other part on upper mantle fragments emplaced on the continental crust.

Part 1: When continents collide, the Earth's crust experiences structural and metamorphic transformations that control the geodynamic evolution of the orogen. Metamorphism of dry, lower crust requires fluid supply and produce mechanically weaker rocks. It is often localized in shear-zones, which provide the available fluid pathways. Several field-based studies show that shear zone development is preceded by brittle faults, frequently portraying evidence for seismic slip rates and introduction of externally derived fluids. However, despite the extensive documentation of lower crustal metamorphism and associated deformation features, a unifying model coupling long-term geological deformation to fluid migration and metamorphic reactions does not exist. A visco-elasto-plastic model demonstrates that the most pertinent features observed in transformed lower crust emerge from basic mechanical principles during the deformation of a coherent rock volume with associated fluid introduction (Figure). Characteristic features include a strikingly dynamic and heterogeneous pressure distribution in the reacting and deforming rock volumes. Lower crustal pressure variations may reach 1 GPa at any given depth. This will have first order effects on the pattern of fluid migration in the lower crust, and may also explain the apparent discrepancies between the relevant tectonic settings and petrologically-inferred burial depths.

Part 2: Serpentinization and carbonation of mantle rocks (peridotite alteration) are fundamentally important processes for a spectrum of geoscience topics, including arc volcanism, earthquake processes, chemosynthetic biological communities, and carbon sequestration. Data from a hydrophone array deployed in the Multi-Borehole Observatory (MBO) of the Oman Drilling Project (Oman-DP) demonstrates that free gas generated by peridotite alteration and/or microbial activity migrates through the formation in discrete bursts of activity. We detected four, hours-long, swarms of gas discharge into Hole BA1B of the MBO over the course of a nine month deployment. The episodic nature of the migration events indicates that free gas accumulates in the permeable flow network, is pressurized, and discharges rapidly into the borehole when a critical pressure, likely associated with a capillary barrier at a flow constriction, is reached. Our observations reveal a previously unknown dynamic mode of fluid migration during serpentinization, and highlight the important role that free gas can play in modulating pore pressure and fluid flow within the alteration vein network.

In an offspin of the project described in part 2, we examines the possibility of storing massive amounts of CO_2 in the oceanic lithosphere of the North Atlantic Igneous Province by mineral sequestration during fluid-rock interactions.

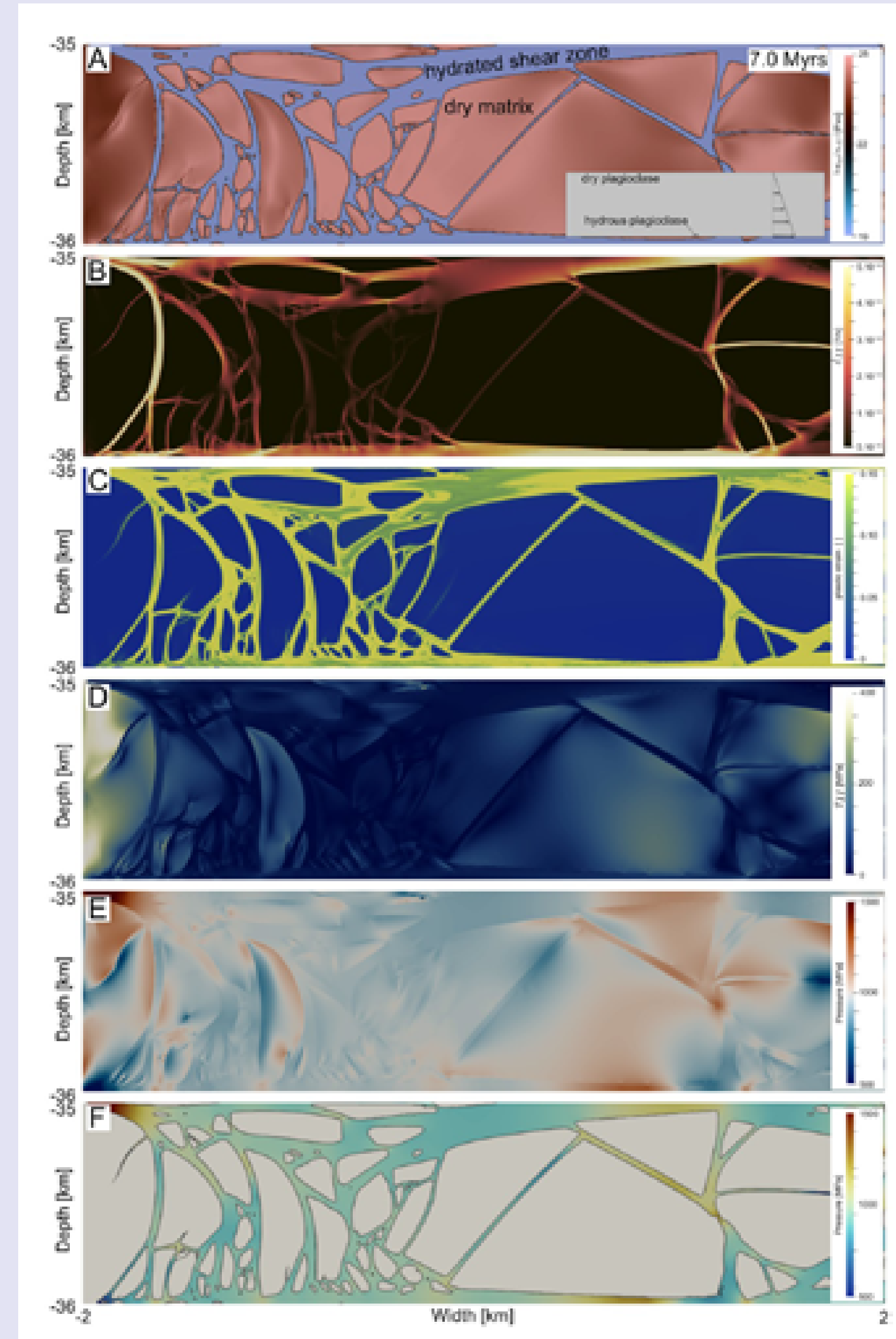


Figure. Numerical simulation of the formation hydrated shear zones in the lower crust
The simulation, using a grid resolution of $4m^2$, started with an initially homogeneous, dry, lower crust (at 650 °C) with a single embedded wet plagioclase dominated inclusion (inset in a). When imposing a constant, sinistral shear strain rate of 5×10^{-15} s^{-1}, brittle shear zones develop, followed by hydrated, weak, shear zones. Shown are snapshots that illustrate **a)** effective viscosity, **b)** effective strain rate, **c)** plastic strain, **d)** second invariant of the deviatoric stress tensor, **e)** dynamic pressure, and **f)** detail of dynamic pressure within the shear zones. Complex shear zone patterns emerge that have significant variations in stresses and dynamic pressures and may explain the coexistence of high and lower pressure assemblages in the same rocks. See supplementary movies 1-3 for animation and supplementary figure S1 for the temporal evolution for a range of imposed strain rates.

Publications in highlights

Moulas, E., Kaus, B., and Jamtveit, B., Dynamic pressure variations in the lower crust caused by localized fluid-induced weakening. *Communications Earth and Environment,* 3, no. 157.

Aiken, J.M., Sohn, R.A., Renard, F., Matter, J., Kelemen, P.B., Jamtveit, B., and the Oman DP Science team, Gas migration episodes observed during peridotite alteration in the Samail ophiolite, Oman. *Geophysical Research Letters,* 49, e2022GL100395. https://doi.org/10.1029/2022GL100395.

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

Funding
The Research Council of Norway
EU Horizon 2020 MSCA CoFund

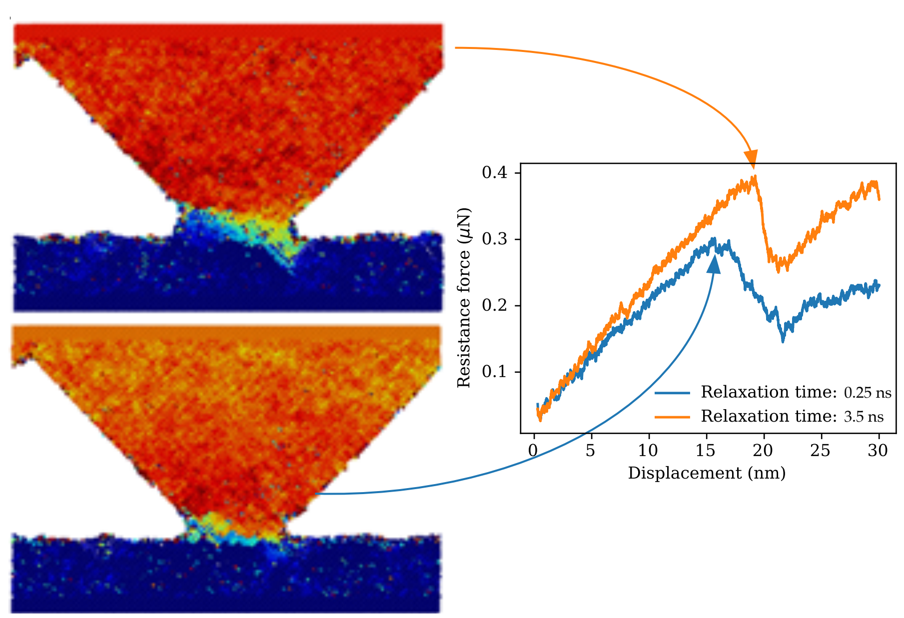
Participants
Henrik Andersen Sveinsson[1], Even Marius Nordhagen[1], Fahimeh Najafi[1], Julien Scheibert[2], François Renard[1], Evangelos Korkolis[1], Anders Malthe-Sørenssen[1]

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

History-dependent friction

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 that 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 re-attachment. 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 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.



Silicon carbide asperities with a different ageing history. 0.25 ns ageing in panel (a) and 3.5 ns in panel (b). Panel (c) shows the loading curves of these two systems when they were subjected to a horizontal load and shows that the maximum loading force increases with the loading time. The colors indicate local horizontal displacement from small (blue) to large (red). In this example, and increased ageing time caused the main failure to happen farther from the contact surface, but also increasing the damage on the base surface.

Publications in highlights

Nordhagen, E. M., Sveinsson, H. A., Malthe-Sørenssen A. (2023). Atomic scale frictional aging in silicon carbide due to diffusion and creep. *In preparation*

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

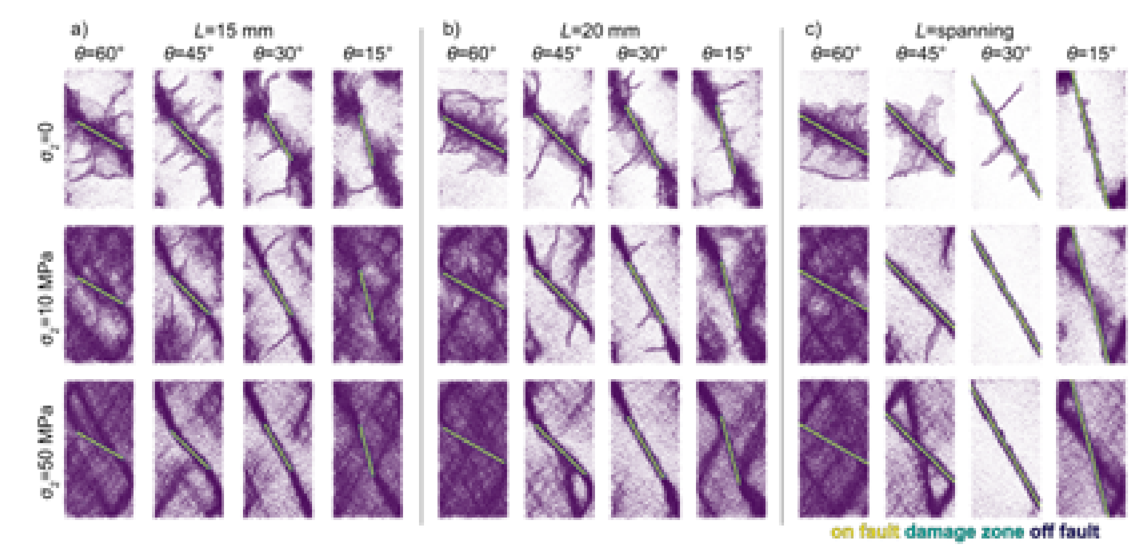
Participants
Jess McBeck[1], Francois Renard[1], Yehuda Ben-Zion[2], Xiaoyu (Bruce) Zhou[2], John Aiken[1], Joachim Matheisen[3]

Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] University of Southern California and the Southern California Earthquake Center
[3] University of Copenhagen

Emergent networks: predicting strain localization and fracture network

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.

During this year of the project, two M.S. students have successfully defended their projects and graduated, and we have collectively published seven papers.



Fracture geometry for discrete element method simulations with **a)** 15 mm long faults, **b)** 20 mm long faults and **c)** system-spanning faults at the end of the simulation, following macroscopic failure. The columns show the simulations with different fault orientations. The rows show the simulations with different confining stresses. The colors correspond to the different types of bonds: on-fault (yellow), damage zone (blue-green), and off-fault (dark blue). From McBeck (2022 PAPG).

Production in highlights

McBeck, J., & Renard, F. (2022) Deriving three-dimensional properties of fracture networks from two-dimensional observations in rocks approaching failure under triaxial compression: Implications for fluid flow. Water Resources Research, e2022WR032783.

McBeck, J. A., Cordonnier, B., & Renard, F. (2022). The evolving representative elementary volume size in crystalline and granular rocks under triaxial compression approaching macroscopic failure. Geophysical Journal International, 232(3), 1898-1913.

McBeck, J. A., Ben-Zion, Y., Zhou, X., & Renard, F. (2022). Precursory off-fault deformation in restraining and releasing step overs: Insights from discrete element method models. Journal of Geophysical Research: Solid Earth, e2022JB024326.

McBeck, J. (2022). Predicting the Timing of Catastrophic Failure During Triaxial Compression: Insights from Discrete Element Method Simulations. Pure and Applied Geophysics, 1-21.

McBeck, J., Ben-Zion, Y., & Renard, F. (2022). Predicting fault reactivation and macroscopic failure in discrete element method simulations of restraining and releasing step overs. Earth and Planetary Science Letters, 593, 117667

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 Menegon1, Jessica Ann McBeck[1], Fabian Barras[1], Yehuda Ben-Zion[3], Mai-Linh Doan[4], Jerome Weiss[4], Wenlu Zhu5, Daniel Eakins[6]

Affiliation
[1] The Njord Center, 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

Break-through rocks

Deformation in Earth's crust localizes 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 the first 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).

The two main challenges 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 will 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. If we can demonstrate that the joint analysis of acoustic emission signals and X-ray microtomography data can be used to predict dynamic rupture in our experiments, we will have discovered an important lead towards laboratory earthquake prediction. 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 2022, we have designed all the experimental apparatuses necessary to accomplish the programme of BREAK: acquisition of a MHz high-speed camera, design of a new triaxial deformation apparatus that will couple X-ray tomography and acoustic emission monitoring, and acquisition of a high-end graphic computer for analysis of synchrotron data.

Synchrotron X-ray microtomography scan of a granite core sample deformed until system-size failure performed on beamline BM18 at the European Synchrotron Radiation Facility - Sample dimensions: 10x20 mm. © Benoit Cordonnier.

Production in highlights

Kandula, N., McBeck, J., Cordonnier, B., Weiss, J., Dysthe, D. K., Renard, F. (2022) Synchrotron 4D X-ray imaging reveals strain localization at the onset of system-size failure in porous reservoir rocks, Pure and Applied Geophysics, 179, 325–350.

McBeck, J., Ben-Zion, Y., Renard, F. (2022) Volumetric and shear strain localization throughout triaxial compression, Tectonophysics, 822, 229181.

McBeck, J., Ben-Zion, Y., Renard, F. (2022) Predicting fault reactivation and macroscopic failure in discrete element method simulations of restraining and releasing step over, Earth and Planetary Science Letters, 593, 117667.

Noiriel, C., Renard, F. (2022) Four-dimensional X-ray micro-tomography imaging of dynamic processes in geosciences, Comptes-Rendus Géosciences, 354, 255–280.

Funding
The Research Council of Norway (FRIPRO)

Participants
Luca Menegon[1], Stephen Michalchuk[1], Hugo van Schrojenstein Lantman[1], Francois Renard[1], Kristina Dunkel[1], Giovanni Toffol[2], and various international collaborators

Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] Department of Geosciences, University of Padua, Italy

Conditions for earthquake nucleation in the lower crust

Earthquake initiation within the deep crust requires very high stresses, 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 (Figure 1). Several mechanisms have been proposed to generate these unusually high stresses, but direct measurements are lacking.

The project CONTINENT was funded by the RCN in 2022 and will formally start in August 2023. Its main goal is understanding 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.

During 2022, we already worked on some of these topics and demonstrated that microstructures can preserved a record of progressively higher stresses approaching a seismogenic fault (1). Furthermore, our nanoindentation experiments demonstrate that the strength of quartz in the low-temperature plasticity regime is independent on the intracrystalline H_2O content of quartz grains, and rather depends on the density of dislocation sources (2).

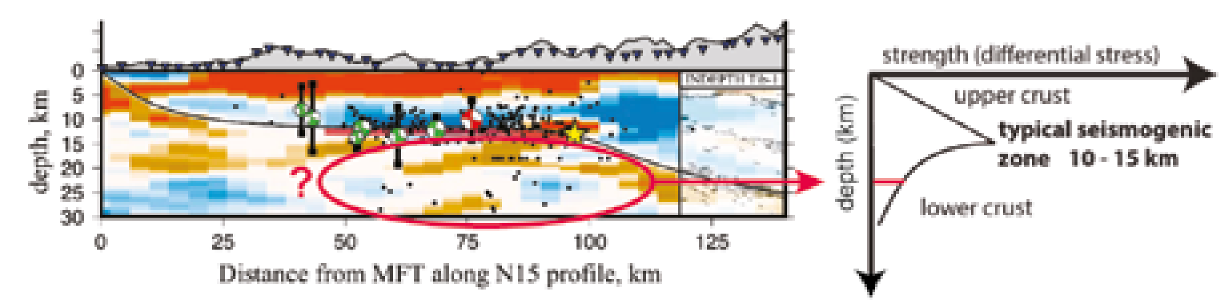


Figure 1. Distribution of aftershocks (black dots) of the 2015 Gorkha earthquake in Nepal (yellow star), and relationships with the main current model of crustal strength. Viscous flow in the lower crust would limit the capability of rocks to build up the high stresses necessary to nucleate earthquakes in the lower crust (red ellipse). Modified from Duputel et al. (2016). MFT = Main Frontal Thrust.

Production in highlights

Campbell, L.R., Menegon, L., 2022. High stress deformation and short-term thermal pulse preserved in pyroxene microstructures from exhumed lower crustal seismogenic faults (Lofoten, Norway). *Journal of Geophysical Research: Solid Earth, 127*, e2021JB023616. https://doi.org/10.1029/2021JB023616

Ceccato, A., Menegon, L., Hansen, L.N., 2022. Strength of dry and wet quartz in the low-temperature plasticity regime: insights from nanoindentation. *Geophysical Research Letters 49*, e2021GL094633. https://doi.org/10.1029/2021GL094633

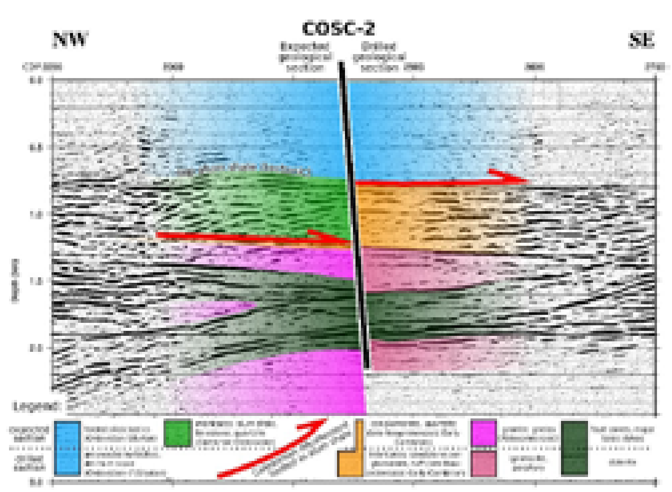
Funding
International Continental Scientific Drilling Program (ICDP)

Participants
Luca Menegon[1], several colleagues from the international COSC ICDP consortium: Are-Jarpen (icdp-online.org)

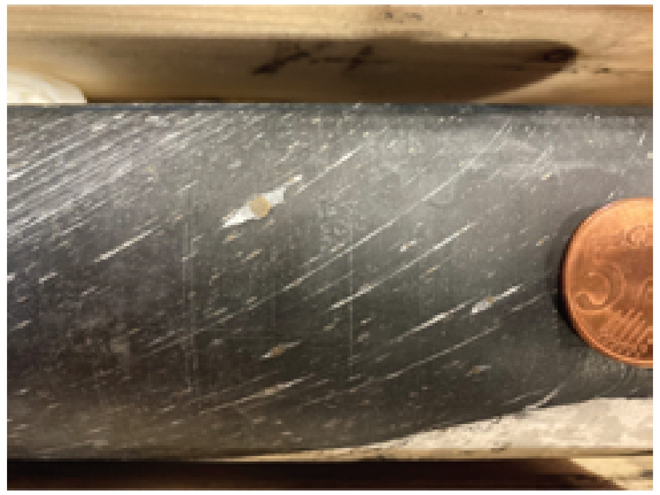
Affiliation
[1] The Njord Center, University of Oslo, Oslo, Norway

Collisional orogeny in the Scandinavian Caledonides (COSC)

The Collisional Orogeny in the Scandinavian Caledonides (COSC) scientific drilling project aims to characterise the structure and orogenic processes involved in a major collisional mountain belt by multi-disciplinary geoscientific research. Located in western central Sweden, the project has drilled two fully cored deep boreholes into the bedrock of the deeply eroded Early Paleozoic Caledonide Orogen. COSC-1 (2014) drilled a subduction-related allochthon and the associated thrust zone. COSC-2 (2020) extends this section deeper through the underlying nappes (Lower Allochthon), the main Caledonian décollement and the upper kilometre of basement rocks. COSC-2 targets include the characterisation of orogeny-scale detachments, the impact of orogenesis on the basement below the detachment, and the Early Cambrian palaeoenvironment on the outer margin of palaeocontinent Baltica. This is complemented by research on heat flow, groundwater flow, and characterisation of the microbial community in the present hard rock environment of the relict mountain belt. COSC-2 successfully recovered a continuous drill core to 2276 m depth. The retrieved geological section is partially different from the expected geological section with respect to the depth to the main décollement and the expected rock types. Although the intensity of deformation in the rocks in the upper part of the drill core might impede the analysis of the Early Cambrian palaeoenvironment, the superb quality of the drill core and the borehole will facilitate research on the remaining targets and beyond. Protocols for sampling in the hard rock environment and subsequent sample preservation were established for geomicrobiological research and rock mechanical testing. For the former, a sparse sample series along the entire drill core was taken, while the target of the latter was the décollement. COSC-2 was surveyed by a comprehensive post-drilling downhole logging campaign and a combined borehole/land seismic survey in autumn 2021. The sampling party took place in June 2022.



The COSC-2 expected geology (**left**) and the drilled geology (**right**) superimposed on the depth converted seismic section that pictures the vicinity of the COSC-2 drill site (from Lorenz et al., 2022)



Core sample of highly deformed Alum Shale from the basal decollement of the Caledonian mountain belt

Production in highlight

Lorenz H., et al. (incl. Menegon L.), 2022. COSC-2 – drilling the basal décollement and underlying margin of paleocontinent Baltica in the Paleozoic Caledonide orogen of Scandinavia. Scientific Drilling 30, 43-57; https://doi.org/10.5194/sd-30-43-2022

Funding
The Research Council of Norway (project PROMETHEUS no. 267775)

Participants
François Renard[1,4], James Johnson[1,2], Maya Kobchenko[1], Nazmul Mondol[1], Benoit Cordonnier[1], Olivier Galland[1], Luc Scholtès[3], Frédéric Donzé[4], Audrey Ougier-Simonin[5]

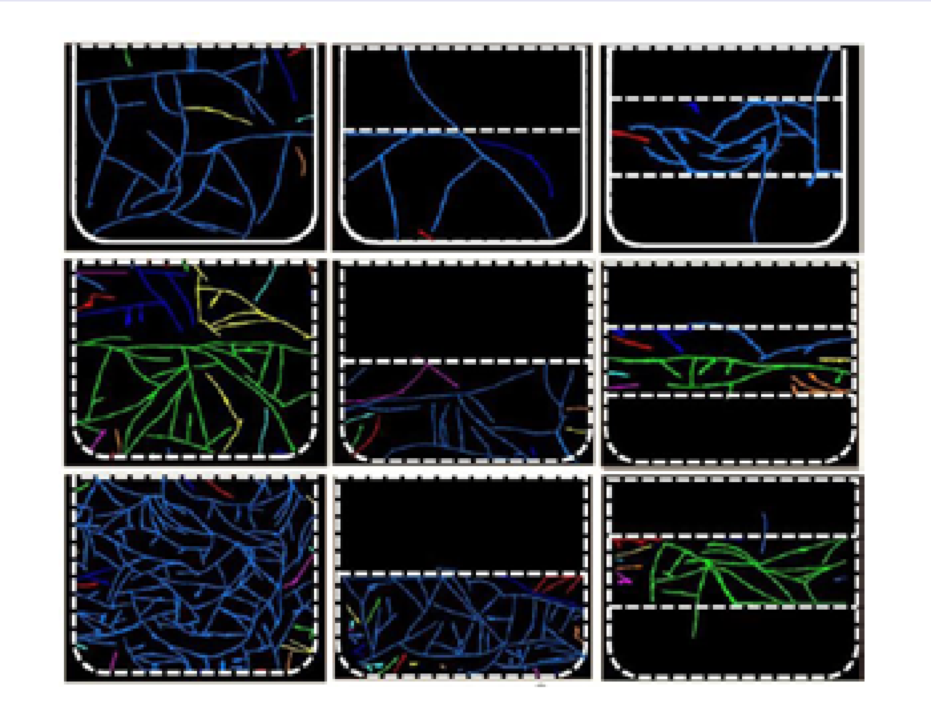
Affiliation
[1] The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Norway
[2] Department of Geosciences, University of Oslo & Norwegian Geotechnical Institute, Norway
[3] University of Nancy, France
[4] ISTerre, University Grenoble Alpes & CNRS, France
[5] British Geological Survey, United Kingdom

Maturation and fracturing of organic-rich shale during primary migration

How hydrocarbons move from source rocks during burial controls how much oil and gas could migrate toward reservoir rocks. Source rocks, also called black shales, are layered sedimentary rocks, which can be almost impermeable for fluids and act as seals and cap-rock, or, if a shale layer hosts a fracture network, it can act as a fluid reservoir and/or conduit. Organic-rich shales contain organic matter - kerogen, which can transform from solid state to oil and gas during burial and exposure to heat. When the organic matter is decomposing into lighter molecular weight hydrocarbons, the pore-pressure inside the shale rock increases and can drive propagation of hydraulic fractures.

In this project, which terminates in 2022, we followed three complementary approaches. First, we developed a baseline understanding of the relationship between organic content and maturation as it relates to the geomechanical components of the rock. Second, we performed a thorough analysis of the kerogen lenses to characterize them (size, shape, fabric, anisotropy, volume of total rock, orientation etc.) and how they interact with fractures (size, shape, fabric, anisotropy, volume of total rock, etc.). Third, we performed analogue modelling of the fracturing process within an anisotropic medium focused on understanding size, shape, density, and orientation of fractures in relationship to the anisotropy.

We have published three articles (see below). In the first article, we have developed an analogue experimental technique that reproduces processes at work during primary migration of hydrocarbons (Johnson et al., 2022a). The second article is a multiscale study of kerogen lenses with a novel multiscale synchrotron microtomography imaging technique (Johnson et al., 2022b). The third article presents a new rock physics template that quantifies how kerogen maturation modifies the geomechanical properties of shales at the basin scale (Johnson et al., 2022c).



Analogue modelling of microfracture network development into an elastic medium made of gelatin where internal fluid production occurs through the fermentation of yeast in presence of sugar (Johnson et al., 2022a). This system reproduces key processes at work during the maturation of organic-rich shales and primary migration of hydrocarbons.

Production in highlights

Johnson, J. R., Kobchenko, M., Johnson, A. C., Mondol, N. H., Renard, F. (2022a) Experimental modeling of primary migration in a layered, brittle analogue system, Tectonophysics, 8 40, 229575.

Johnson, J. R., Kobchenko, M., Mondol, N. H., and Renard, F. (2022b) Multiscale synchrotron microtomography imaging of kerogen lenses in organic-rich shales from the Norwegian Continental Shelf, International Journal of Coal Geology, 253, 103954.

Johnson, J., R., Hansen, J., A., Renard, F., Mondol, N. H. (2022c) Mapping the maturity of organic-rich shale with combined geochemical and geophysical data, Draupne Formation, Norwegian Continental Shelf, Marine and Petroleum Geology, 138, 105525.

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

Participants
Olivier Galland[1], Luca Menegon[1], Andreas Carlson[2], Sonja Greiner[3], Freysteinn Sugmundsson[3], Virginie Pinel[4], Rodolphe Lescoutre[5], Marta Rincón[6], Xia Wen[7]

Affiliation
[1] The Njord Centre, University of Oslo, Norway
[2] Mathematics department, University of Oslo, Norway
[3] University of Iceland
[4] ISTerre, Université Savoie Mont Blanc, France
[5] Uppsala University, Sweden
[6] Universidad Rey Juan Carlos, Madrid, Spain
[7] South China University, China

Volcanic plumbing systems

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 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:

- Novel monitoring of volcano-tectonic deformation in sandbox models using the Microsoft Kinect sensor (Rincón et al., 2022);
- Field work on intrusion-induced doming (Galland et al., 2022);
- Sill emplacement in the crystalline basement of Scandinavia (Lescoutre et al., 2022);
- The structural control of layering (Wen et al., in preparation) and of pre-existing fractures (Greiner et al., submitted) on dyke emplacement;
- The effects of viscoelastic properties of rocks and magma on the dynamics of sill and laccolith emplacement (Sæter et al., in revision);
- The effects in Mohr-Coulomb layering on the structure and onset of caldera collapse (Reutz and Galland, 2023).

Galland experienced a research visit at ISTerre Université Savoie Mont Blanc to establish new collaborations with the Volcano Geophysics group there. This inspiring stay was the foundation of a successful Aurora application for scientific exchange between Njord and ISTerre in 2023 and 2024. In addition, Galland is the PI of a funded FRIPRO Researcher project to be implemented in 2023-2028. 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.

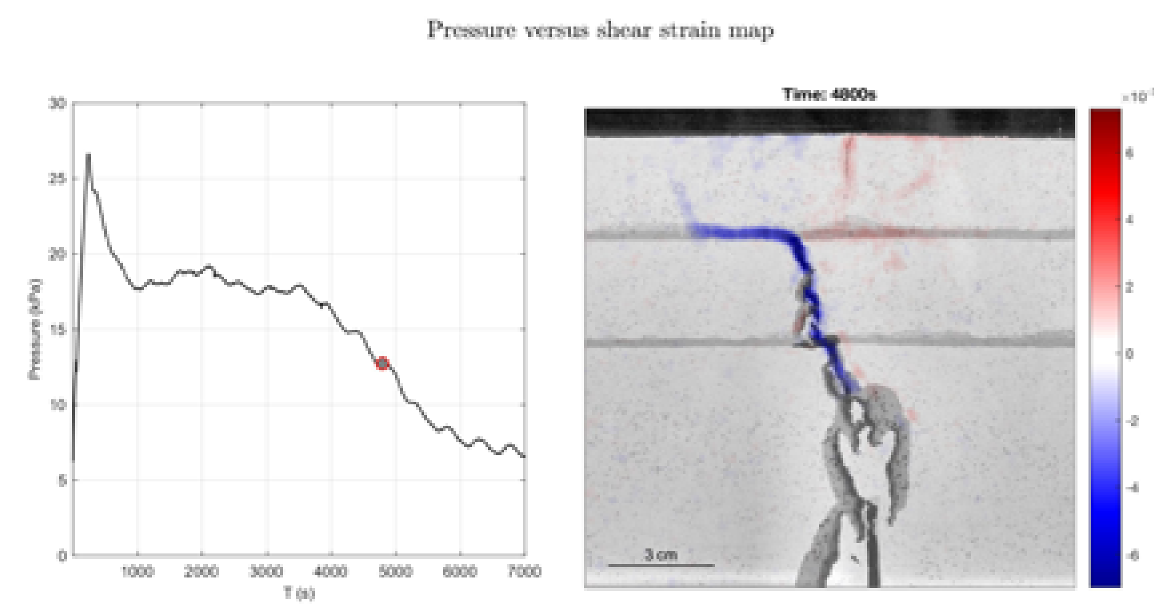


Figure. Characteristic results from 2-dimensional sandbox experiments of dyke emplacement in a layered crust (Wen et al., in preparation). Left. plot of injecting liquid pressure as a function of time during the experiment. The dot indicates the time of the photograph displayed in b. Right. Sideview photograph of the experiment. The dark grey feature is the intruding liquid, the two horizontal light grey layers are low cohesion/low friction granular layers. Displacements induced by liquid emplacement was monitored, and the calculated shear strain (red and blue: positive and negative shear strain, respectively) is overlaid on the photograph.

Production in highlights

Galland, O., de la Cal, H., Mescua, J., and Rabbel, O., 2022, 3-dimensional trapdoor structure of laccolith-induced doming and implications for laccolith emplacement, Pampa Amarilla, Mendoza Province, Argentina: Tectonophysics, p. 229418.

Reutz, E., Galland, O., 2022, The effect of weak layers on the onset of caldera collapse – Insights from limit analysis modelling. *Journal of Volcanology and Geothermal Research*

Rincón, M., Marquez, A., Herrera, R., Galland, O., Sanchez-Oro, J., Concha, D., Montemayor, A.S., 2022, Monitoring volcanic and tectonic sandbox analogue models using the Kinect v2 sensor. *Earth and Space Science*, https://doi.org/10.1029/2020EA001368

Lescoutre, R., Almqvist, B., Koyi, H., Berthet, T., Hedin, P., Galland, O., Brahimi, S., Lorenz, H., and Juhlin, C., 2022, Large-scale, flat-lying mafic intrusions in the Baltican crust and their influence on basement deformation during the Caledonian orogeny: GSA Bulletin, v. 134, no. 11-12, p. 3022-3048, doi: https://doi.org/10.1130/B36202.1

Sæter, T., Galland, O., Feneuil, B., Carlson, A., in revision, Growth of a viscoplastic blister underneath an elastic sheet. *Journal of Fluid Mechanics*

Greiner, S. H. M., Burchardt, S., Sigmundsson, F., Galland, O., Geirsson, H., Interaction between propagating basaltic dykes and pre-existing fractures, *Journal of Geophysical 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*

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

Participants
Olivier Galland[1], Ole Rabbel[1], Dougal Jerram[2], Karen Mair[1], José Mescua[3], Hernán de la Cal[4], Octavio Palma[5], Héctor Villar[6]

The impact of volcanism on petroleum systems

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 emplaces 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 and hydrocarbon systems remain poorly known. In this project, mainly through geological study in the Neuquén Basin, Argentina, we address the following aspects:

- The doming structure induced by laccolith emplacement (Galland et al., 2022, Lombardo et al., in preparation);
- The effect of magma cooling and fracturing on basin-scale fluid circulations (Rabbel et al., in revision);
- The long-term effects of solidified igneous intrusions on fluid migrations (Galland et al., Submitted; in preparation).

Production in highlights

Galland, O., de la Cal, H., Mescua, J., and Rabbel, O., 2022, 3-dimensional trapdoor structure of laccolith-induced doming and implications for laccolith emplacement, Pampa Amarilla, Mendoza Province, Argentina: Tectonophysics, p. 229418.

Galland, O., Mescua, J., Villar, H. J., Medialdea, A., Zanella, A., Leanza, H. A., Jerram, D. A., and Planke, S., submitted, An igneous conduit erupting petroleum: the Cerro Alquitrán, Neuquén Basin, Argentina: Basin Research.

Rabbel, O., Galerne, C., Hasenclever, J., Galland, O., Mair, K., Palma, J.O., in revision, Importance of permeability evolution in igneous sills for hydrothermal flow in volcanic basins. *Solid Earth*

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) DougalEarth Ltd., UK
3) CONICET Mendoza, Argentina
4) ROCH SA, Argentina
5) Y-TEC, Argentina
6) GeoLab Sur, Argentina

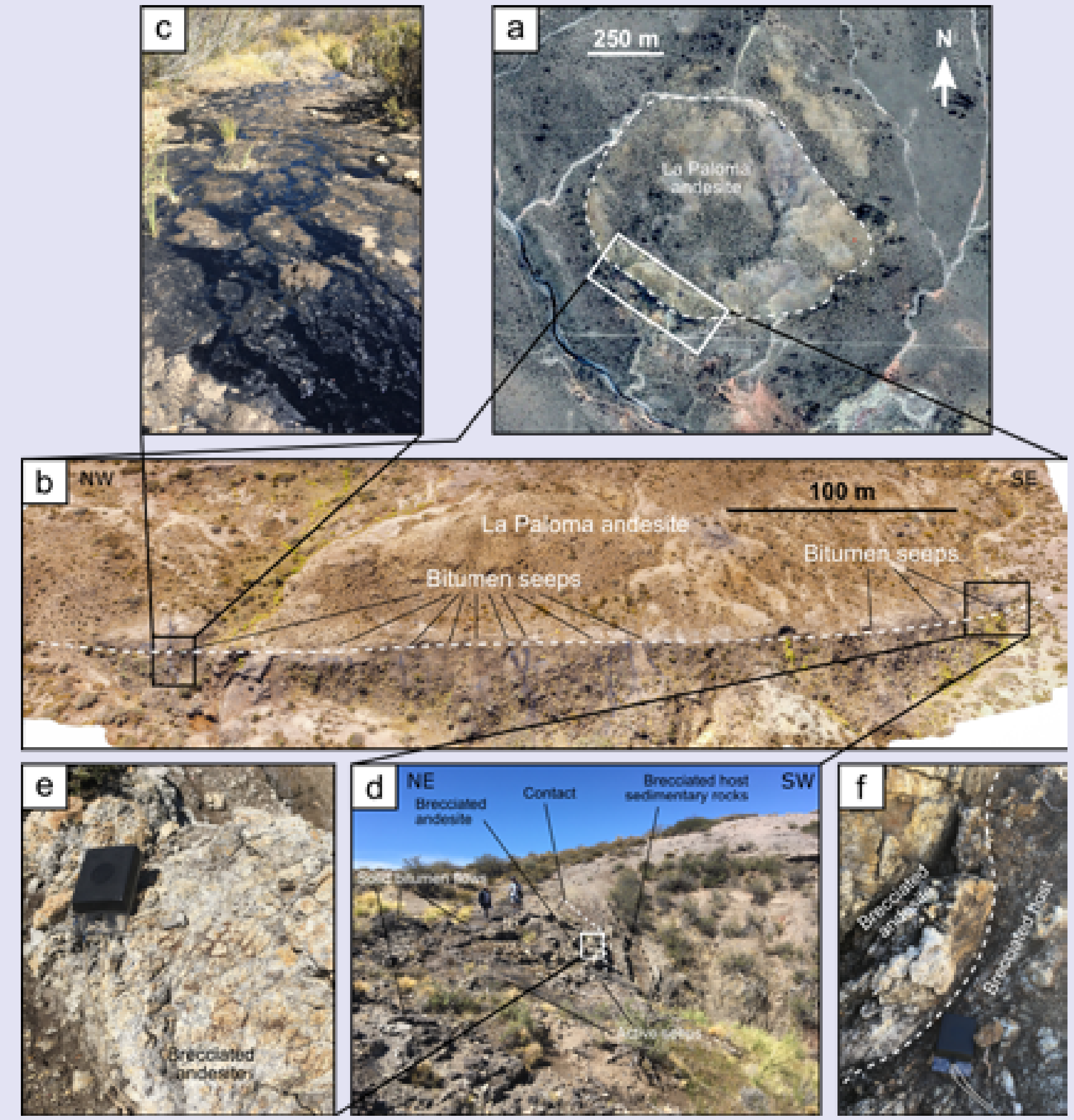
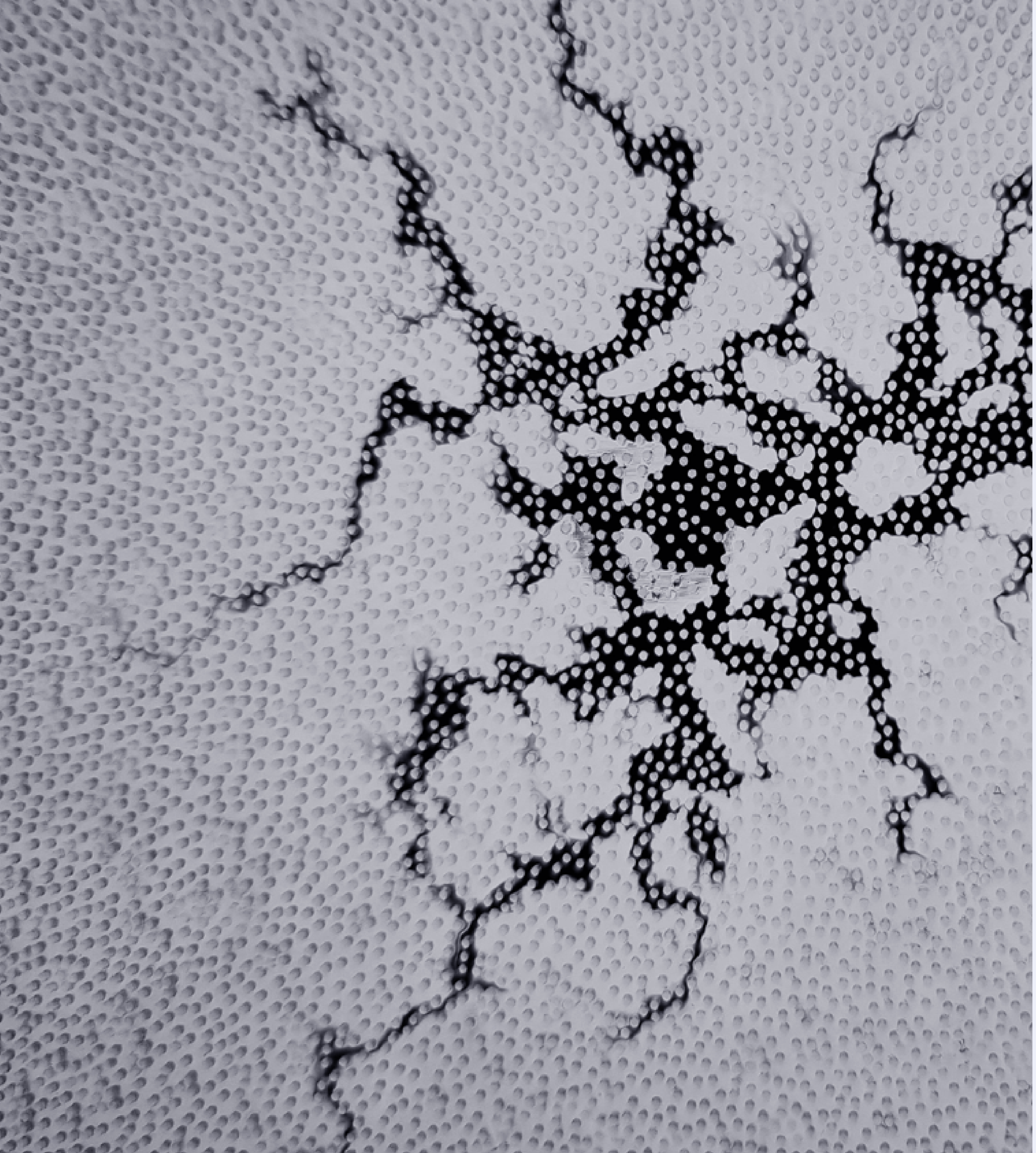


Figure. a. Satellite image of Cerro La Paloma intrusion. White dash line marks estimated intrusion contact. White rectangle located image of b. b. 3D virtual model of bitumen seeps located along SW margin of Cerro La Paloma intrusive (see location in a). c. Field photograph of liquid bitumen seep (see location on b). d. Field photograph showing the subvertical contact of the Cerro La Paloma intrusive body with the sedimentary host rock (see location in b). Liquid bitumen seeps out from the andesite. e. Field photograph of brecciated andesite next to the intrusive contact (see location in d). f. Detailed field photograph of intrusive contact. Both the andesite and sedimentary host rock are heavily brecciated and impregnated with bitumen. From Galland et al., (in preparation).

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 preparation, 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 preparation, 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*



Chapter 3 | Part 3

Couplings at the Nanoscale

1. Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity
2. Modelling and imaging flow in rocks across scales
3. Molecular dynamics simulations of nanoscale geological processes
4. Collective states of active matter with stochastic reversals: emergent chiral states and spontaneous current switching

Funding
The Research Council of Norway (FRIPRO Researcher project with international mobility).

Participants
Joanna Dziadkowiec[1,2], Anja Røyne[1], Dag Kristian Dysthe[1], Markus Valtiner[2]

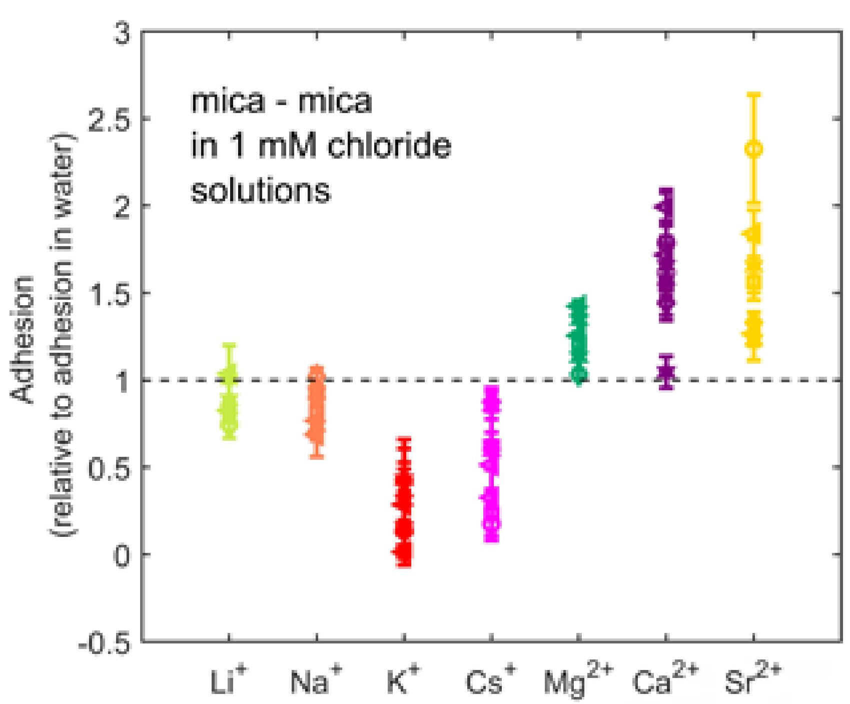
Affiliation
[1] The Njord Center, University of Oslo, Norway
[2] Vienna University of Technology, Vienna, Austria

Solid-solid interfaces as critical regions in rocks and materials: probing forces, electro-chemical reactions, friction and reactivity

The composition of aqueous solutions confined between two mineral surfaces determines the strength of water-wet solid-solid contacts. Using non-reactive mica surfaces, we show that disjoining pressure acting between two mineral surfaces is evidently ion-dependent even at very low ionic strength (Figure 1). For more reactive minerals, disjoining pressure is further affected by solution-induced surface dissolution and reprecipitation. In this project, we explore to what extent the solution properties influence the strength of solid-solid interfaces and seek methods to strengthen weak mineral contacts.

Our basic experimental tool is the surface forces apparatus (SFA). SFA measures nm-range surface forces acting between two surfaces immersed in fluid while providing simultaneous, interferometric information about topography of the whole μm-sized contact region. Thus, SFA is suitable for studying forces acting between reactive solids. Our most recent experiments use SFA to study mineral growth in confinement, where a wedge-shaped pore is formed by pressing two semi-cylindrical SFA disks together [1].

Our experiments show that dissolved ions are most effective to influence disjoining pressure between highly charged minerals, such as mica. For more reactive and weakly charged minerals like calcite, this effect is less evident. We further demonstrated two systems, in which strong adhesion is facilitated by nanoparticles. In the first system, adhesion is provided by water-dispersed silica nanoparticles, which seal the contact upon drying due to capillary force-induced cohesion [2]. In the second system, we show that calcium silicate hydrate (C-S-H) nanoparticles growing in the contact induce adhesion between rough surfaces. This is due to the soft, gel-like character of C-S-H and high-surface charge of the C-S-H [3].



Forces between two mica surfaces measured with SFA in 1 mM chloride salt solution. Adhesion is shown relative to the adhesion measured in water.

Production in highlight

Dziadkowiec J., Linga G., Kalchgruber L.,Kavunga S., Valtiner M. (2023). Electrochemical precipitation of calcite in confinement. *In preparation*.

Dziadkowiec, J., Cheng, H.-W., Ludwig, M., Ban, M., Tausendpfund, T. P., von Klitzing, R., Mezger M., Valtiner, M. (2022). Cohesion gain induced by nanosilica consolidants for monumental stone restoration. *Langmuir*, 38, 22, 6949–6958

Liberto, T., Nenning, A., Bellotto, M., Dalconi, C., Dworschak, D., Kalchgruber, L., Robisson, A., Valtiner M., Dziadkowiec, J. (2022). Detecting Early-Stage Cohesion Due to Calcium Silicate Hydration with Rheology and Surface Force Apparatus. *Langmuir*.

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

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

Affiliation
[1] The Njord Centre, Departments of Geosciences and Physics, 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

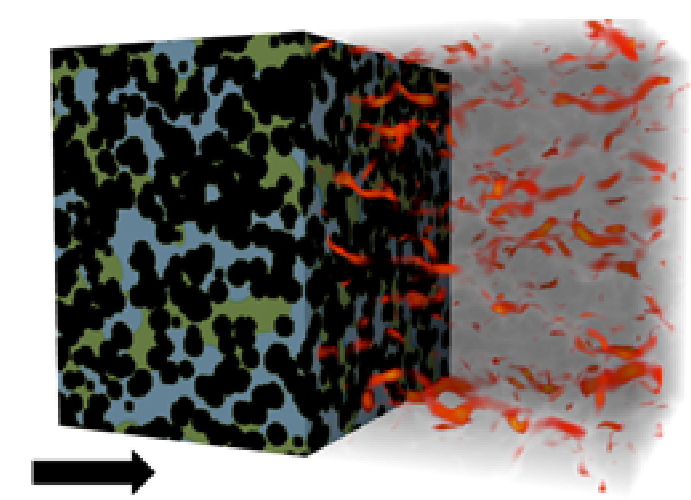
Modelling and imaging flow in rocks across scales

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, 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 faults.

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 flow intermittency significantly enhances transverse spreading as well as the folding and stretching of fluid filaments, which is a hallmark of chaotic mixing. The figure below shows this intermittency in three-dimensional numerical simulations of solute transport in immiscible two fluid flow.

Fluid flow also has an impact on the fracture network itself, as the injection of fluid can further open existing cracks. Understanding such processes is essential to assess the safety and integrity of underground storage (e.g. CO_2, hydrogen). We have designed a numerical method to solve the coupled dynamics of fluid flow and fracture growth.

Three-dimensional modelling of dispersion in multiphase fluid flow in porous media. Two fluids (blue has properties of water, green has properties of oil) flow together into a porous medium (black circles). The orange to red colors indicate the fluid velocity that is highly heterogeneous and varies in time due to capillary forces. This behavior leads to intermittency that enhances solute dispersion. The black arrow shows the direction of fluid flow.



PoreLab
NTNU-UiO Porous Media Laboratory

Production in highlights

Renard, F. (2022). Neutron imaging of fluid flow in rocks and applications to subsurface processes, Conference on the Nordic perspectives on advanced neutron imaging, Lyngby, Denmark, 24 November 2022.

Renard, F. (2022). Using large instruments to image fluid flow and deformation in rocks, University of Tromsø, 18 November 2022.

Renard, F. (2022). Using Large Instruments to Image Flow and Deformation Processes in Rocks, Gordon Research Conference on Flow and Transport in Permeable Media, 17-22 July 2022, Les Diablerets, Switzerland.

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

Molecular dynamics simulations of nanoscale geological processes

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 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. During the last year, we have also started training 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.

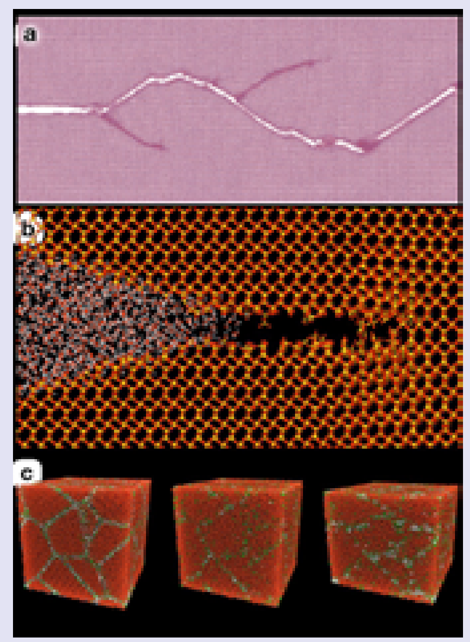


Figure: Molecular dynamics simulations of nanoscale failure processes. (**a**) Dynamic crack in quartz. Instabilities and crack branching setting the stage for pulverization. (**b**) Water entering the pore space behind a dynamically propagating crack. (**c**) Creep behavior of a methane hydrate polycrystal under compression.

Production in highlights

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). https://doi.org/10.1029/2022GL100468

Sveinsson, H. A., Cao P (2023). Distinct creep regimes of methane hydrates can be predicted by a monatomic water model. *In preparation*

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K.S.O. acknowledges support from the Nordita Fellowship program. Nordita is partially supported by NordForsk. L.A. and E.G.F. acknowledge support from the Research Council of Norway through the Center of Excellence funding scheme, Project No. 262644 (PoreLab).

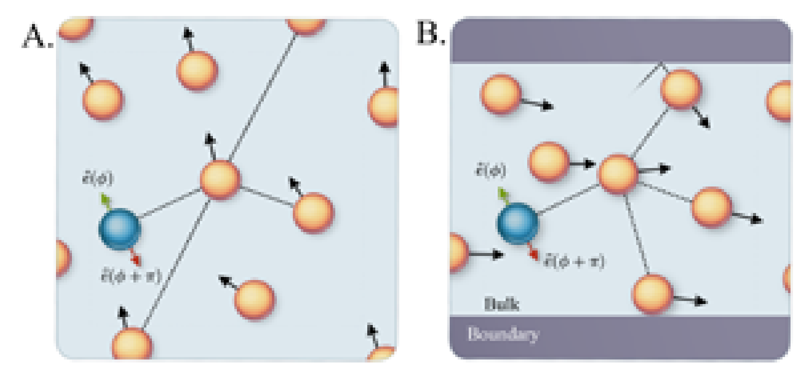
Participants
Kristian S. Olsen[1], Eirik G. Flekkøy[2], Luiza Angheluta[2]

Affiliation
[1] Nordita, Royal Institute of Technology and Stockholm University, Sweden
[2] PoreLab, The Njord Centre, University of Oslo, Norway

Collective states of active matter with stochastic reversals: emergent chiral states and spontaneous current switching

Collective behaviour is ubiquitous in biological systems, ranging from collective migration of cells and bacteria to flocks of birds and other animals [1]. Multistability is often present in realistic swarming behaviour, where the system undergoes a series of transitions between different collective states, triggered by perturbations. Often such perturbations are external, e.g. in the form of disordered media, obstacles of applied fields. In biological systems however, perturbations may be internal in the sense that a particle at rare instances performs more drastic dynamics. For example, several species of bacteria are known to suddenly reverse their direction of motion, while their normal dynamics only includes smooth slow reorientations. It is the goal of this project to unveil which collective states may be produced when such reversals are combined with interparticle interactions.

In particular, we consider active particles that move with a constant self-propulsion speed in two dimensions [2]. Particles interact with a random selection of other particles, and tries to align its direction of motion with the interaction partners. Randomly, but at constant rate, the particles reverse their direction of motion. See figure for sketch of the dynamics.



Sketch of the system under consideration. Self-propelled particles align through continuous-time alignment interactions and undergo stochastic reversals of their direction of motion at random times (see e.g., blue particle). Particles interact with a fixed number of other particles irrespective of their physical separation. Both collective dynamics in open space (**fig. A**) and confined to a 2D channel (**fig. B**) is considered.

When the particles move in open unconfined space (part A in figure), surprising collective states appears. At weak interaction strengths the flock of particles performs seemingly random motion. As the interaction strength increases the flock becomes chiral, with the mean direction of motion of the whole picks up an angular velocity. At intermediate interaction strengths this angular velocity randomly switches signs, while at strong interactions it is constant. Similar effects are found when the particles are put in a channel (part B in figure); in this instance the flock can collectively move either to the right of to the left in the channel, and the collective states undergo transitions between these two possible states.

[1] M. C. Marchetti, J.-F. Joanny, S. Ramaswamy, T. B. Liverpool, J. Prost, M. Rao, and R. A. Simha, Hydrodynamics of soft active matter, Rev. Mod. Phys. 85, 1143 (2013).

[2] Olsen, K. S., Angelutha, L., Flekkøy, E. G., (2022). Collective states of active matter with stochastic reversals: Emergent chiral states and spontaneous current switching. Physical Review Research 4, 043017.

Production in highlights

Olsen, K. S., Angelutha, L., Flekkøy, E. G., (2022). Collective states of active matter with stochastic reversals: Emergent chiral states and spontaneous current switching. Physical Review Research 4, 043017.

04

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 Olaf	h.o.austrheim@geo.uio.no	Professor Emeritus
Dunkel	Kristina	kristina.dunkel@geo.uio.no	Associate Professor
Dysthe	Dag Kristian	d.k.dysthe@fys.uio.no	Professor
Flekkøy	Eirik Grude	e.g.flekkoy@fys.uio.no	Professor
Galland	Olivier	olivier.galland@geo.uio.no	Research Professor
Helgesen	Geir	geir.helgesen@fys.uio.no	Adjunct professor (20%)
Jamtveit	Bjørn	bjorn.jamtveit@geo.uio.no	Vice Dean
Le Borgne	Tanguy	tanguy.le-borgne@univ-rennes1.fr	Adjunct professor (20%)
Mair	Karen	karen.mair@geo.uio.no	Professor
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	Senior Researcher
Røyne	Anja	anja.royne@fys.uio.no	Lecturer
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
Aupart	Claire	claire.aupart@outlook.fr	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
Korkolis	Evangelos	evangelos.korkolis@mn.uio.no	Postdoctoral Fellow
Lantman	Hugo	h.w.van.s.lantman@mn.uio.no	Postdoctoral Fellow
Linga	Gaute	gaute.linga@mn.uio.no	Postdoctoral Fellow
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
Thøgersen	Kjetil	kjetil.thogersen@fys.uio.no	Researcher (20%)
Vincent-Dospital	Tom	tom.vincent-dospital@fys.uio.no	Postdoctoral Fellow
Zertani	Sascha	sascha.zertani@mn.uio.no	Researcher

Doctoral Research Fellows

Last name	First name	E-mail	Function
Aspaas	Andreas	a.g.aspaas@geo.uio.no	Doctoral Research Fellow
Baldelli	Beatrice	beatrice.baldelli@fys.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
Jain	Harish	harishpj@fys.uio.no	Doctoral Research Fellow
Johannesen	Rakul	r.m.johannesen@mn.uio.no	Doctoral Research Fellow
Johnson	James Ronald	j.r.johnson@geo.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
Olsen	Kristian	k.s.olsen@fys.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

Supporting Staff

Last name	First name	E-mail	Function
Hu	Yi	yi.hu@fys.uio.no	Senior engineer
Jankov	Mihailo	mihailo.jankov@fys.uio.no	Senior engineer
Thorud	Nina Mino	mino@mn.uio.no	Adm. coordinator
Sannesmoen	Trine	trine.sannesmoen@geo.uio.no	Senior excecutive
Hoff	Janne	janne.k.hoff@mn.uio.no	Adm. coordinator
Nigar	Abbasova	nigar.abbasova@astro.uio.no	Adm. support

Visiting guests

Last name	First name	E-mail	Visiting from
Brantut	Nicolas	n.brantut@ucl.ac.uk	UK
Bolibar	Jordi	j.bolibar@uu.nl	Netherlands
Buendin	Gloria	buendiag@gmail.com	Venezuela
Heier	Nick	nheier@asu.edu	USA
Larose	Eric	eric.larose@univ-grenoble-alpes.fr	France
Meakin	Paul	paulzmeakin@gmail.com	USA
Nlep	Elodie	elodienlep@yahoo.fr	Cameroon
Rogowitz	Anna	anna.rogowitz@univie.ac.at	Austria
Thielman	Marcel	Marcel.Thielmann@uni-bayreuth.de	Germany
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@astro.uio.no	Dag Kristian Dysthe, Luiza Angheluta-Bauer
Blum	Cletus	cletusb@student.geo.uio.no	Amanda Johansen DiBiagio, Hans Petter Jostad, Karen Mair, 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
With Due	Thor	tgdue@student.geo.uio.no	Luke Griffiths, François Renard
Falkeid	Silje	smfalkei@student.geo.uio.no	Luca Piciullo, Anders Solheim, Karen Mair
Kings	Jonathan	jonathan.kings@fys.uio.no	Eirik Flekkøy
Milos	Joksimovic	milos.joksimovic@fys.uio.no	Luiza Angheluta-Bauer
Moen	Emily	e.q.z.moen@fys.uio.no	Luiza Angheluta-Bauer
Payabyab	Ronald	rmpayaby@student.geo.uio.no	François Renard, Desiree Silvana Treichler
Reiakvam	Are	arereia@hotmail.com	Hendrik Sturm, Elin Skurtveit, Karen Mair
Reykdal	Helene	helenrey@student.geo.uio.no	Axel Bernd Müller, Bjørn Jamtveit
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 and Bernd Etzelmüller
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
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 Jørge Kjøll, Sverre Planke
Johnson, James	Microfractures in organic shales and their transport properties	Nazmul Mondol, François Renard
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, Francois Renard and Kristina Dunkel
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 and Sverre Planke (VBER and Universitetet i Oslo/CEED).
Rønning, Jonas	Turbulence in Bose-Einstein condensates and active matter	Luiza Angheluta, 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

PhDs completed in 2022

Candidate	Title/Topic	Supervisor(s)
Marthe Guren	Imaging and modelling nanoscale dynamics of mineral-mineral and mineral-fluid interfaces during mechano-chemical transformations	François Renard, Henrik Andersen Sveinsson, Anders Malthe-Sørenssen
James Johnson	Microfractures in organic shales and their transport properties	Nazmul Mondol, François Renard

Postdoc projects

Candidate	Title/Topic	Supervisor(s)
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
Dospital, Tom	Fluid flows in porous materials with a controlled disorder	Knut Jørgen Måløy
Dziadkowiec, Joanna	Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity	Anja Røyne, Dag Kristian Dysthe, Markus Valtiner
Fu, Yuequn	Atomistic insights into nano-scale cavitation on the silica surface	Eirik Grude Flekkøy, Knut Jørgen Måløy
Guren, Marthe	Nanoscale modeling of reaction-induced fracturing	François Renard, Henrik Andersen Sveinsson, Anders Malthe-Sørenssen
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
Korkolis, Evangelos	History-dependent friction	Anders Malthe-Sørenssen, François Renard
Lantmann, Hugo	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	Connectivity enhancement due to thin liquid films in porous media flows	Moura, Marcel
Thøgersen, Kjetil	Friction controls on glacier motion	Anders Malthe-Sørenssen
Zertani, Sascha	The cyclic interplay of seismic and aseismic deformation in the lower continental crus	Luca Menegon, Bjørn Jamtveit

Guest talks, workshops and seminars

Date	Speaker and name of talk
January 14th	Osvanny Ramos, Université Claude Bernard Lyon 1. "The LabQuakes project: from a granular fault to earthquake statistics"
January 21st	Njord Seminar Series: Kristina Dunkel, "Earthquakes in the lower crust - origins and consequences"
January 28th	Marcel Thielmann, University of Bayreuth. "Crushed and fried: collaborative generation of deep earthquakes due to grain size reduction and shear heating"
February 4th	Njord Seminar Series: Vidar Skogvoll & Marcel Moura, "A phase-field crystal framework for 3D dislocation dynamics" & "Capillary pumping: the spreading of pollution in porous media"
February 11th	Salima Rafai, Université Grenoble Alpes. "Flowing Active Suspensions: plankton as a model active particle"
February 18th	Njord Seminar Series: John Aiken & Paiman Shafabakhsh "Understanding serpentinization rates in Oman through hydrogen degassing events" & "Neutron imaging of reactive-mixing in porous rocks".
March 4th	Karianne Bergen, Brown University. "Big data for small earthquakes: Data mining, deep learning and explainable AI"
March 11th	Njord Seminar Series: Thomas Combriat & Andreas Aspaas "Cells on the move - Tickling biology with ultrasonic waves" & "What causes transient deformations in the Åknes landslide, Norway?"
March 17th	Brendan Dyck, University of British Columbia. "Unravelling 150 million years of metamorphism and deformation along the Great Slave Lake Shear Zone"
March 25th	Njord Seminar Series: Per Arne Rikvold & Henrik Sveinsson "Fluctuations and cascades in models of evolving ecosystems" & "Predicting fracture strength in silica using machine learning"
April 4th	Kick-off meeting for the CO2Basalt project. Organizing committee: François Renard, Trine Sannesmoen
April 22nd	Shyam Nandan, ETH Zurich. "Triggering of large earthquakes is driven by their twins"
April 29th	Mazi Jalaal (UvA): Free surface flow of yield stress materials on small scales
May 6th	Njord Seminar Series: Joanna Dziadkowiec & Fabian Barras "Mineral growth in confinement - experiments in surface forces apparatus" & "Cracks in the code"
May 12th	Vito Rubino, California Institute of Technology: "Earthquake rupture behavior and evolution of dynamic friction revealed by laboratory experiments"
May 20th	Ruby Fu, California Institute of Technology: "Solidification Flows in Porous Media: Stories from Gas Hydrate and Snow"
June 10th	Friction Workshop at the Njord Centre, UiO. Organizing committee: Fabian Barras, François Renard, Trine Sannesmoen
June 15th and 16th	The EarthFlows Seminar. Organizing committee: Vidar Skogvoll, Torstein Sæter, Trine Sannesmoen, François Renard, Luiza Angheluta-Bauer
September 1st	Renelle Dubosq (Max-Planck-Institut für Eisenforschung GmbH): Bridging materials and Earth sciences through correlative microscopy
September 23rd	Njord Seminar Series: Marthe Grønlie Guren (Njord, UiO) "Linking dissolution rates at carbonate surfaces using X-ray tomography and numerical modelling" Paiman Shafabakhsh (Njord, UiO) : "Neutron and X-ray imaging of reactive-mixing in porous rocks" Dag Kristian Dysthe (Njord, UiO) - An update on his work.
September 30th	Luca Dal Zilio (ETH) in Zurich. "Cross-scale modeling of fluid-induced seismic and aseismic slip"
October 14th	Internal seminar: New people at Njord - Presenting their projects
October 21st	Alissa Kotowski, University of Utrecht. "Strength and deformation mechanisms of amphibole-rich rocks in hot and cold subduction zones".
October 28th	Iain Stewart, University of Plymouth. "Selling Planet Earth: communicating geoscience to the public".
October 31th	M4: Mixing in Multiphase flow through Microporous Media Progress seminar. Organizers: Gaute Linga and Janne Hoff
November 1th	Johan Gaume, EPFL in Lausanne. "Supershear snow slab avalanches".
November 18th	Timo Koch, UiO. "Network models for flow and transport in porous media".
November 25th	Freysteinn Sigmundsson, University of Iceland. "Improving understanding of dike intrusion and eruption precursors".
December 2nd	Internal seminar: Luca Menegon, Olivier Galland and John Aiken. The new projects at Njord funded by FriPro NFR
December 8th	The CO2Basalt seminar. Organizing committee: Marthe Grønlie Guren, Marija Plather Rosenqvist, Rakul Maria Johannsen
January - December	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

Production list 2022

Published in 2022

1. Acharya, Amit; **Angheluta, Luiza** & Viñals, Jorge (2022). *Elasticity versus phase field driven motion in the phase field crystal model.* Modelling and Simulation in Materials Science and Engineering. ISSN 0965-0393. 30(6).

2. **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.

3. **Austrheim, H.**, Engvik, A. K., Granerød, M., **Dunkel, K. G.** & Velo, M. R. (2022). *Low-grade Prehnite-Pumpellyite facies metamorphism and metasomatism in basement rocks adjacent to the Permian Oslo rift; the importance of displacive reactions.* Journal of Metamorphic Geology, 40(9), 1467- 1492.

4. Alonso-Llanes, L., Sánchez-Colina, G., Batista-Leyva, A. J., Clément, C., Altshuler, E., & **Toussaint, R.** (2022). *Sink versus tilt penetration into shaken dry granular matter: The role of the foundation.* Physical Review E, 105(2), 024903.

5. Alonso-Llanes, L., Martínez, E., Batista-Leyva, A. J., **Toussaint, R.**, & Altshuler, E. (2022). *Continuous to intermittent flows in growing granular heaps.* Physical Review E, 106(1), 014904.

6. **Baldelli, B., Linga, G., Flekkøy, E. G.** (2022). *Thermal conduction through a cool well.* Physical Review Fluids 7, 103503.

7. **Bouchayer, C., Aiken, J. M., Thøgersen, K., Renard, F.**, & Schuler, T. V. (2022). *A machine learning framework to automate the classification of surge-type glaciers in Svalbard.* Journal of Geophysical Research: Earth Surface, e2022JF006597.

8. Bouchon, M., Socquet, A., Marsan, D., Guillot, S., Durand, V., Gardonio, B., ..., **Renard F.**, & Boullier, A. M. (2022). *Observation of rapid long-range seismic bursts in the Japan Trench subduction leading to the nucleation of the Tohoku earthquake.* Earth and Planetary Science Letters, 594, 117696.

9. **Brodin, J. F., Moura, M., Toussaint, R., Måløy, K. J.**, & **Rikvold, P. A.** (2022). *Visualization by optical fluorescence of two-phase flow in a three-dimensional porous medium.* In Journal of Physics: Conference Series, 2241(1), 012004.

10. **Brodin, J., Rikvold, P., Moura, M., Toussaint, R.**, & **Måløy, K.** (2022). *Competing Gravitational and Viscous Effects in 3D Two-Phase Flow Investigated With a Table-Top Optical Scanner.* Frontiers In Physics, 10. doi: 10.3389/fphy.2022.936915.

11. Cabrita, D. I., Faleiros, F. M., Ribeiro, B. V., **Menegon, L.**, Cawood, P. A., & Campanha, G. A. (2022). *Deformation, thermochronology and tectonic significance of the crustal-scale Cubatão Shear Zone, Ribeira Belt, Brazil.* Tectonophysics, 828, 229278.

12. Cao, P., Sheng, J., **Sveinsson H.A.**, Wu, J., & Ning, F. (2022). *Electric Field-Controlled Structural Instability and Mechanical Properties of Methane Hydrates.* Crystal Growth & Design 2022 22 (5), 3107-3118.

13. Campbell, J. M., Sandnes, B., **Flekkøy, E. G.**, & **Måløy, K. J.** (2022). *Dynamics of Dendritic Ice Freezing in Confinement.* Crystal Growth & Design, 22(4), 2433-2440.

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Published in 2023 or in processes for publishing

1. Aslan, G., de Michele, M., Raucoules, D., **Renard, F.**, Dehls, J., Penna, I., Hermanns, R., Cakir, Z. *Dynamics of a giant slow landslide complex along the coast of the Aral Sea, Central Asia*. Landslides, submitted.

2. Bouchon, M., Guillot, S., Marsan, D., Socquet, A., Jara, J., Durand, V., Gardonio, B., Campillo, M., Perfettini, H., Schmittbuhl, J., **Renard, F.**, Boullier, A. M. *Rapid seismic bursts linking the foreshocks and epicenter to the deep slab where dehydration occurs preceded the Iquique megathrust earthquake*, submitted.

3. **Barras, F., Thøgersen, K., Aharonov, E., Renard, F.** *How do earthquakes stop? Insights from a minimal model of frictional rupture.* Journal of Geophysical Research: Solid Earth, submitted.

4. Gratier, J.-P., **Menegon, L.** and **Renard, F.** *Pressure solution grain boundary sliding as a large deformation mechanism of superplastic flow in the upper crust.* Journal of Geophysical Research: Solid Earth, submitted.

5. Hansen, A., **Flekkøy, E.**, Sinha, S., & Slotte, P. (2023). *A statistical mechanics framework for immiscible and incompressible two-phase flow in porous media*. Advances In Water Resources, 171, 104336.

6. Hibert, C., Noël, F., Toe, D., Talib, M., Desrues, M., Wyser, E., ... , **Toussaint R.**, Malet J.-P. & Jaboyedoff, M. *Machine learning prediction of the mass and the velocity of controlled single-block rockfalls from the seismic waves they generate.* EGUsphere, 1-25. (preprint)

7. Keers, H., Nyberg, B., **Mair, K.**, & Stordahl, E.M. *Geoscience education, technology and the pandemic: Results from two worldwide surveys.* Journal of Geoscience Education special issue (submitted)

8. Julia, M., Putnis, C. V., King, H. E., **Renard, F.** *Coupled dissolution-precipitation and growth processes on calcium carbonate exposed to cadmium-rich aqueous solutions.* Chemical Geology, submitted.

9. Mathijssen, A. J., Lisicki, M., Prakash, V. N., & **Mossige, E. J.** *Culinary fluid mechanics and other currents in food science.* arXiv preprint arXiv:2201.12128v2.

10. **Mathiesen, J., Linga, G., Renard, F.**, Le Borgne, T. *Dynamic fluid connectivity accelerates solute dispersion in multiphase porous media flow.* Submitted.

11. **McBeck, J., Cordonnier, B.,** and **Renard, F.** (2023). *The evolving representative elementary volume size in crystalline and granular rocks under triaxial compression approaching macroscopic failure.* Geophysical Journal International, 232, 1898–1913.

12. Montes-Hernandez, G., Feugueur, L., Vernier, C., Van Driessche, A., **Renard, F.** *Efficient removal of antibiotics from water via aqueous portlandite carbonation*. Journal of Water Process Engineering, in press.

13. Nordbotten, J. M., & **Mossige, E. J.** *The dissolution of a miscible drop rising or falling in another liquid at low Reynolds number.* arXiv preprint arXiv:2211.01242.

14. **Rønning, J.**, Marchetti, M. C., & **Angheluta, L.** *Defect self-propulsion in active nematic films with spatially-varying activity.* arXiv preprint arXiv:2209.00333.

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

16. Razbani, M. A., Jettestuen, E., **Røyne, A.**, *Direct pore-scale numerical simulation of microbially induced calcium carbonate precipitation*. Journal of Water Resources Research, in press.

Invited talks

1. **Barras F.** *Dynamic rupture driven by shear localization*. EarthFlows Meeting, University of Oslo, 15-16 June 2022.

2. **Dunkel K.** *Weakening mechanisms in dry lower-crustal pseudotachylytes.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

3. **Dziadkowiec J.** *Experimental measurements of surface forces between mineral surfaces.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

4. **Linga G.** *Mixing in intermittent multiphase flow in porous media*. EarthFlows Meeting, University of Oslo, 15-16 June 2022.

5. **McBeck J.** *Predicting fault reactivation in numerical models of segmented fault networks.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

6. **Renard F.** *Damage during dynamic rupture: insights from high speed experiments on rocks.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

7. **Renard, F.** *Neutron imaging of fluid flow in rocks and applications to subsurface processes.* Conference on the Nordic perspectives on advanced neutron imaging. Lyngby, Denmark, 24 November 2022.

8. **Renard, F.** *Using large instruments to image fluid flow and deformation in rocks.* University of Tromsø, 18 November 2022.

9. **Renard, F.** *Anatomy of earthquakes in the lower continental crust.* University of Potsdam, Germany, 7 November 2022.

10. **Renard, F.** *How do earthquakes stop? Insights from a minimal model of frictional rupture.* GFZ Potsdam, Germany, 2 November 2022.

11. **Renard, F.** *Dynamic damage during earthquake propagation.* Freie University of Berlin, Germany, 28 October 2022.

12. **Renard, F.** *Storing CO_2 into basalts. Geological Survey of Faroe Islands*, 23 August 2022.

13. **Renard, F.** *The road to system-size failure in rocks.* Workshop Friction and Wear Across Scales, ETHZ, Ascona, Switzerland.

14. **Renard, F.** *Using Large Instruments to Image Flow and Deformation Processes in Rocks.* Gordon Research Conference on Flow and Transport in Permeable Media, 17-22 July 2022, Les Diablerets, Switzerland.

15. **Sveinsson, H. A, Nordhagen E. M, Malthe-Sørenssen A.** *Creep and friction of silicon carbide contacts: molecular dynamics simulations*. Friction and Faulting Processes, University of Oslo

16. **Skogvoll V.** *Phase field modelling of dislocation dynamics with elastic interactions.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

17. **Menegon, L.** *Geology and structure of an earthquake source in the lower crust.* NORSAR, 26 January 2022

18. **Menegon, L.** *The Goldschmidt Laboratory: A national infrastructure for geochemical and microstructural analysis of solid Earth materials.* University of Bergen, 25 April 2022

19. **Menegon, L.** *CONTINENT - Conditions for earthquake nucleation in the lower crust.* Njord, UiO, 2 December 2022.

20. **Menegon, L.** *High stress deformation and short-term thermal pulse preserved in the microstructure of exhumed lower crustal seismogenic faults.* DRT Conference, Catania, Italy, 6 July 2022.

21. **Menegon, L.** *Earthquake Nucleation and Rheological Transitions in the Lower Crust.* Gordon Research Conference on Rock Deformation. Bates College, USA, 10 August 202

22. **Moura, M.** Complexity: *"More is Different" also in porous media flows.* University of Minnesota, USA, 3 October 2022.

23. **Moura, M.** *Drainage experiments in porous media: from viscous fingers to compact invasion to film flow.* 5th National Workshop on Porous Media, InterPore Norway, Trondheim, Norway, 1 December 2022.

24. **Van Schrojenstein Lantman, H.** *Elastic stain relaxation around stressed quartz inclusions in garnet.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

25. **Vincent-Dospital, T.** *Dual phase flow in graded sediment layers.* EarthFlows Meeting, University of Oslo, 15-16 June 2022.

Other talks

1. **Austrheim, H.** *Formation of Magnesium Silica Hydrate-cement in nature.* Muenster-Granada Workshop.

2. **Dunkel, K. G., Menegon, L.,** and **Jamtveit, B.** *Weakening mechanisms in dry, lower-crustal pseudotachylytes.* EGU General Assembly Conference Abstracts, EGU22-8365.

3. **Johannesen, R. M.**, Ólavsdóttir, J., Boldreel, L. O., *How to obtain a better overall geological understanding of the central Faroe Islands by usage of Construction of a geomodel in Petrel software by integrating geological and geophysical data of different scale and age.* Nordic Geological Winter Meeting 2022.

4. **Johannesen, R. M.** *The potential for permanently storing CO_2 in basaltic lava flows.* A multiscale structural reservoir study of the Faroe Islands Basaltic Group. Hammer Talk, University of Oslo.

5. **Johannesen, R. M., Galland O.**, Ólavsdóttir, J., Kjøll, H. J., Eidesgaard, Ó., Planke, S. *The potential for permanently storing CO_2 in basaltic lava flows. A multiscale, structural reservoir study of the Faroe Island Basalt Group.* CO2Basalt Seminar, University of Oslo.

6. **Johannesen, R.M.** *Fractures in basalt as a reservoir for permanent CO_2 storage on the Faroe Islands.* CO2-Basalt seminar, University of Oslo.

7. Johnson, J., Bailey, A., Mondol, N. H., & **Renard, F.** *Using Microscopy Image Analysis to Calculate the Mineral Brittleness Index in Organic-Rich Shale.* In Sixth International Conference on Fault and Top Seals (Vol. 2022, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

8. Johnson, J., Kobchenko, M., Mondol, N., & **Renard, F.** *Potential Alternative to Rock-Eval or Wireline Calculations of Toc? Case Study from the Norwegian Continental Shelf.* In 83rd EAGE Annual Conference & Exhibition (Vol. 2022, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

9. Julia, M., Putnis, C. V., King, H. E., & **Renard, F.** *The effect of cadmium on calcium carbonate growth and dissolution* (No. EGU22-2361). Copernicus Meetings.

10. Julia, M., Putnis, C. V., King, H. E., & **Renard, F.** *The effect of cadmium on the growth and dissolution of calcium carbonate.* In 2022 Goldschmidt Conference.

11. **Michalchuk, S., Menegon, L., Renard, F.,** Chogani, A., and Plümper, O. *Dynamic evolution of porosity in lower crustal faults during the earthquake cycle.* EGU General Assembly Conference Abstracts, EGU22-2375.

12. **Dziadkowiec J.**, Javadi S., Ban M., **Jamtveit B., Røyne A.** *Ion-dependent adhesion between calcite surfaces.* EGU General Assembly Conference Abstracts, EGU22-3016.

13. **Rosenqvist, M. P.**, Meakins, M., Planke, S., Millett, J.M., Kjøll, H.J., **Jamtveit, B.** *Reservoir potential of the FaroeIslands basalt lava flows: an anologue study of the potential for CO_2 storage in volcanic margin basalt sequences.* Nordic Geological Winter Meeting 2022.

14. **Rosenqvist, M. P.**, Meakins, M., Planke, S., Millett, J.M., Kjøll, H.J., Voigt, M.J., **Jamtveit, B.** *Investigating the potential for CO_2 storage in the North Atlantic Igneous Province: reservoir properties and reactivity of the Faroe Islands Basalt Group. The impacts of volcanism on sedimentary basins and their energy resources.* The Geological Society of London.

15. **Rosenqvist, M. P.** *Investigating the potential for CO_2 storage in the North Atlantic Igneous Province: examples from the Faroe Islands.* CASP Annual General Meeting.

16. **Rosenqvist, M. P.** *Multiscale flow pathways in basalts of the North Atlantic Igneous Province: implications for CO_2 storage.* Hammer Talk, University of Oslo.

17. **Guren, M. G.** *DeePMD potentials for fracturing of quartz and basalt.* CO2Basalt seminar, University of Oslo.

18. **Rosenqvist, M.P.** *Internal architectures of volcanic margin basalt reservoirs of the North Atlantic Igneous Province: examples from the Faroe Islands.* CO2Basalt seminar, University of Oslo.

19. **Menegon, L.**, Campbell, L.R. *High stress deformation and short-term thermal pulse preserved in exhumed lower crustal seismogenic faults (Lofoten, Norway).* EGU General Assembly Conference Abstracts, EGU22-4692.

20. **Zertani, S., Menegon, L.**, Pennacchioni, G., Corfu, F., **Jamtveit, B.** *Repeated metamorphism and deformation localized in a shear zone recording the formation-subduction-exhumation history of the continental crust.* EGU General Assembly Conference Abstracts, EGU22-7532.

21. Giuntoli, F., Vitale Brovarone, A., **Menegon, L.** *Hydrocarbon-bearing fluid migration produces brecciation at high pressure condition in subduction.* EGU General Assembly Conference Abstracts, EGU22-11350

22. **Moura M., Brodin J., Måløy K. J., Rikvold P. A., Flekkøy E. G., Jankov M.**, Schäfer G. and Toussaint R. *Thin film flow: fluid transport and pollution spreading in porous media*. Workshop Deformation, Flow & Fracture of Disordered Materials: Taming Geophysical Hazards. Courmayeur, Italy.

23. **Van Schrojenstein Lantman, H.W.**, Wallis, D., Bonazzi, M., Thomas, J., Hamers, M., Drury, M., Alvaro, M. (2022). *Strain relaxation around stressed quartz inclusions in garnet.* EGU General Assembly Conference Abstracts, EGU22-575

24. **Vincent-Dospital, T.** and **Moura, M.** *Toward a thermal weakening theory for shear thinning fluids?* Workshop on Non-Newtonian Flow in Porous Media. Fortaleza, Brazil.

25. **Vincent-Dospital, T.** and **Moura, M.** *Watching paint dry and the making of the non-Newtonian doughnut.* Workshop on Non-Newtonian Flow in Porous Media. Fortaleza, Brazil.

Posters and PICOs

1. **Aiken, J.**, Sohn, R. A., Kelemen, P. B., **Renard, F.,** & **Jamtveit, B.** (2022). Detecting H2 degassing events related to serpentinization in Oman (No. EGU22-521). Copernicus Meetings.

2. **Aspaas, A.**, Lacroix, P., Kristensen, L., Etzelmüller, B., & **Renard, F.** (2022). What causes transient deformations in the Åknes landslide, Norway? (No. EGU22-1718). Copernicus Meetings.

3. Julia, M., Putnis, C. V., King, H. E., & **Renard, F.** (2022). The effect of cadmium on calcium carbonate growth and dissolution (No. EGU22-2361). Copernicus Meetings.

4. **Michalchuk, S., Menegon, L., Renard, F.**, Chogani, A., and Plümper, O. (2022). Dynamic evolution of porosity in lower crustal faults during the earthquake cycle. Gordon Research Conference on Rock Deformation.

5. **Moura M., Eriksen K. F., Jankov M., Turquet L. A.,** and **Måløy K. J.**, (2022). Transition from viscous fingers to compact displacement during unstable drainage in porous media. 2022 Gordon Research Conference on Flow and Transport in Permeable Media.

6. **Van Schrojenstein Lantman, H.W.**, Wallis, D., Bonazzi, M., Thomas, J., Hamers, M., Drury, M., Alvaro, M. (2022). Elastic strain relaxation around stressed quartz inclusions in garnet. Gordon Research Conference on Rock Deformation.

In media

1. **Galland O., Menegon L.** *Unge forskere får millioner til lovende prosjekter.* Titan, 9 September. [News]

2. **Jamtveit B., Renard F., Moura M., Linga G.** *Feiret forskere som har kapret eksklusive stipender.* Titan, 7 April. [News]

3. **Flekkøy E. G., Brodin J.** *Vil bruke nytt superteleskop til å avsløre om 'Oumuamua er en støvdott.* Titan, 4 April. [News]

Outreach

1. **Bouchayer C.**, Nanni U. *Accessing the inaccessible, the hidden secrets of glacier stability.* French Institute in Norway, 6 October [Talk]

2. **Dziadkowiec J.**, Valtiner M. *Can nanoparticles save historic buildings?* European Union Observatory for Nanomaterials - Nanoopinion [Blog]

3. **Dziadkowiec J.**, Valtiner M. *Wie stoppen Nanopartikel den Verfall alter Gebäude?* (2022). Servus TV [Documentary, Television]

4. **Galland O.** *Les volcans*, Ecole Montessori, Méry, France, May [Talk]

5. **Galland O.** *Introduction of the National Geographic film "Fire of Love" on the life of Katia and Maurice Krafft*, Pix Film Festival, Oslo, August [Talk]

6. **Galland O.** *Vulkaner*, Steinerskole i Oslo, November [Talk]

7. **Galland O.** *Les volcans*, Lycée Francais à Oslo, December [Talk]

8. **Galland O.** *Unroofing volcanoes' roots, understanding of magma travel through volcanic plumbic systems.* French Institute in Norway, 6 October [Talk]

9. **Johannesen R. M.** *Frá útláti til stein, CO_2 goymsla í føroysku undirgrundini.* Researchers week, Research Council Faroe Islands [Talk]

10. **Johannesen R. M.**, *The potential for permanently storing CO_2 in basaltic lava flows. A multiscale structural reservoir study of the Faroe Islands Basaltic Group.* Faroe Islands field course: a window to the geology of the Northeast Atlantic, Aarhus University [Talk]

11. **Skogvoll V.** *Hvordan piffe opp daff festivaløl?* Abels tårn på Øya, 12 August [Podcast]

12. **Sveinsson, H. A.** *Bruker du denne feil? Med dette trikset kan du kanskje spare litt tid foran mikrobølgeovnen.* [Web]. TV2 Video.

13. **Sveinsson, H. A.** *Praktisk info med Jon Almaas: Kokosnøtter og sprekk-mekanikk.* [TV]. TVNorge/Discovery+.

To advance our understanding of complex Earth-like systems we build on our diversity and a high level of technical skills.

Project portfolio

Active projects in 2022

Project leader	Project title	Host	Funding Source	Project Start Date	Project End Date	Total Funding (NOK in 1000)
Aiken, John	Summer school Finse	The Njord Centre	RCN	01.03.2022	30.09.2022	100
Angheluta, Luiza & Renard, François	Interface dynamics in geophysical flows (EarthFlows 2)	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	Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity	The Njord Centre	RCN	01.04.2019	31.03.2022	3 234
Jamtveit, Bjørn	Disequilibrium metamorphism of stressed lithosphere (DIME)	Dept. of Geosciences	EU, ERC	01.09.2015	28.02.2022	21 200
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	31.06.2023	9 229
McBeck, Jessica	Emergent networks: predicting strain localization and fracture network	The Njord Centre	RCN	01.09.2020	28.02.2025	6 852
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
Måløy, Knut Jørgen	Porous Media Laboratory (PoreLab)	Dept. of Physics	RCN	01.07.2017	30.06.2027	66 400
Renard, François & Knut-Jørgen Måløy	COLOSSAL: Collaboration on flow across scales (Norway, Brazil, France, USA)	The Njord Centre	RCN	01.12.2020	31.05.2025	4 499
Renard, François	PoreFlow: Visualizing multiphase flow in porous media with neutron imaging	NTNU (UiO partner)	RCN	01.12.2020	30.06.2024	900
Renard, Francois; Jamtveit, Bjørn	MODIFLOW: Modelling flow across scales	The Njord Centre	Equinor	01.01.2019	31.12.2023	9 048
Renard, François	Break-through rocks (BREAK)	The Njord Centre	EU, ERC	01.01.2022	31.12.2026	35 000
Renard, François	CO2 Basalts	The Njord Centre	UiO	01.04.2022	31.03.2025	7 695

Projects starting 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
Dziadkowiec, Joanna	Surface Forces Apparatus studies of mineral growth in confinement	The Njord Centre	UiO	01.01.2023	31.12.2023	135
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
Menegon, Luca	Conditions for earthquake nucleation in the lower crust (CONTINENT)	The Njord Centre	RCN	08.01.2023	31.07.2027	12 000
Renard, Francois	Friction and fracture and the onset of geohazards (FricFrac)	CAS/ The Njord Centre	CAS	01.08.2023	01.06.2024	3 500

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

N J R D

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