UNIVERSITETET I OSLO

NJORD

Annual report 2021

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

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01

About Njord

Preface

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“Intelligence is the ability to adapt to change”

– Stephen Hawking

In 2021, we have learned to live and work with the pandemic and we adapted. The activity at Njord has been at its highest since the creation of the centre in 2018. The number of publications, peaking at around 70, is exceptional for a group led by nine professors only. Njord researchers have initiated and installed three new laboratories: the LagLivLab, a collaboration between the Department of Physics and the Life Science initiative, the national Goldschmidt laboratory at the Geoscience Department, and the nano-indentation platform. The large number of research proposals submitted by senior and junior researchers this year witnesses a vibrant research environment where people feel strongly involved in the group and recognize that success is often an anomaly rather than the norm in the competitive scientific arena. We were lucky to receive five major grants this year: one advanced grant from the European Research Council, two young research talent grants from the Research Council of Norway, and two internal grants at the University of Oslo. Together with the PhD students recruited in the EU-funded CompSci project, more than ten early career researchers will start in Njord in 2022. I want to take this opportunity to welcome them warmly in our inclusive and international research environment.

In the spirit of Giorgio Parisi's quote *"In physics there are many simple problems that have complex solutions"*, Njord researchers study natural processes in an approach where we simplify them to unravel their complexity. The way we explore the interface between physics and geosciences in Njord is original and demonstrates that our diversity represents a benefit to tackle outstanding scientific questions and renew ideas. Through our ability to share laboratory and computational competences, often validated by observations in the field, we progressed in 2021 on the physics of lower crust earthquakes, flow in porous and granular media, pattern formation, and complex couplings between bio-chemical and mechanical systems from the scale of nanometres to the scale of continents. Studies that use machine learning have diffused efficiently across disciplines in our group to process experimental and field data, and analyse results of numerical models. Activities in biophysics or astrophysics have emerged through our unique laboratories and competences in microscopy imaging, and on the physics of active matter and porous media. These evolutions are possible because Njord always welcomes creativity and because opening new research directions is part of our *art de vivre*.

In 2022, Njord will continue in these directions. I hope we will be able to expand our attendance to scientific conferences and seminars, host international guests, and disseminate our research more toward the public in Norway and beyond. Njord will be involved in the Sustainability strategy implemented by the Faculty of Mathematics and Natural Sciences and we plan to be an enthusiastic driver in this initiative.

Oslo, December 30th, 2021

François Renard
Director of the Njord Centre

About Njord

The Njord Centre is a cross-disciplinary geoscience-physics center at the Faculty of Mathematics and Natural Sciences at the University of Oslo. The center 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 deformable porous media, fracturing and fragmentation, pattern formation in biological and geological systems, and interface dynamics during geophysical flows. 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, avalanche dynamics, 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 collaboration 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 (CoE) PGP (Physics of Geological Processes 2003-2013), the Oslo node of the fourth generation CoE PoreLab (Porous Media Laboratory running 2017-2027), and the third generation Centre of Excellence for Education CCSE (Centre for Computing in Science Education running 2016-2026).

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 developed 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:

- Maintain and develop a world-leading cross-disciplinary research center in physical and earth sciences at UiO with a focus on a fundamental understanding of the dynamics of complex fluid-solid systems.
- Build the next generation of computational competences and experimental laboratory facilities for the study of processes in fluid-rock/fluid porous-media systems in 4D from molecular to field scales.
- Provide a unique basis for making predictions relevant for CO2-sequestration, exploration and exploitation of natural resources, transport of contaminants in the subsurface, gravitational instabilities and other geohazards.
- Generate an outstanding environment for research-based education at the Masters and PhD levels.
- Communicate knowledge and research concerning the complex earth system to the public in an understandable and exciting manner.

Our research strategy is to:

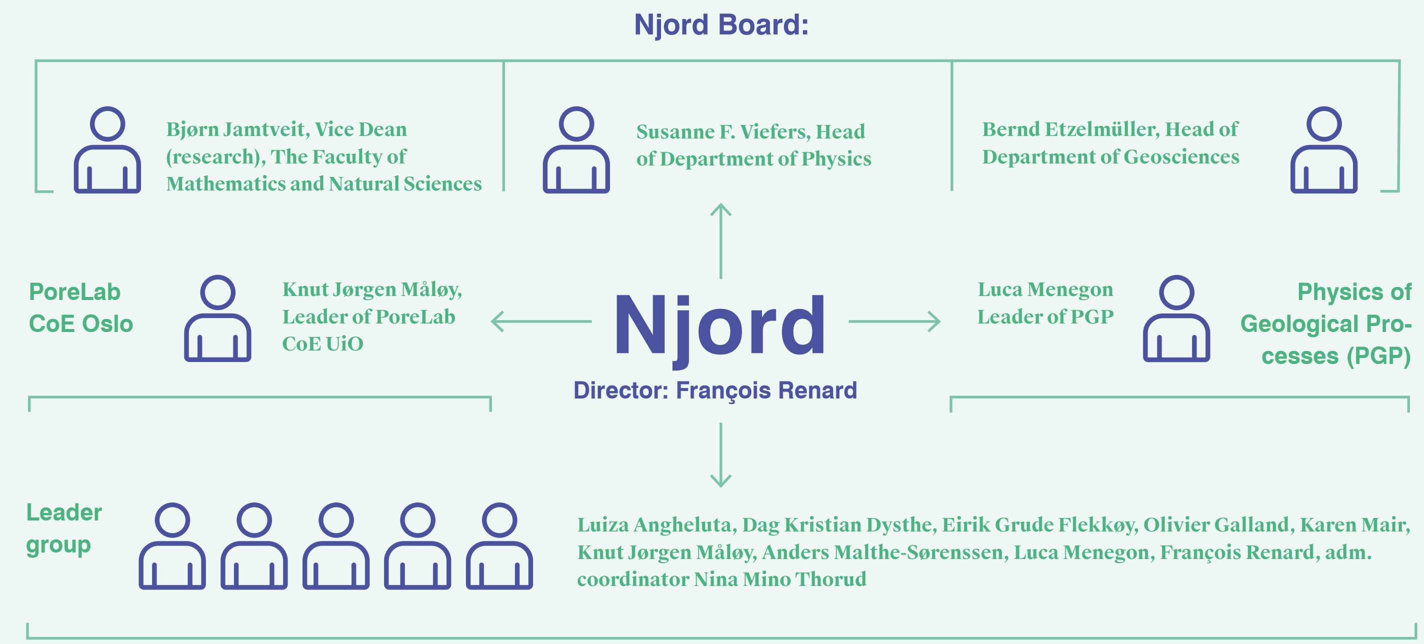
- Create an interactive co-localized organization of geoscientists and physicists conducting field geology, theory, numerical modelling and experiments in concert.
- Be an active, and often leading, partner in international collaborations
- Participate in international projects (IODP, ICDP, Excite) and be a user of large-scale national and international facilities where Norway is a partner (ESRF, ESS, 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 society in general.

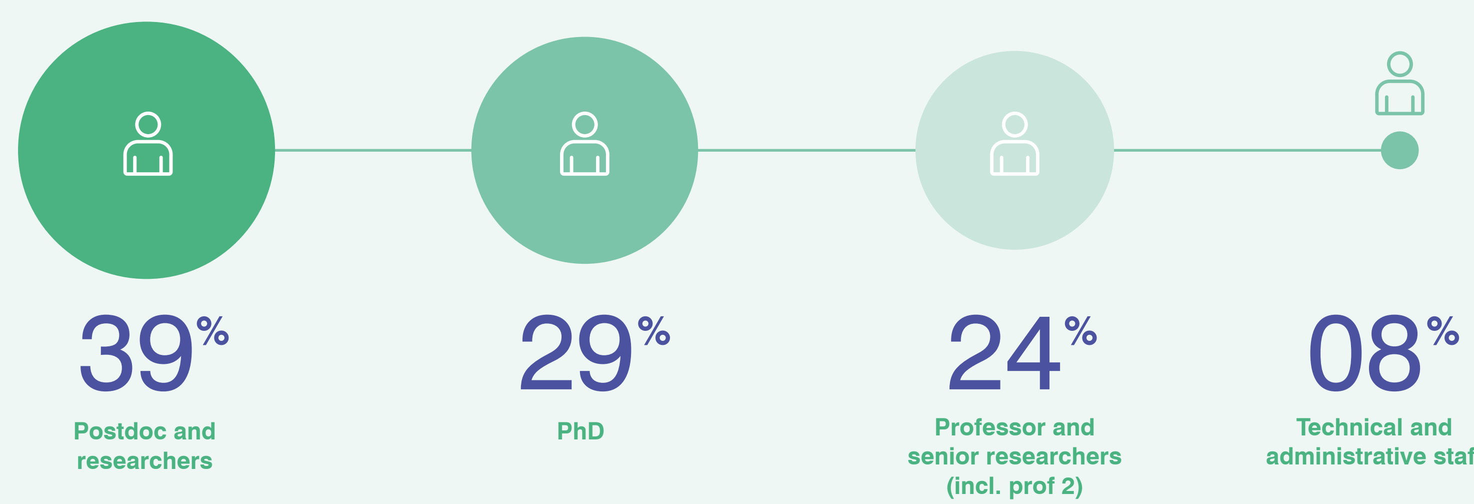
Organization

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, Nina Mino Thorud, 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 permanent professors. In total, Njord comprises about 60 members, 24 % of which are women. There are members employed by the Department of Physics, the Department of Geosciences and directly by the Njord Centre.



Staff



Geographical origins of Njord employees

Norway

37%

Geographical origin by percentage

France	16%	Germany	05%
India	05%	Iran	05%
Canada	03%	Italy	03%
Serbia	02%	Switzerland	02%
USA	02%	Brazil	02%
China	02%	Denmark	02%
Greece	02%	Israel	02%
Phillipines	02%	Poland	02%
Romania	02%	Russia	02%
UK	02%		

Finances and Funding

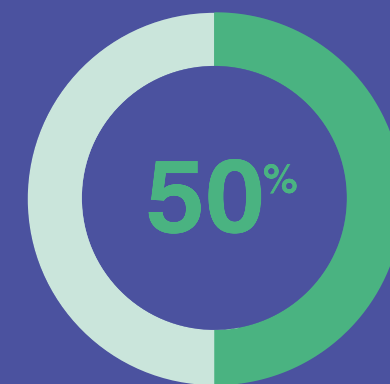
45 MNOK

Funding in total in 2021

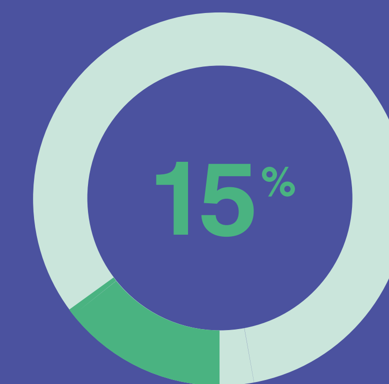
The Njord centre is funded by overhead from externally funded projects, the Department of Physics and the Department of Geosciences at the University of Oslo.

The staff at Njord is employed by either one of the departments or by projects at Njord. The centre did in the first two years of running receive 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. From 2020 the centre has had enough external funding to cover the running costs and has been self-sufficient. Overheads from projects at Njord are split between the centre and the host department of the project leader. External funding from projects at Njord covers around 50% of all the expenses.

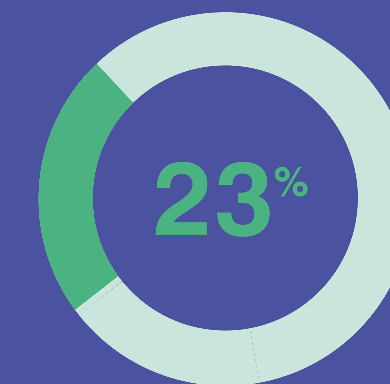
Distribution of funding



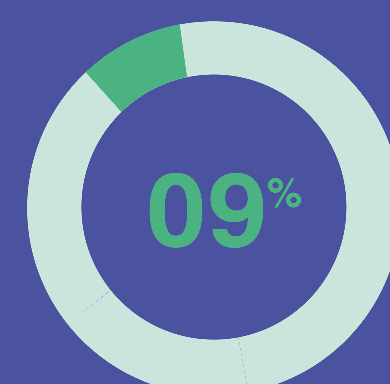
University of Oslo



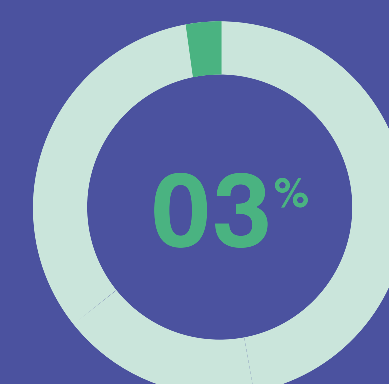
CoE from NRC



Other NRC-grants

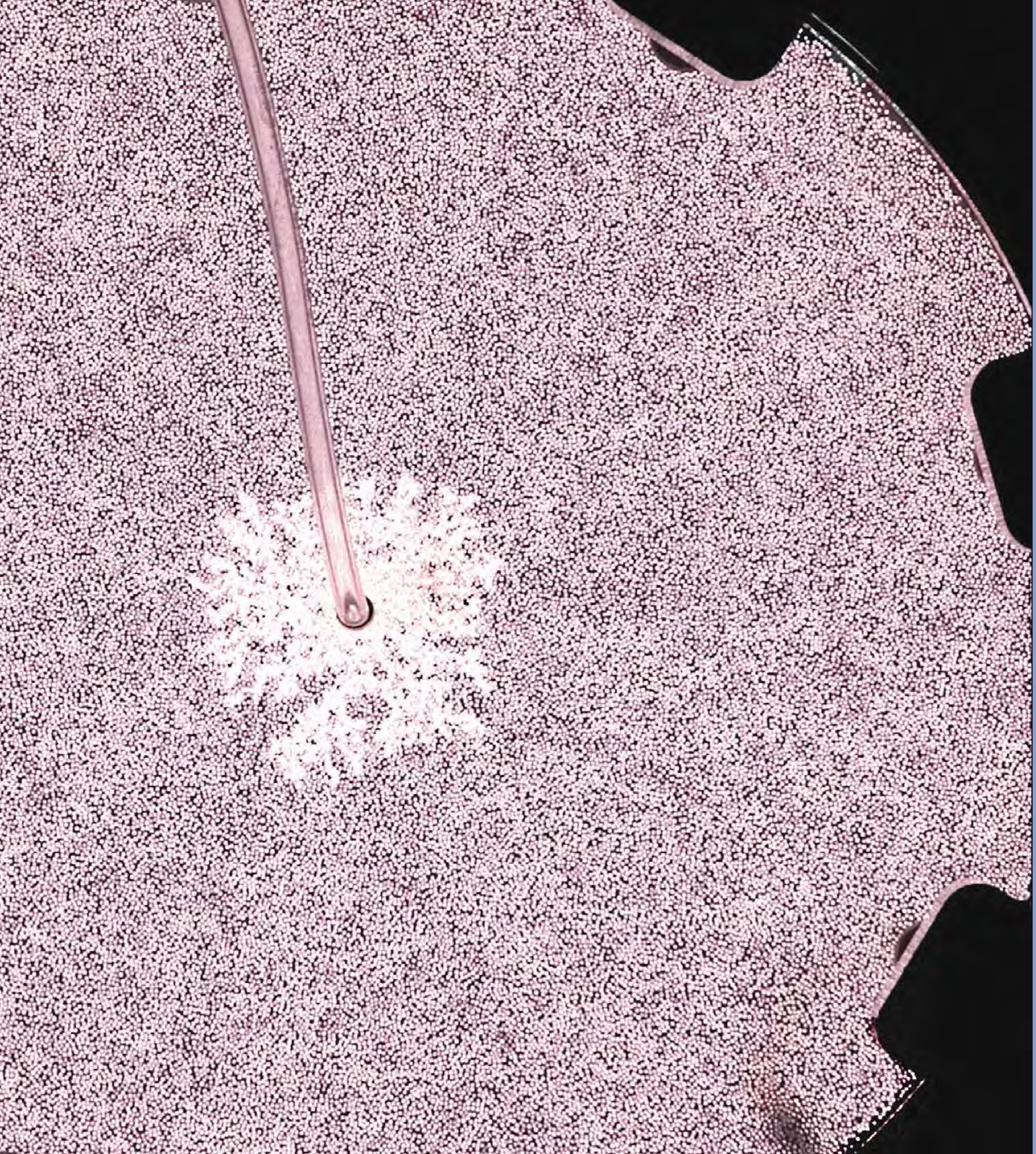


EU/ERC



Industry and others

Funding in total



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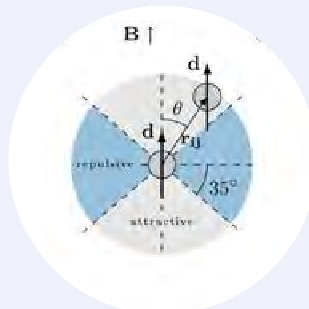
Activity at Njord

Highlights of 2021

January

The new laboratory LagLivLab, partially located in the Njord laboratories, opens.



April

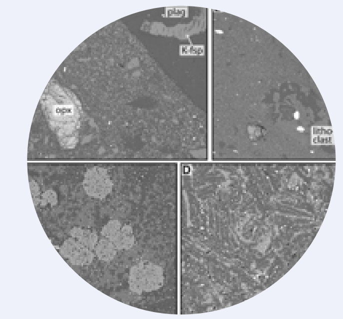
Louison Thorens, Knut Jørgen Måløy, Mickael Bourgoin and Stephane Santucci publish "Magnetic Janssen effect" in *Nature communications*.

June

The Norwegian Physics Community awards Joachim Falck Brodin the Martin Landrø Prize for outstanding work on his master thesis.

June

Xin Zhong, Arianne J. Petley-Ragan, Sarah Incel, Marcin Dabrowski, Niels H. Andersen, and Bjørn Jamtveit publish "Lower crustal earthquake associated with highly pressurized frictional melts" in *Nature Geoscience*.



September

Kristina Dunkel, Xin Zhong, Paal Ferdinand Arnestad, Lars Vesterager Valen, and Bjørn Jamtveit publish "High transient stress in the lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten Archipelago, northern Norway" in *Geology*.

November

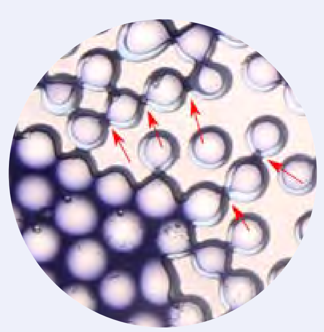
The PoreLab junior forum is held at the University of Oslo.

April

François Renard receives an Advanced grant from the European Research Council to fund the project "Break-Through Rocks" (BREAK).

June

Marcel Moura and Gaute Linga are awarded the Young Talent projects *FlowConn* and *M4* funded by the RCN.

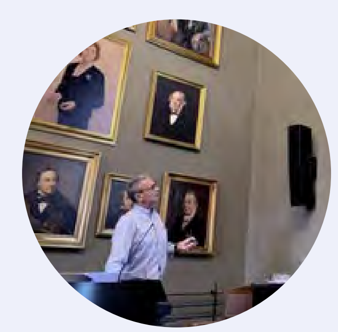


June

PoreLab displays beautiful images from experiments and simulations in an exhibition in the square next to Oslo City Hall.

September

The "Breaking the crust"-seminar takes place over two days at the Norwegian Academy of Science and Letters. The seminar has a diverse program with many international speakers.

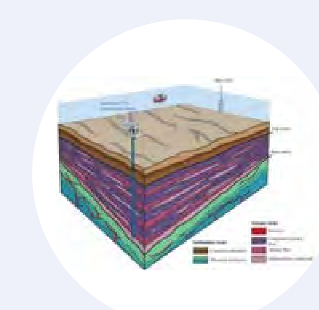


October

Three new PhD-candidates start at Njord as part of the EU-funded CompSci-project

December

The project CO2Basalt is awarded funding from the MN faculty at UiO. The project will study the possibilities for CO2 storage in volcanic basalt sequences.



Interview

Name
Henrik Andersen Sveinsson

Current position:
Assistant professor

Been at UiO since:
2010

Henrik Andersen Sveinsson

"This curiosity-driven way of doing physics by peeling off details to get to the basic underlying processes that guided the Earth's past and might play a key role in shaping its future, is what I find fascinating and has attracted me to PGP, in the first place, and now the Njord centre."

What has led you to the kind of research you do now at Njord?
When I started studying at UiO, I took the first good research opportunity that appeared. That happened to be a friction modelling project at PGP, and this changed the course of my studies towards statistical and computational physics with geoscience type applications. I enjoy looking for the link between simple rules and complex behavior. Before I got in contact with Physics of Geological Processes, I actually started studying economics, which also tries to explain a complex system with simple rules, but I learned that physics is probably an even better arena for this.

What are your current research projects?
I mostly work on projects related to nanoscale mechanical failure processes such as fracture, friction, and creep. One project is on the mechanical properties of ice and gas hydrates. Gas hydrate is a type of ice with gas molecules embedded in the crystal structure, and that turns out to be important. One of the main puzzles is that while hydrates and ice are both crystalline, hydrogen-bonded substances made of water molecules, they have very different mechanical properties under compression. This has introduced me to the world of polycrystals, crystal defects, grain boundaries and plasticity.

I also look at mineral-water interactions on the nanoscale and try to explain how these interactions couple with friction and fracture behavior. Things behave differently on the nanoscale, and even something seemingly harmless, like a bubble in water, may damage rocks if they collapse in the right way. Such bubbles can also nucleate in the brain during an impact, and the collapse of these bubbles can be an important mechanism for brain injury.

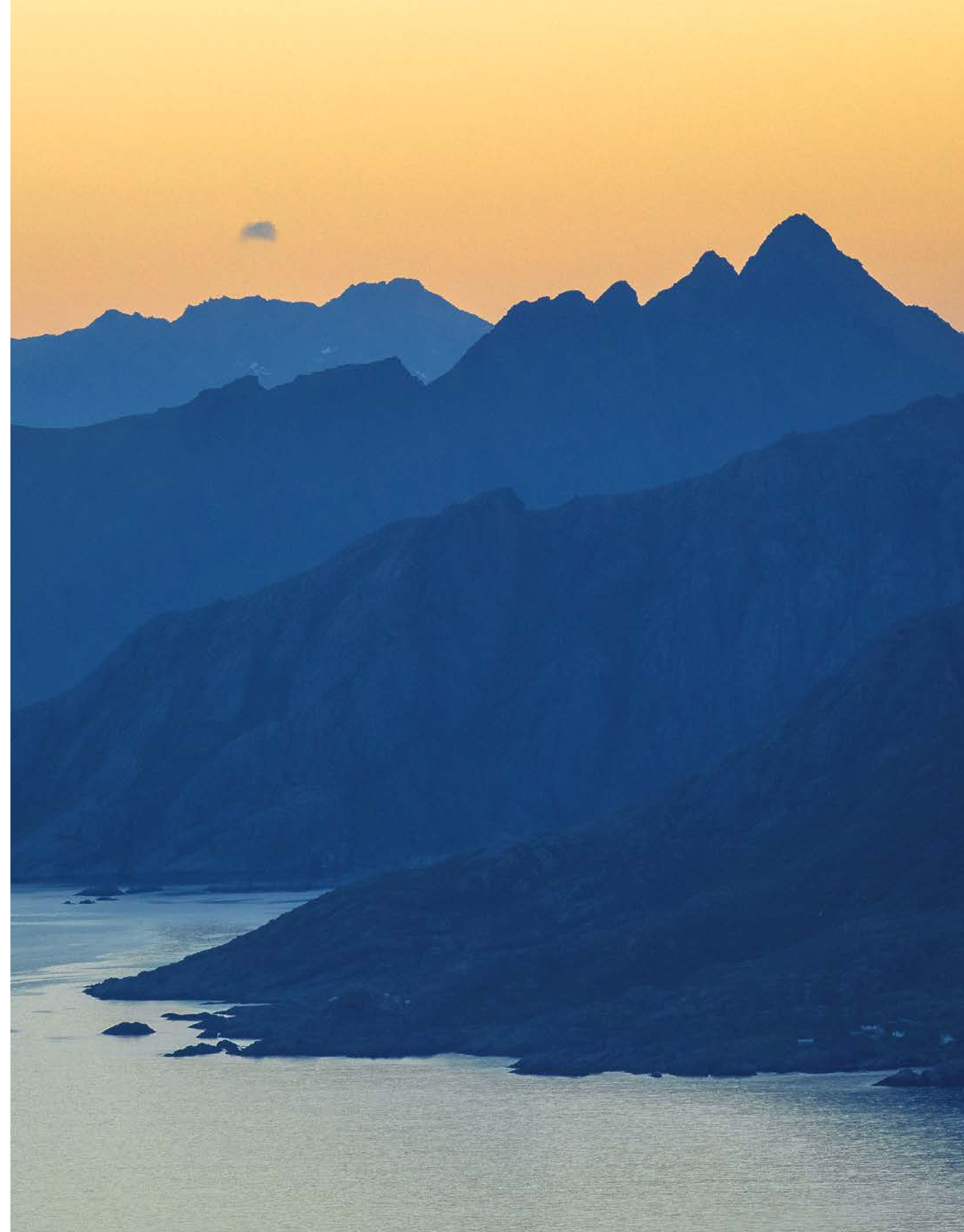
I am also involved in a slightly more technologically focused project on designing patterns with prescribed mechanical or frictional properties.

Is there any particular research, publication or scientist that has inspired you, in your research?
The 1972 paper "More is different" by Anderson and 1976 paper "Life at low Reynolds number" by Purcell. For two reasons. First, they show how the nanoscale behaves very differently from the macroscale, and they do so in an intuitive way. But they also bring the message about why science is possible: When you change spatial and temporal scales, some things cease to be important. So, although the world is a big mess of particles, you can extract order and make predictions.

Where do we usually find you?
You almost always find me in my office in the Njord-satellite section over at CCSE. I am a computational physicist, and I can connect to the supercomputer from anywhere, but the office is comfortable.

What do you think/hope your research can do beyond academia?
I am deeply impressed by the complexity that Nature is able to produce from a set of simple rules and I mainly want to understand how the world does this because it is interesting. Fortunately, history has shown that scientific progress is also useful, and I guess that is why the greater society is willing to pay for it. This is actually very fortunate because the time it takes from a fundamental scientific discovery to be useful beyond academia can be so long that the application cannot be the only motivation.

But to almost answer your question, I care a lot about what humanity can achieve as a species. It would please me if some of my work would contribute even the slightest to enable new cool stuff such as affordable space travel, extraterrestrial settlements or artificial consciousness. And who knows? Perhaps peace research and social science efforts to prevent human self-destruction is the key. Or maybe, just maybe, the details of nanoscale damage by dynamics cracks can be exploited for carbon storage, buying just the time someone else needs to figure it out.



Interview

Name
Kristina Dunkel

Current position:
Associate Professor

Been at UiO since:
2013

Kristina Dunkel

"Like several of the other geoscientists at Njord, I work on earthquakes in the lower crust using the beautiful natural laboratory of Lofoten islands."

What has led you to the kind of research you do now at Njord?
As early career scientists, it is normal to move a lot. I am in the unusual (and unusually lucky) position to have been at Physics of Geological Processes, and then Njord, continuously for eight years now. Obviously, working in different groups has its advantages as well, but for me, it was very beneficial to be able to stay in one place, have continuity in my research, develop my methods, and slowly expand my research topics.

My main topic of research, the interplay of mineral reactions and deformation, has certainly been molded by the environment at Njord. I started with a background in petrology and mineralogy, but since coming to Njord, I have become more and more aware of the importance of physics in all kinds of geological processes. Through contact with others at Njord, I also learned that numerical modelling is not all that scary after all. Breaking down complex geological situations so that I can talk about them with some of my colleagues from physics has taught me to focus on the core of the problem.

Do you have an example of how the group has evolved during your eight years here?
My research methods are centered on microanalytical techniques, especially electron backscatter diffraction (EBSD). With EBSD, we can analyze the crystallographic orientation of minerals and learn about the mechanisms of mineral deformation. My first contact with EBSD was during my PhD, which was part of a Marie Curie Initial Training Network. Through that network, I met an EBSD-specialist, who introduced me to the method and helped me with my first measurements and analyses. I started using this technique more and more, and today, we have a fully functional EBSD-system of our own in Oslo! Luca Menegon, who is an expert in this technique, joined Njord as a professor in 2019, and now several people at Njord use EBSD in their work.

What are your current research projects?
I am currently involved in three different projects, which is fun because they are quite diverse. Like several of the other geoscientists at Njord, I work on earthquakes in the lower crust using the beautiful natural laboratory of Lofoten islands. I study the behavior of minerals in seismic faults during and after an earthquake using microstructural techniques.

I am also involved in the NFR-funded NATSORB-project, which investigates the formation and properties of hydrous magnesium carbonate minerals. Those minerals are interesting for two reasons: They sequester CO_2 from the atmosphere, and their high surface area makes them good candidates for the remediation of contaminated water.

My third project is in collaboration with archeologists. We work with pottery shards from the Iron Age. If pottery is well classified, it can be used to trace trade routes and the distribution of manufacturing routines, for example. Characterizing the different components of the pottery on a micro-scale adds another dimension to the classification schemes traditionally used in archeology.

How do your current projects tie in with Njord's diverse family?
"Advanced material characterization" is the keyword integral to Njord that all my projects have in common. I am quite close to the geology end of the geology-physics spectrum at Njord, but still feel very much at home in our mixed group.

Where do we usually find you?
Most of the time, I am in my office reading, writing, analyzing data, or using the optical microscope. My favorite place at work is clearly the electron microscopy lab – I am always happy when I have new samples to dive into there. In the spring semester, I am also often in the geosciences building, where I teach mineralogy and petrology.

Interview

Name
Tom Vincent-Dospital

Current position:
Post-doctoral fellow

Been at UiO since:
January 2021

Tom Vincent-Dospital

"When it comes to the 'real world' relevance of the effect of disorder on the flow of matter, actual applications are potentially endless. If you look around you, wherever you stand, you will not actually see much more than flowing matter and disorder."

What has led you to the kind of research you do now at Njord?
Like often in life, a mix of interest-driven choices and lucky opportunities. After an early education in mathematics and physics, I became a geophysicist. I was really interested by the – literally – down to earth scientific challenges in this field. After having graduated, I have spent some time in the geoscience industry, completed a PhD thesis on the dynamics of fractures, and then had the great opportunity to join Njord.

What are your current research projects?
In most of my projects, I seek to understand how material and thermal disorders impact the flow of fluids and solids in porous materials. More specifically, I am currently investigating the displacement of fluids in randomly generated porous matrices. There, if the noise level can be well characterized, the complex patterns in the fluids' distribution may be understood.

In line with my thesis subject, I also keep studying the rupture of solids. After all, I have always been good at breaking things and it is very nice to do it professionally.

How do your current projects tie in with Njord's diverse family?
Njord's main mission is to advance the understanding of transformation processes in Earth- and manmade porous materials. I would say that these projects tie in rather well! But, to be fair, falling completely outside of Njord's range is somewhat challenging. Lately, I decided to humor my subversive side with a project on biological materials… only to realize that other researchers in the center were also into biophysics. A strength of Njord is no doubt its grand diversity!

Is there any particular research, publication or scientist that has inspired you, in your research?
The first person who comes to my mind here is Renaud Toussaint, my former thesis supervisor. He always has been of great advice and guidance in my research. Let me make use of this interview opportunity to thank him again.

Where do we usually find you?
Over the past years, far too often working from home, which is something that most of us have experienced and that I do not particularly enjoy… But in more normal periods, one finds me in the laboratory, 3D printing some porous structures, forcing fluids through them, or tearing some materials in front of cameras. My current projects are mainly experimental, but I try to keep theoretical and numerical developments in my work as well. I indeed find the most exciting results being those that successfully combine experiments and theories. Of course, one also often finds me writing or reading at my desk.

What do you hope your research can do beyond academia?
Hopefully a lot! While I do believe that pure research for the sole sake of knowledge is to be cherished, I am even more motivated if I believe that what I do every day can be or will be useful outside of academia. When it comes to the 'real world' relevance of the effect of disorder on the flow of matter, actual applications are potentially endless. If you look around you, wherever you stand, you will not actually see much more than flowing matter and disorder.

Interview

Name
Joanna Dziadkowiec

Current position:
Postdoctoral Researcher

Been at UiO since:
2015

Joanna Dziadkowiec

"These are exciting experiments since electrochemistry can quickly alter physicochemical properties of the studied liquid-mineral interfaces, for example giving us insight into the transport of ions across tiny, confined pores."

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

It was mainly a PhD position in the NanoHeal project led by Anja Røyne and Dag Dysthe that inspired my research! I have been always interested in how we can use minerals as functional but at the same time low-impact materials. It all began in 2012 when I started my first master project, which focused on the use of clays as catalysts. Later on, I studied clay minerals as potential drug delivery carriers. Then in 2015, I came across a PhD offer at Njord, which dealt with the healing of weak mineral interfaces with organics. I quickly got interested in the surface properties of minerals, in how they interact with each other, and how we can engineer their behavior. I found this research direction particularly appealing, with an output that is relevant not only to material science but also to many dynamic geological environments, including anthropogenic operations such as subsurface fluid storage.

What is your current research project?

I am in the last year of my own NFR FRIPRO Mobility project: Solid-solid interfaces as critical regions in rocks and materials. I was gone from Njord for the last two years to learn more about surface forces, electrochemistry, and mineral reactivity in confinement. It was great to explore these topics in Markus Valtiner's Applied Interface Physics group at TU Wien and to enjoy Vienna before lockdowns started everywhere! I will spend the final year of the project at Njord. I am going to introduce electrochemical methods to our surface forces lab. These are exciting experiments since electrochemistry can quickly alter physicochemical properties of the studied liquid-mineral interfaces, for example giving us insight into the transport of ions across tiny, confined pores.

Why is this research important?

My project explores confined mineral-mineral contacts at the nanoscale. What happens at grain contacts is of tremendous importance for many deformation processes occurring not only within subsurface rock bodies but also during weathering, which slowly disintegrates materials and rocks exposed at the surface. This is often because tiny pores between contacting grains comprise the only available pathways for fluid migration. If the fluids are out of equilibrium with mineral grains, they can alter local mineral assemblages. Even more subtle changes in fluid chemistry can cause changes, for example, trigger a global loss of grain cohesion within granular rocks. Using the surface forces apparatus, I can access this information by measuring distance-resolved interaction forces between mineral grains. While sometimes it may be initially hard to link the very nanoscale measurements to large-scale processes in the subsurface, I hope that our Njord surface forces lab will become recognizable also for the measurements of nanoscale interaction forces in a geophysical context.

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

I am always looking up to all the female professors who get there and strive. They are still underrepresented (~33% as of 2020 in Norway)[1]!

Where do we usually find you?

Most often, you can find me down on the 1st floor, in our surface forces lab. I am usually in front of the surface forces apparatus or the atomic force microscope. Come for a visit and see what is going on, especially if this is the first time you hear about these (really awesome!) pieces of equipment.

What do you hope your research can do beyond academia?

I boldly hope that my research can bring a tiny improvement into how we use and manage the Earth's mineral resources.

1. https://kifinfo.no/en/content/statistics

Interview

Name
Vidar Skogvoll

Current position:
Doctoral research fellow

Been at UiO since:
August 2012

Vidar Skogvoll

"The primary object of study in my research is structure and how defects in this structure respond to each other and other stresses. Crystal structure is a universal phenomenon that emerges in almost all types of science and many fundamental geological processes can be explained by the mineral's crystal structure. "

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

I have always been drawn towards understanding stuff from the bottom up, and love finding patterns and their underlying cause. For my master's degree in theoretical quantum physics, I studied the symmetries of ultra-cold rotating boson soups and at Njord, I am studying the fundamental symmetries of crystalline lattices. Knowing Audun Skaugen from choir singing, choosing to come work here with Luiza Angheluta and the rest of Njord was not a difficult decision, based on his recommendations.

What are your current research projects?

I employ a model called the "Phase-Field crystal", which has an atomic resolution in space, but where thermal vibrations are averaged out to potentially simulate longer time scales than those accessible to other microscopic models. Its simple mathematical framework allows for much theoretical insight, which we have used both to track crystal dislocations (defects) and to find laws for their motion. Lately, we have been extending the model to three dimensions to find strain-stress relations in polycrystalline materials.

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

The primary object of study in my research is structure and how defects in this structure respond to each other and other stresses. Crystal structure is a universal phenomenon that emerges in almost all types of science and many fundamental geological processes can be explained by the mineral's crystal structure. For instance, one of the key minerals that control the rheology of lower crustal rocks, quartz, owes many of its elastic and plastic properties to its microscopic structure.

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

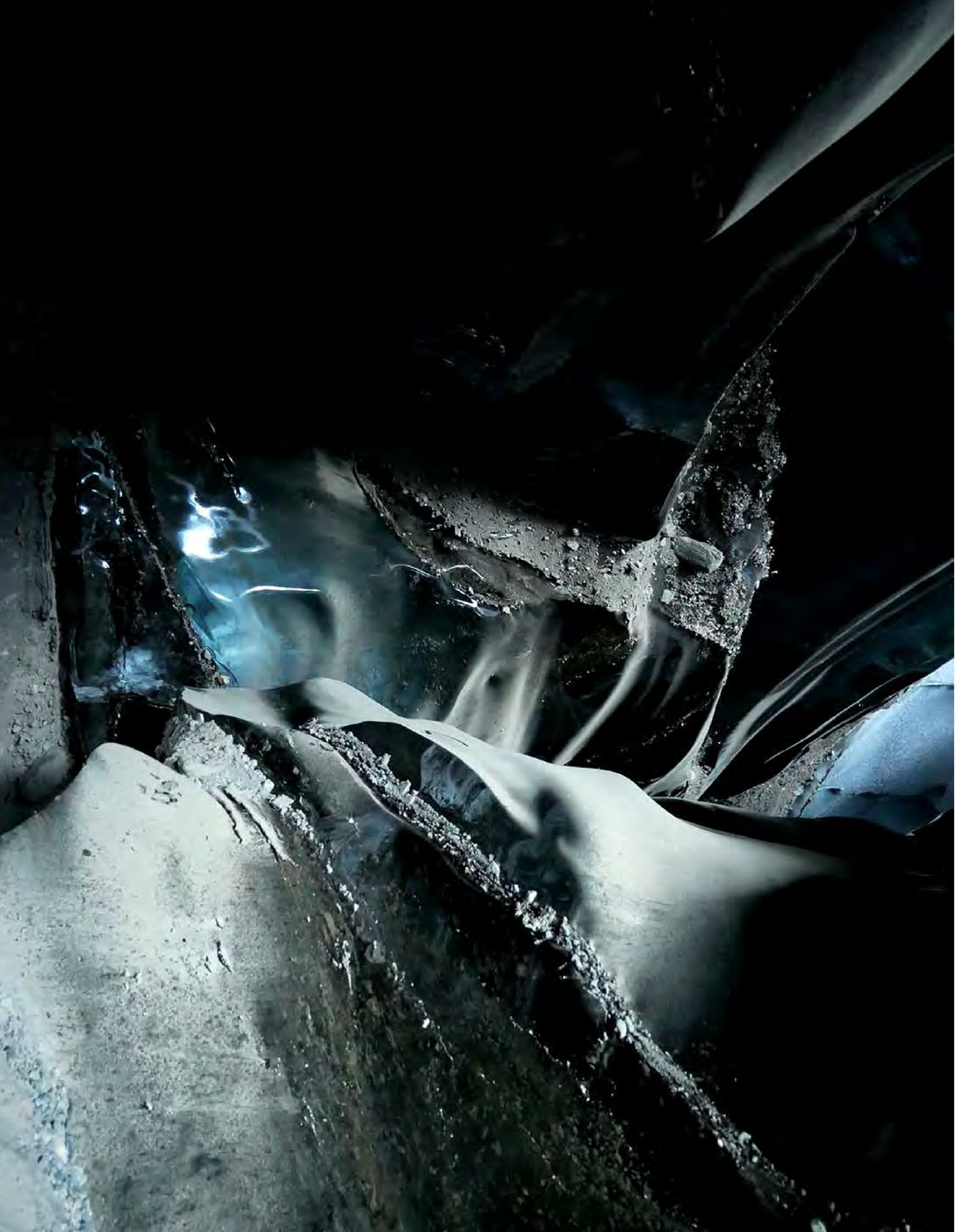
Not that I can think of on the spot. Although I really enjoy reading publications that have nice visual aids. It is a badly kept secret that I have always envied Kristian Olsen's drawing skills...

Where do we usually find you?

I love reading, calculating, doing simulations, teaching, and drinking coffee. In any order or all at once. Thus, you are likely to find me at my desk, in the library or in a classroom. I typically try to keep a regular schedule so that I can leave in the afternoon to go sing, act and dance (although this has been hard to do this last year).

What do you hope your research can do beyond academia?

As I do primarily theoretical research, it may take some years before it becomes practically useful. But a better understanding of the dynamics of dislocations that cause some materials to fail may someday lead to more stable bridges, or robust walls to contain the immense forces of a cold nuclear fusion plant. More concretely, I believe some of the tracking algorithms and structure analysis code that we have developed could also be used in other practical settings.



Interview

Name
Coline Bouchayer

Current position:
Doctoral research fellow

Been at UiO since:
September 2019

Coline Bouchayer

"The main implication of my work beyond academia is probably that my research helps me to have a deep understanding of glaciers' processes and their dramatic retreat under pressure of global warming. "

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

I have spent most of my childhood in the mountains looking at the surrounding glaciers. I stepped into glaciology at Grenoble doing my bachelor thesis on the evolution of the biggest French glacier. I continued with a research master there and a thesis focusing on snow avalanches forecasting. The year 2017 enriched my strong attraction towards the arctic and Antarctic region by having the opportunity to go to Svalbard in summer followed by 14 months of winter over in the French-Italian station Concordia in Antarctica. During this time on ice… well it became quite clear that I developed a strong relationship with frozen worlds and their mechanisms. In 2019, I had the opportunity to start a PhD position at Njord together with the GeoHyd section at the Department of Geosciences about understanding the transient flow of glaciers.

What is your current research project?

I am currently working on surging glaciers. These glaciers are experiencing cyclic advances with high velocities due to a substantial decrease of friction at the interface between the ice and the substrate before returning into a calm, slow, quiescent phase. The dynamic of these glaciers remains not fully understood. Using a machine learning approach, we quantify the probability for the glaciers in Svalbard to be surge-type and we try to understand the features that are controlling surging mechanisms. On the other hand, we are doing fieldwork on one surging glacier in Svalbard, Kongsvegen, to acquire observations. We have drilled a 340 m borehole in Spring 2021 through the ice to the bedrock and we have instrumented it with several sensors. We hope that these data will give us access to the physical processes that lead to a surge.

How does your current project tie in with Njord's diverse family?

One research focus of Njord is friction processes – especially in rock material. My research brings the experience to another material, ice. Working with experts on earthquake processes, I realized that there may be a strong analogy between earthquake phenomena and surging glaciers. Indeed, the deformation of the fault gauge during sliding is quite similar to the processes happening under a glacier before a surge. This is really an amazing opportunity to work at Njord to develop new ideas, and bridge the gap between different geoscientific communities!

Where do we usually find you?

I would say that it is hard to find me usually, since I am partitioning my time between coffee breaks at Njord, having meetings in the geology building and being in front of my computer in my office. A good working environment for me is a place where I am happy to go to work to discuss, science or not, with my colleagues even if it means staying late in the evening to have a full productive day. I believe that the best ideas and research projects are born by talking informally to other researchers.

What do you think your research can do beyond academia?

The research I am conducting is tied to one of today's hot topics – climate change. This being said, I do not necessarily feel like I am saving the world every day sitting in front of my computer, dealing with programming and equations. The main implication of my work beyond academia is probably that my research helps me to have a deep understanding of glaciers' processes and their dramatic retreat under pressure of global warming. I try whenever I can to communicate these complex processes to help people to measure the impact of what is happening and the consequences in present and future days. I would say that we need to know and search a lot to be able to give our findings to a more general community. Not saying that this is always a success but at least, I am trying to do that.

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 Volcano 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 2021, 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 2021, 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).

Environmental Geology
GEO3100

Environmental Geology covers the interactions between geology and human activities and gives an overview of environmental problems and challenges in geosciences. It deals with, e.g., water- and soil-resources, contaminated sediments, and carbon capture and storage (CCS).

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.

Hydrogeology
GEO4190

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

Petrography and Microstructures
GEO4810

This course is designed to provide an overview and practical training in the deformation and metamorphism of the Earth's lithosphere. Analysis, interpretation and application of structural data will be undertaken along with analysis of metamorphism in the field and in thin sections.

Dissemination, outreach and media highlights

To disseminate our research and findings is an important part of Njord's mission. We communicate to the international academic world and to the public, both in Norway and abroad. We aim to convey our knowledge and to increase appreciation and understanding of science through our outreach projects. To achieve this goal, we collaborate with media, renowned artists and industry partners. We encourage all our researchers to communicate their work, and several of Njord's researchers are particularly skilled at this task.

Our research is curiosity-driven and many of our scientific results have direct societal impact. The research is directly relevant to a wide range of applications, including transport of water and pollutants in porous and fractured rocks, carbon sequestration and storage, landslides and glaciers dynamics, earthquakes and other geohazards. This makes our research easily relatable to the public.

The scientists at Njord have a long track record of inviting artists to collaborate and to give a new perspective on their research. In April 2021, the magazine Physics Today interviewed Bjørn Jamtveit about collaborations between scientists and artists. He explained that while his original ambition with engaging in collaborations with artists was to increase the chances of future funding by excelling in outreach, he has gained more than that: "I've become a better observer because of my interactions with the artists."

Njord not only collaborates with artists, our scientists also produce art. In June 2021 PoreLab opened a public art exhibition in the square outside Oslo City Hall. How fluids and gases move in nature is crucial for all life and most of our energy production. The laws for how fluids flow and how they affect the medium they flows through have been poorly understood until now, but are now the main focus of PoreLab's research. The images in the exhibition were chosen for their aesthetic value from experiments and simulations, but they had all been taken for the sake of science. The art curators left it to the audience to decide whether the most beautiful pictures also were the most interesting.

If hunting for fossil earthquakes in Lofoten becomes as popular as hunting Pokémon in 2021, it might be because of Njord. Njord's annual field trip to Lofoten in the summer of 2021 caught the attention of media, and our

"The research is directly relevant to a wide range of applications, including transport of water and pollutants in porous and fractured rocks, carbon sequestration and storage, landslides and glaciers dynamics, earthquakes and other geohazards."

scientists were interviewed by several media outlets, like the magazine Titan, the newspaper Lofotposten and the national broadcaster NRK. In addition, Luca Menegon has given talks about his hunt for fossil earthquakes at the University Library and at a pub (!) as part of the event "A pint for science".

In the last couple of years Njord's geoscientist Oliver Galland has become one of Norwegian media's favorite volcano-experts, probably the one favorite. In 2021 Galland was interviewed several times about the volcanic eruption on La Palma by newspapers like VG, Aftenposten and magazines like Titan and forskning.no. The interviewers were all eager on getting the answer to how long the eruption would last, and they turned to Galland for answers, but not even Galland could give them the answers to this – no one can. Luckily Galland had a lot of other interesting facts about volcanos to share with them.

Have you ever wondered about how ultrasound works on people? Or did you know that there is actually eight ways to break things? Maybe you are curious to what historians and philosophers can use algorithms for. This is just some of what scientists at Njord have given talks, written blogs or been interviewed about in 2021.

In 2020 it became clear to us that not even a pandemic could stop us, and we have managed to keep a high level of activity through 2021 as well. In 2022 we will continue to convey our knowledge and to increase appreciation and understanding of science through our outreach projects; exciting, new plans have already been set in motion.

Fieldwork

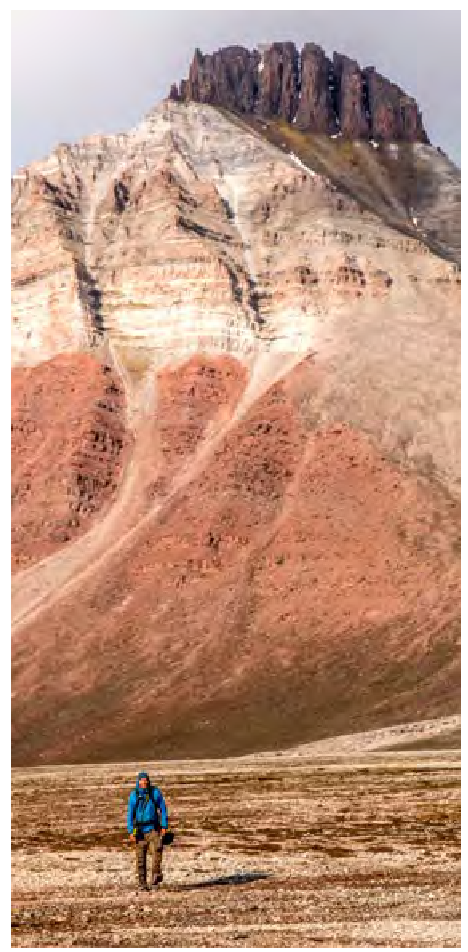
A number of the projects carried out at Njord are based on geological fieldwork. This involves geological mapping and sampling programs on a wide range of scales. Fieldwork both constrains and inspires experimental and modelling approaches to our studies of geological processes. The pandemic has had an impact on our activity at Njord, also in 2021. Restrictions on travelling during large parts of the year have especially impacted our fieldwork. Luckily, you do not have to go that far to find interesting geological localities when you are in Norway, and we have been able to do some fieldwork while keeping safe, e.g., in Lofoten and on Svalbard.

In May Luca Menegon, Steven Michalchuk, and Vidar Skogvoll from Njord and Hans Jørgen Kjøll from the Department of Geosciences went for four days to Western Norway, visiting the famous geological localities of Stryn, Måløy and Kråkeneset. The objective of the trip was to look at the effects of deep subduction of continental crust in the geological record. The team has also identified key stops for the 2022 field trip for the Tectonics master course that will be led by Luca Menegon and Hans Jørgen Kjøll.

In June, Luca Menegon, Sasha Zertani, Steven Michalchuk, Olivier Galland, and François Renard from Njord, and journalist Eivind Torgersen from Titan.no, spent two weeks in the Lofoten archipelago to study lower crust earthquakes. The Lofoten archipelago has a high density of lower crustal rocks that have recorded fossil earthquakes. These rocks, called pseudotachylytes, contain 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. Thanks to the presence of Eivind Torgersen, a series of four articles was produced in titan.uio.no that showcases how geologists work in the field. This outreach activity has also attracted lots of attention in other media with articles released in NRK and Lofotposten.

In July, Olivier Galland from Njord, Hans Jørgen Kjøll (UiO), Jonathan Runge (UNIS-U. Copenhagen), and Rafael Horota (UNIS) went for a ten-day fieldtrip to Svalbard. The first aim of the expedition was to map in 3D a large volcanic sill of Lower Cretaceous age emplaced in Permian carbonate sedimentary rocks of Dicksonland, central Spitzbergen. The mapping involved long hikes in rough terrains and a large-scale drone survey for computing 3D virtual outcrop models. The second aim of the expedition was to study the thermal effects of the sill on its carbonate host rock by sampling profiles in contact aureoles of the sills in order to assess how much the carbonates have been affected by contact metamorphism. This information can be crucial for discussing the climatic impacts of volcanism in Svalbard.

More fieldwork on Svalbard was conducted by a team of geoscientists looking at the Kongsvegen surging glacier. The team consisted of Coline Bouchayer (Njord), Thomas Schuler (UiO), Jon Hulth (UiO), Ashley Morris (NPI), Basile de Fleurian (UiB). In April-May the team drilled a 340 m deep borehole into the glacier to reach the bedrock. In the hole, they installed geophones, water pressure and thermistor sensors, and a ploughmeter at the bottom of the borehole to study the properties of the sediment when the glacier is sliding. In August they collected the data.



A sill intrusion on top of a mountain with a happy Hans Jørgen Kjøll in the foreground.

The surging glacier team on top of the Kongsvegen glacier, Svalbard.

In October, a group of eleven master students from UiO led by François Renard from Njord and Clara Sena (UiO), together with a group of eighteen students and five teachers from the University of Rennes, including Tanguy Le Borgne (Njord, University of Rennes), spent one week of fieldwork near the city of Ploemeur, France. This was done as part of the Hydrogeology master course at UiO. The fieldwork allowed to strengthen the collaborations between the universities of Oslo and Rennes in the domain of hydrogeology, in the framework of an international mobility project funded by the Research Council of Norway (INTPART Colossal).

Also in October, Kristina Dunkel, Olivier Galland, Luca Menegon and colleagues from the Department of Geosciences visited key localities in the Oslo fjord in a field trip led by the Geology Advisor of the Buskerud Telemark Vestfold County Councils, Sven Dahlgren. The objective of the trip was to discuss the feedback between igneous, volcanic and deformation processes during the development of the Oslo Rift, and to identify key localities for future research collaborations and field training for students.

In November, Olivier Galland, Fabian Barras, Gaute Linga, Eirik Flekkøy, Jessica McBeck went for a one-day field trip to Hovedøya in the Oslo Fjord. The aim of the trip was to establish a cross-disciplinary discussion between geologists and physicists to reveal the physics governing magma transport through the Earth crust. They visited small magmatic dykes exposed at the southwestern tip of Hovedøya, where the dyke tip structures in the host rock are well exposed. The fruitful discussions will lead to the writing of a work package in a proposal submitted to NFR (FRIPRO NFR: “Beyond Elasticity”).

Also in November, Kristina Dunkel (Njord), Christian Rødsrud (Museum of Cultural History, UiO) and Per Ditlef Fredriksen (Department of Archaeology, Conservation and History, UiO) went on a two-day trip to Southern Norway, where a pottery production site was excavated in the 1970s. The artefacts discovered back then are being re-evaluated now in the context of the local surroundings. One purpose was to analyze the landscape forms around the site to be able to place the workshop in its social context. The other aim was to sample local raw materials (clay and rocks) that may have been used during the manufacturing process.

We at Njord find fieldwork to be highly valuable for us in solving questions and in the processes of merging our cross-disciplinary expertise. In 2022, we plan to involve more the physicists of Njord in field activities.

Fabian Barras happily looking at deformation around an intrusion on Hovedøya in the Oslo Fjord.

Laboratories

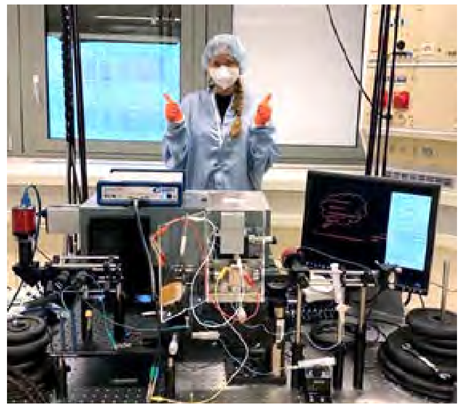
"PoreLab has developed a 3D optical scanner which makes it possible to measure 3D fluid structures in refraction index matched porous media."

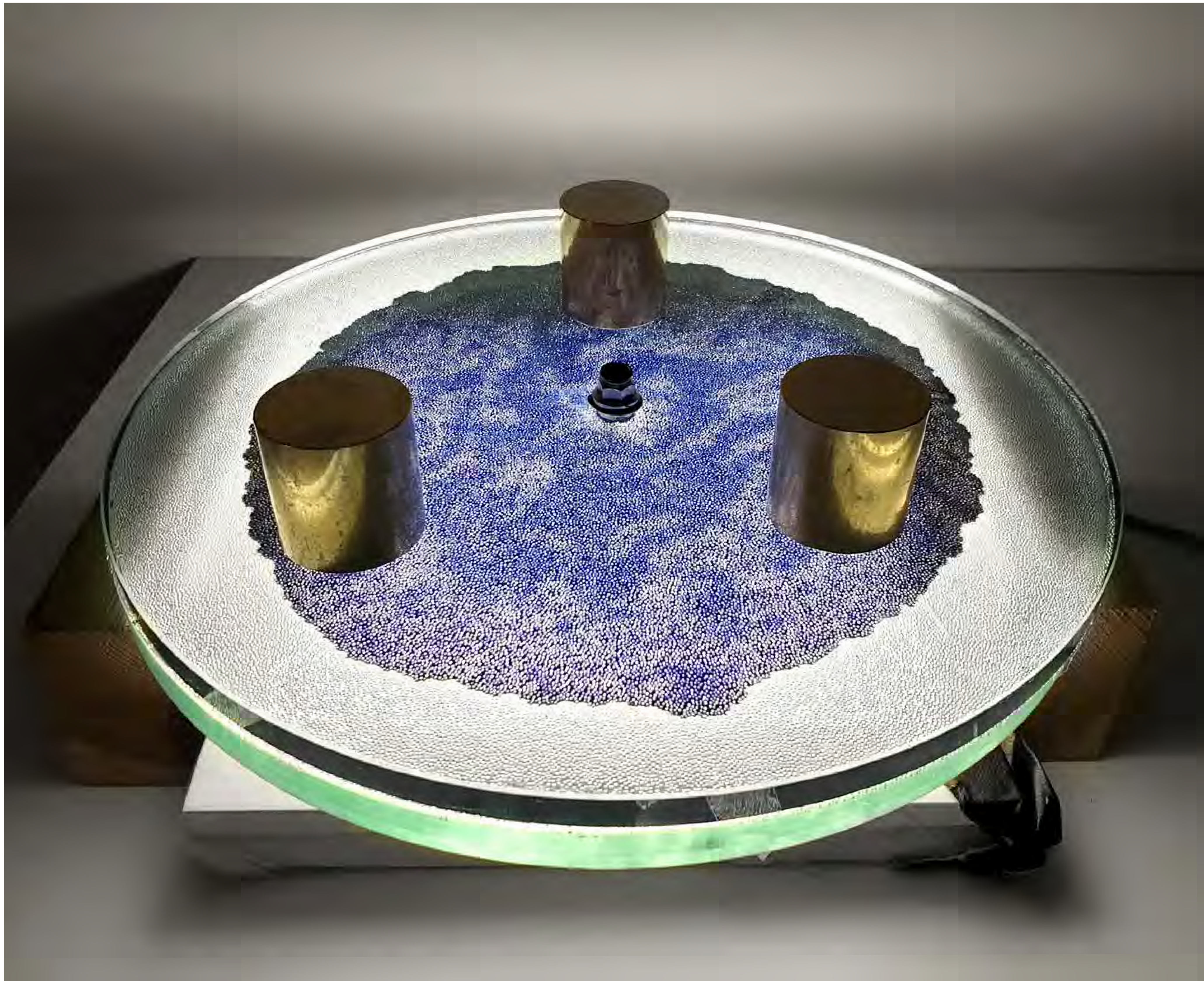
The research at Njord relies on unique experimental data acquired in our laboratories that have been fully equipped in the past years. Together with collaborations involving large instruments (neutron and synchrotron sources), the development of the national Goldschmidt laboratory at the Geoscience Department,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

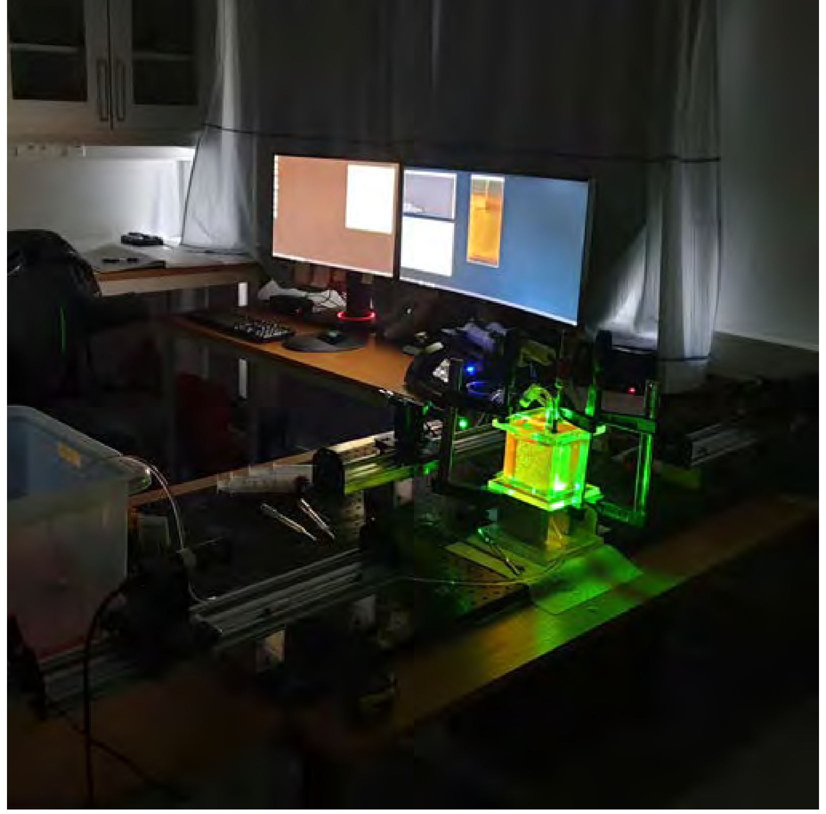
Njord's researchers from both the Departments of Physics and Geosciences are responsible of five laboratory facilities: the four experimental rooms of the Centre of Excellence PoreLab, the FrictionLab, the NI-Earth lab, the OsloAnalogueLab, and the three rooms of the FlowLab, which all are equipped with state-of-art techniques and apparatuses. Njord's researchers also contribute to the the LaglivLab and have initiated the national Goldschmidt laboratory.

PoreLab laboratories at UiO are specialized for the study of the dynamics and structure of flow in 2D and 3D porous media. The laboratories have a full range of high-resolution and high-speed imaging techniques, including two ultrafast Photron Ultima (SA5 and APX) cameras. In 2020, PoreLab acquired a Carbide Shapeoko XL CNC milling machine and two Formlabs Form 3D printers that are based on a new Low Force Stereolithography (LFS) technology. In 2021, we expanded our 3D printing capabilities by adding a Form 3L, a higher volume SLA printer, to our 3D printing cluster. 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. We have also acquired two new high-speed cameras (Photron WX100) capable of taking 4MP images at 1000fps. PoreLab also has a high-resolution FLIR SC300 infrared camera used for real-time measurements of heat dissipation and a wide variety of digital single-lens reflex (DSLR) cameras and accompanying optics. Microscale experiments can be imaged via far field microscopy using a Zeiss Stemi 2000-C distortion-free stereomicroscope that couples to our high-speed and high-resolution cameras. Illumination sources tailored for the different applications (including high-speed microscopy) are also available. PoreLab has recently bought a Krüss DSA25 drop shape analyzer to perform direct measurements of surface tension, wetting properties and surface free energy. 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 developed a 3D optical scanner which makes it possible to measure 3D fluid structures in refraction index matched porous media.

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







"Together with collaborations involving large instruments (neutron and synchrotron sources), the development of the national Goldschmidt laboratory at the Geoscience Department, and the involvement in the EXCITE European platform, our state-of-the art laboratories are open to national and international users, and master and PhD students can use them for their training."

microtomograph at the National Science Museum in Oslo for imaging samples during deformation. We have developed triaxial rock deformation apparatus, the HADES rig and KORE rig, which are installed at the beamline ID19 at the European Synchrotron Radiation Facility. These rigs allow imaging rocks during deformation using dynamic X-ray microtomography. We have also developed three rock core holders that can reach up to 10 MPa confining pressure. These holders are installed at neutron sources (Institut Laue Langevin in Grenoble and Paul Scherrer Institute in Villigen near Zürich) for neutron tomography imaging of fluid flow in rocks. In 2021, we have acquired new equipment in the framework of the European Research Council project BREAK: an ultrafast camera (Shiimadzu HPV-2 and a triaxial rock deformation apparatus, ZEUS, will be installed in 2022 on the beamlines ID19 and BM18 at the European Synchrotron Radiation Facility.

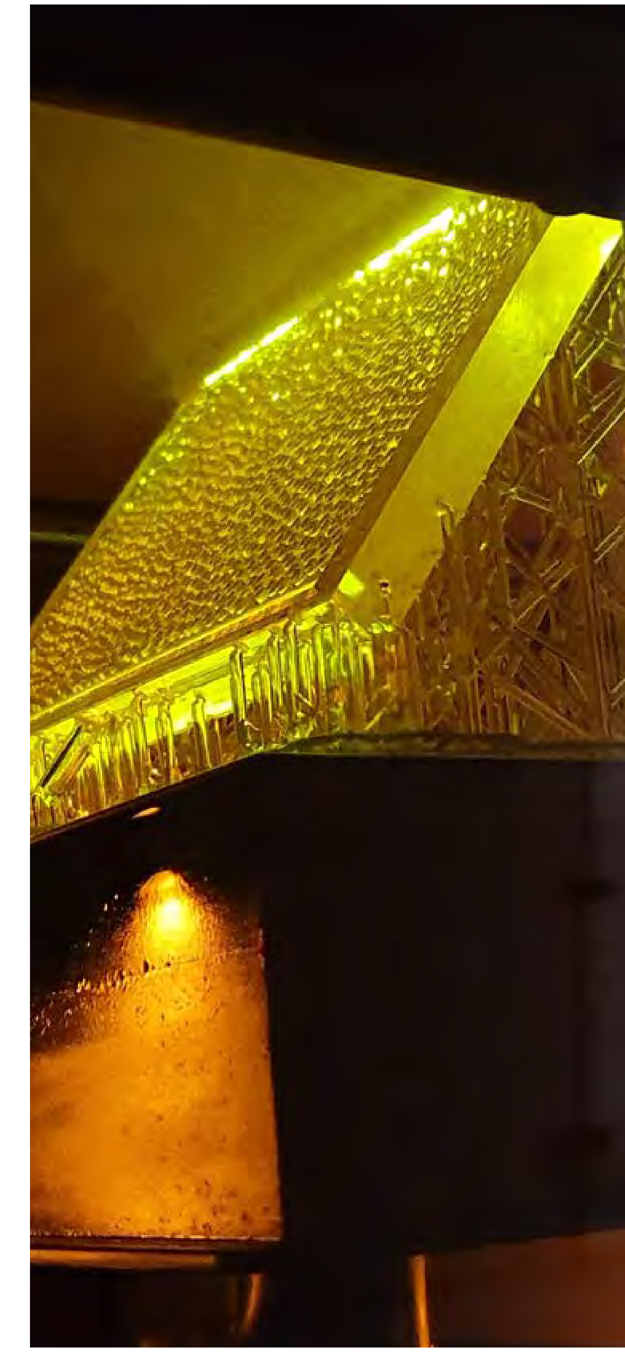
In 2021, Njord has installed the new **NI-Earth lab** for nanoindentation of Earth materials. The new lab hosts a G200X nanoindenter from KLA, which is capable of measuring Young's modulus, hardness and creep of geological materials at room temperature and at up to 500 °C using a laser-heating system.

The **OsloAnalogueLab** (previously VolcanoLab) has been relocated to a fully renovated room thanks to support from the Physics Department. This laboratory focuses on the quantitative simulation of various geological 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.

At **FlowLab**, we have a Surface Forces Apparatus (SFA 2000) equipped with a Spectrometer IsoPlane SCT320 that enables direct 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 from 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 image collection and processing. We also have a white light interferometer microscope, NT1100.

In 2021, the **Goldschmidt Laboratory**,a Norwegian national infrastructure for geochemical, microstructural, and geochronological characterization of solid Earth materials, was installed under the leadership of the Department of Geosciences and Njord. A new isotope dilution thermal ionization mass spectrometer (ID-TIMS) and a new Noble gas mass spectrometer (NGMS) were installed at UiO and at the Geological Survey of Norway in Trondheim, respectively. Furthermore, the SEM lab at UiO was expanded with the cutting-edge technique of high-angular resolution electron backscatter diffraction (HR-EBSD).

The new nano-indenter at Njord ready to perform mechanical tests on minerals.



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 that is dedicated to cell cultures and contains a MARS Class II biological safety cabinet and a PHCBi CO2 incubator which is used to grow cells.

Njord is also playing a leading role in UiO's participation in the H2020 INFRAIA **"EXCITE"** project (funded in 2020), which aims to establish a European network in electron and X-ray microscopy for imaging of Earth materials.

Njord and COVID-19

The year of 2020 left us hopeful for 2021. But even though the situation changed a lot since March 2020, COVID-19 has had a huge impact on us and our activity in 2021. The pandemic has impacted many aspects of our lives and the work of everybody in Njord. We learned a lot in 2020 about adjusting to the new situation; in 2021 we implemented this and we have kept on learning.

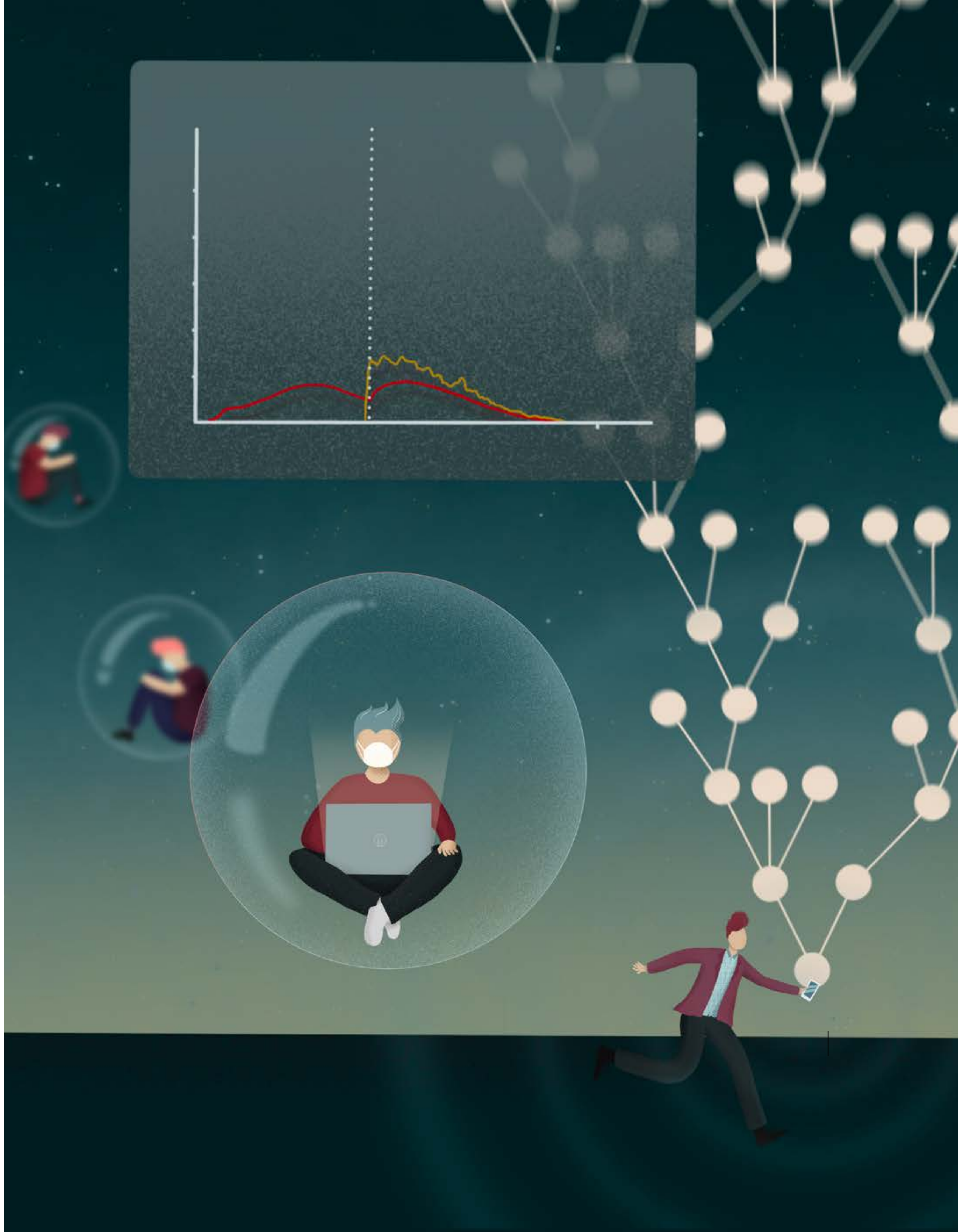
The safety measures and rules implemented both at the university, by local and national authorities and in other countries around the world has meant that we have had to do things differently. We have had to make changes at the office, and for periods of time we have had to avoid the office. We have again cancelled seminars, trips, fieldwork and parties. We have been kept from the social arenas that we find important for meaningful collaboration with colleagues. These informal arenas that contribute to holding our diverse group together are an important foundation for the synergy and innovation we have in our group.

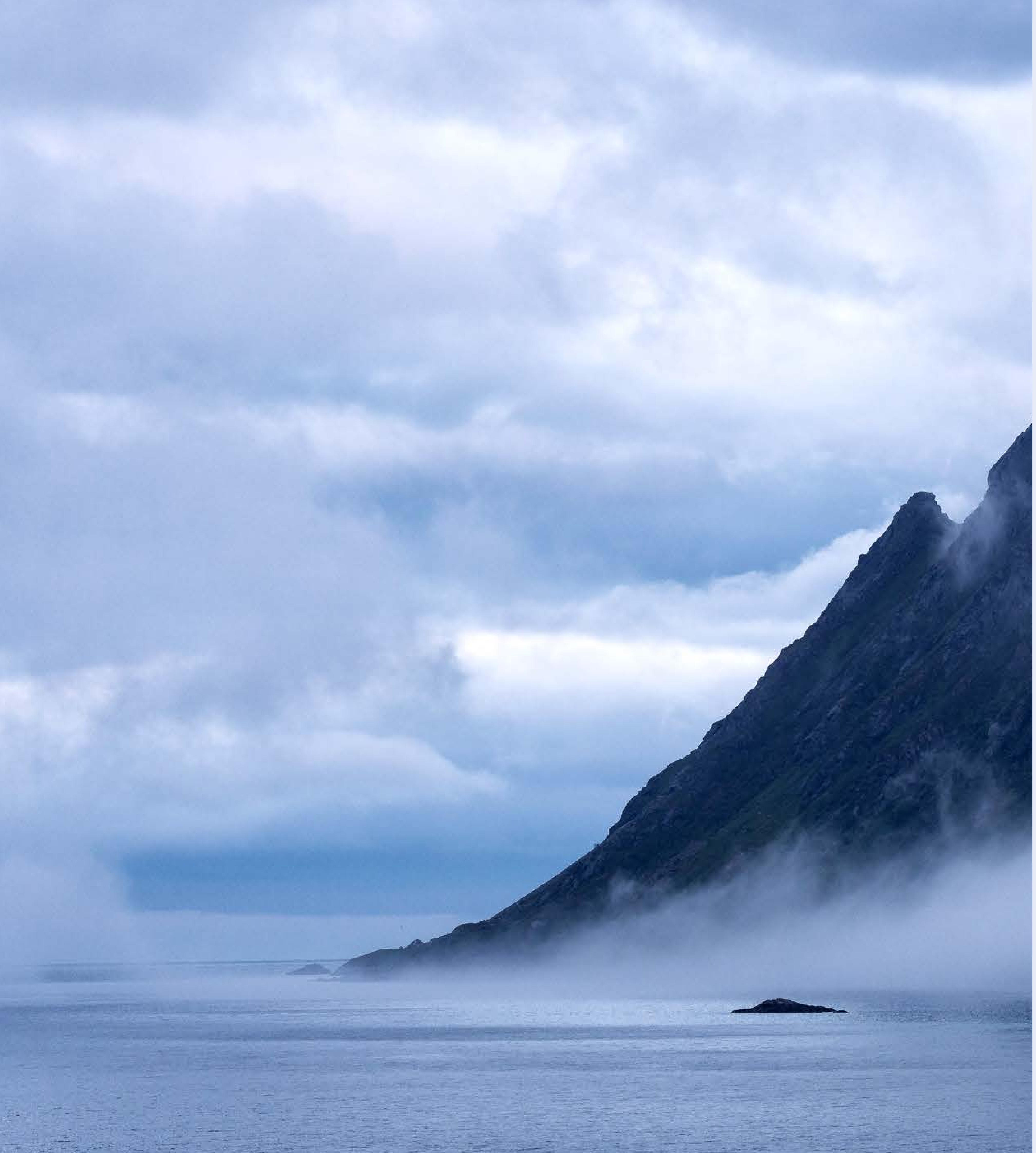
But thankfully 2021 has brought with it some highlights as well, like the Breaking the Crust-seminar in September 2021. Originally planned for October 2020, the seminar was highly anticipated when it finally took place one year later. With a diverse group of international guests, the seminar gave a long awaited boost with scientific discussions and socializing with peers for the members of Njord and the invited guests.

In 2021 we also had visits from international guests that have stayed with us for shorter or longer periods of time. Despite travel restrictions we have had guests from China, India, France, Denmark and Poland, all enriching our group. The Njord Seminar, which was a huge success in 2020, has continued all through 2021 as a hybrid-seminar, with a diverse group of speakers. The seminar has been highly valued by staff at Njord, and attracted audiences from across the globe.

Hybrid has become the new normal for meetings and seminars. The fact that the pandemic put such heavy restrictions on our office life and our travelling has led to the acceptance of virtual attendance. Virtual meetings have limitations, but they have also opened a world of new possibilities for easier and cheaper communication and interaction around the globe. We do not think it will or should replace physical meetings in the future, as these are still of high value to us, but hopefully we can continue with virtual events and communication in addition to other interactions.

We look forward to 2022. Hopefully we can travel to conferences, fieldwork and collaborators in 2022, but if not we will keep on finding ways to adjust to the situation and continue to progress.





03

Research projects

About Chapter 3 Introduction

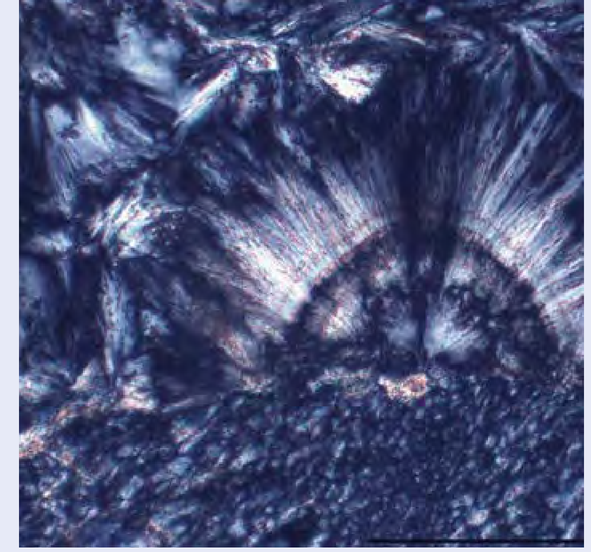
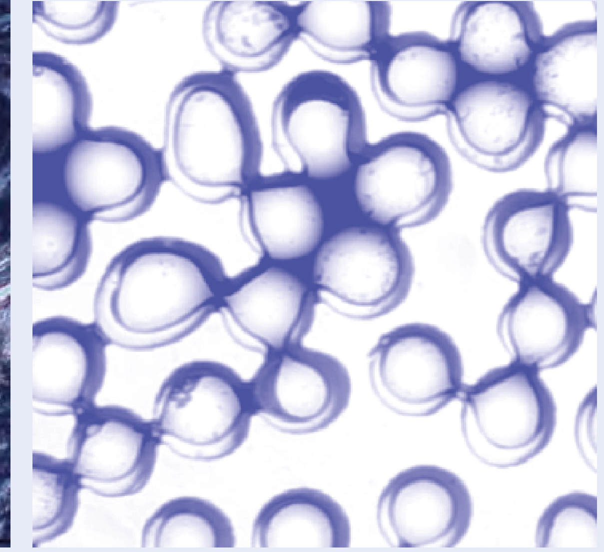
The research at Njord is organized around four key topics: 1) Fluid Flows in Complex Media, 2) Mechano-Bio-Chemical Processes across Scales, 3) Fracture, Friction and Creep, and 4) Pattern Formation and Dynamical Systems.

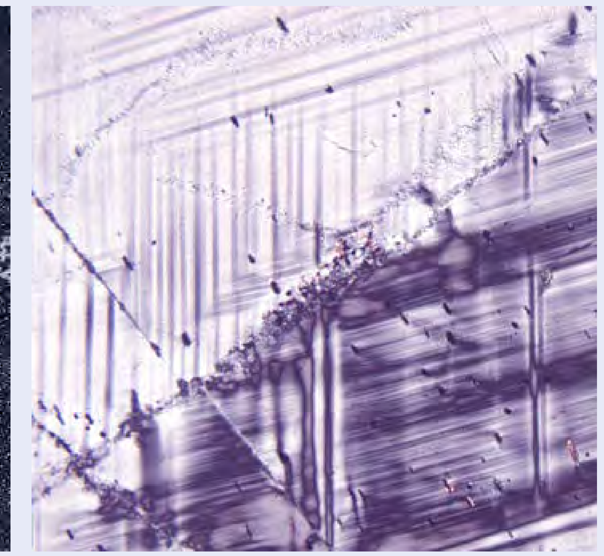
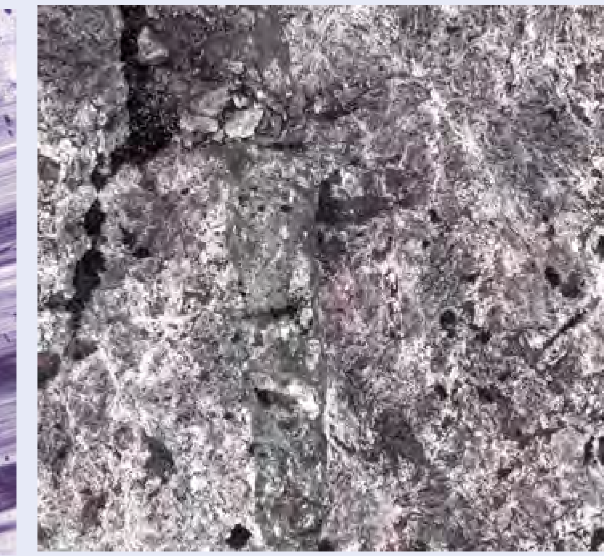
Many researchers at the Njord Centre focus on the dynamics of fluid migration through porous materials and geological media. Some of them address single or multi-phase fluid dynamics in the confinement of a complex pore space where fluid-solid interactions vary along the interfaces **(Part 1)**. In other situations, the solid confinement is deformable and changes shape as a response to the forces imposed by fluid pressure gradients or to external forces. Another level of complexity, very often realized in geological systems, arises if the solid interacts chemically with the pore-filling fluid. In this case, the pore space may evolve both by dissolution or precipitation of solids and by stress perturbations induced by growth processes **(Part 2)**.

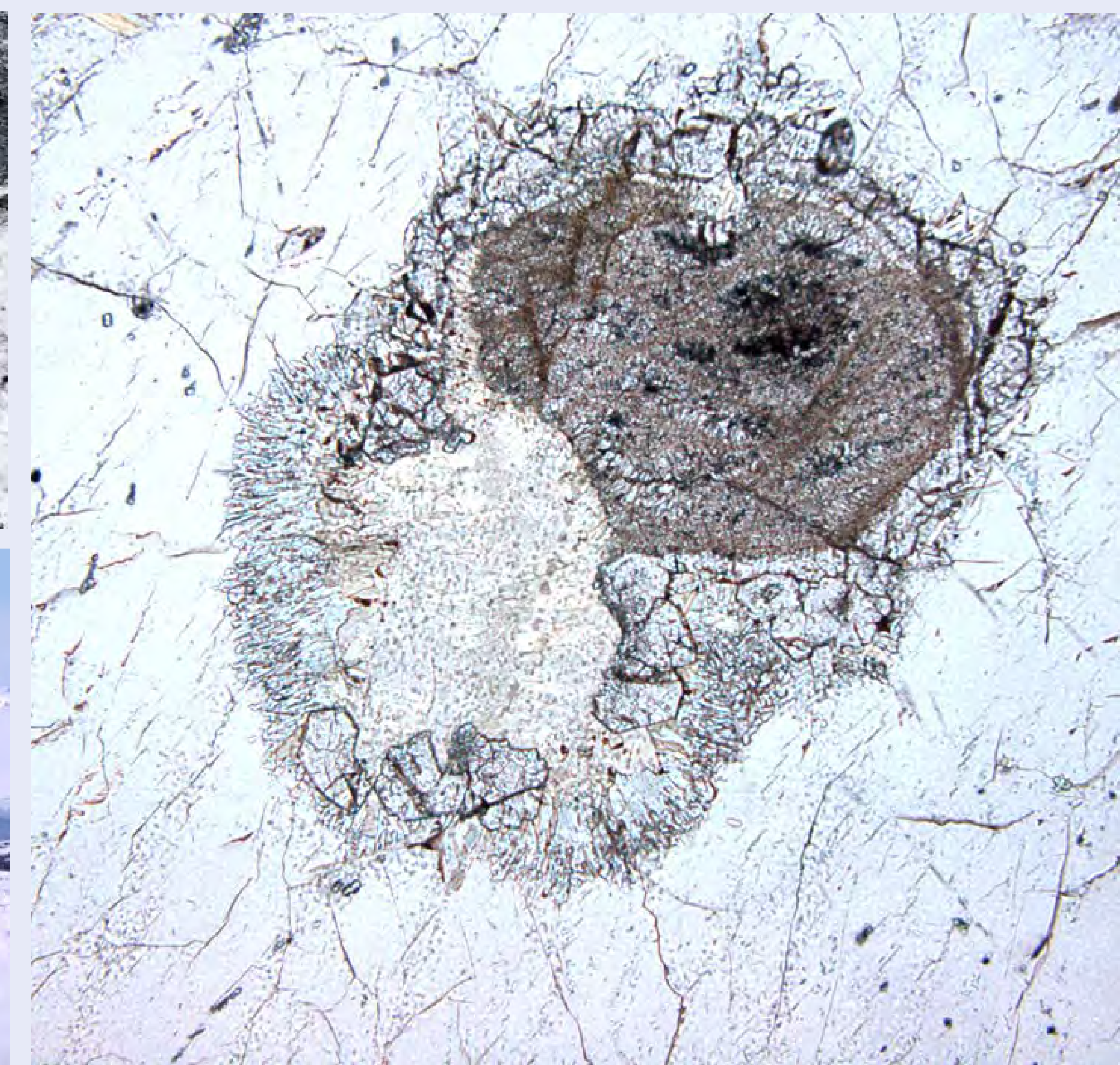
Fluids often enter the solids through fractures. Hence, the physics of fracturing is a central Njord activity **(Part 3)**. In natural systems, fracturing is often associated with displacement along the fracture surface and the frictional properties of fractured surfaces control energy dissipation. This situation applies both to the slow slip encountered in aseismic deformations of faults, landslides, glaciers, and volcanos and to the high slip rates associated with natural earthquakes or glacier surges.

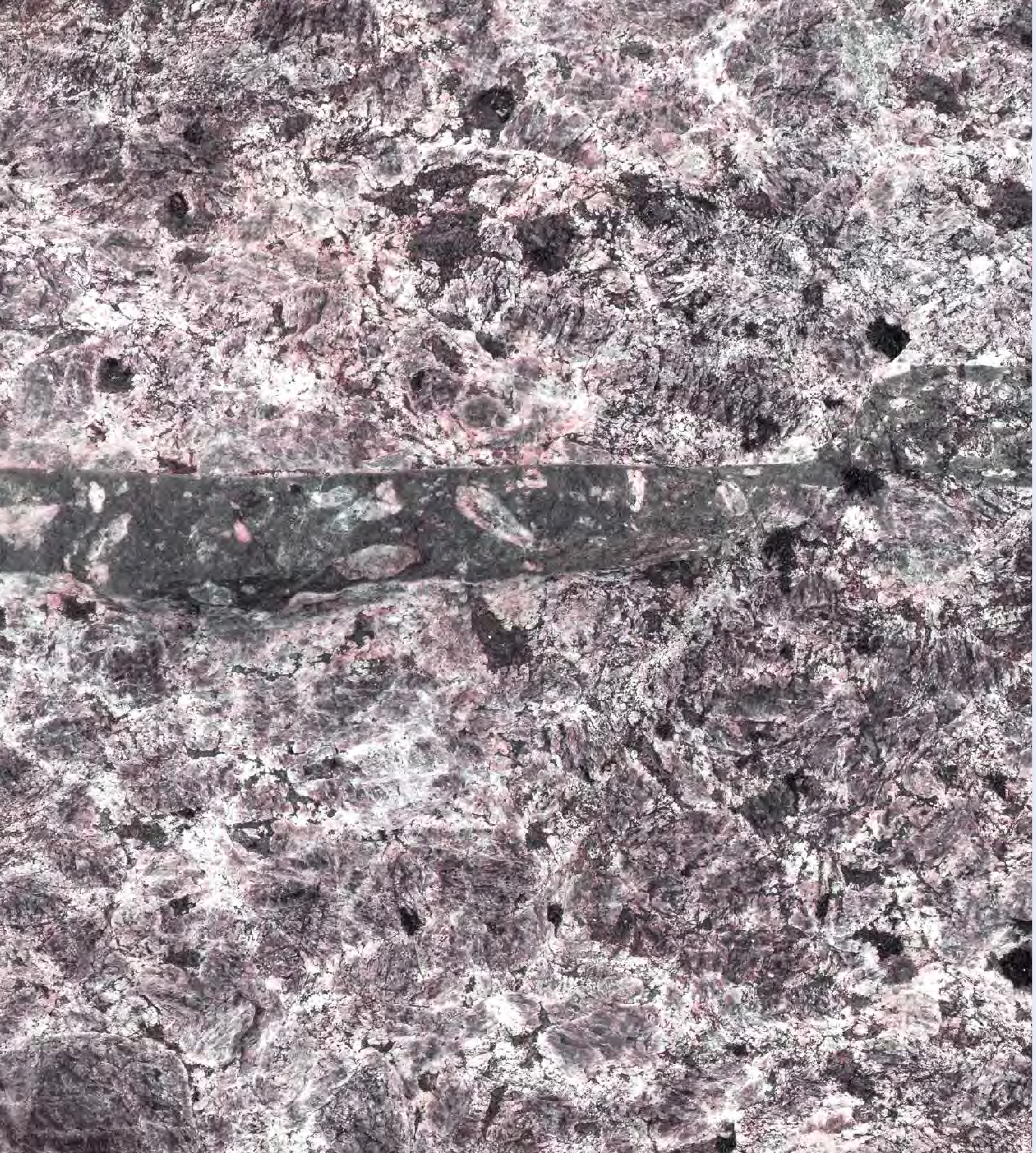
Finally, most of the systems studied at Njord evolve far from equilibrium and are often characterized by nonlinear relations between forces and fluxes and the emergence of 'self-organized' patterns **(Part 4)**. Such patterns may contain valuable information about underlying processes. This is particularly 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.

Part 1 Fluid Flows in Complex Media page 47
Part 2 Mechano-Bio-Chemical Processes across Scales page 63
Part 3 Fracture, Friction and Creep page 73
Part 4 Pattern Formation and Dynamical Systems page 83



Chapter 3 | Part 1

Fluid Flows in Complex Media

1. Three-dimensional experiments on multi-phase flow in porous media
2. Burst dynamics, upscaling and dissipation of slow drainage in porous media
3. Capillary pumping: the spreading of pollution in porous media
4. Collaboration on flows across scales (Brazil, France, Norway, USA)
5. EarthFlows
6. Mixing in multiphase flow through microporous media
7. Magma emplacement mechanics in volcanic plumbing systems
8. Modelling and imaging flow in rocks across scales
9. Neutron imaging of fluid flows in rocks
10. Taylor dispersion in rough channels
11. Tunable interactions inside deformable porous media

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

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

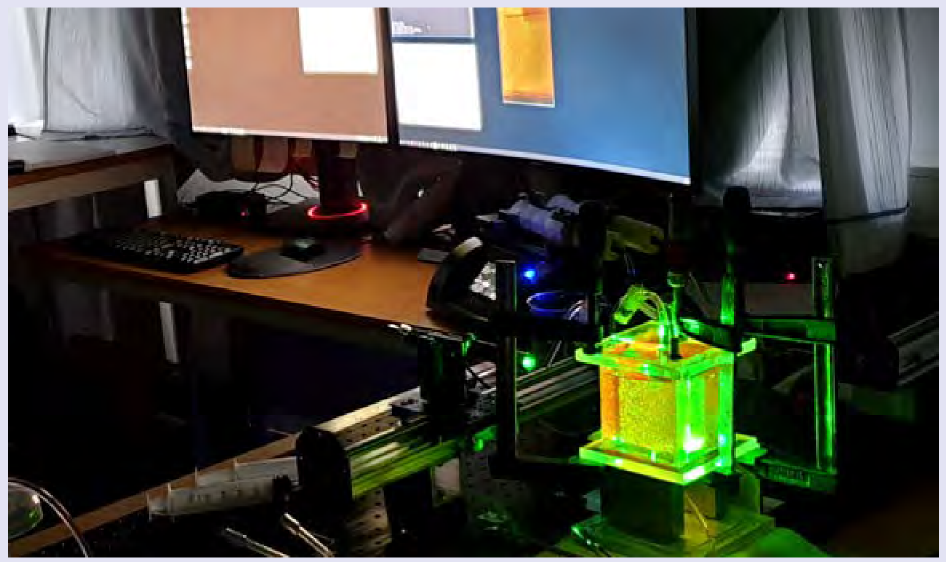
Affiliation
1) PoreLab, The Njord Centre, University of Oslo, Norway
2) Universite de Strasbourg, CNRS, IPGS UMR 7516, France

Three-dimensional experiments on multi-phase flow in porous media

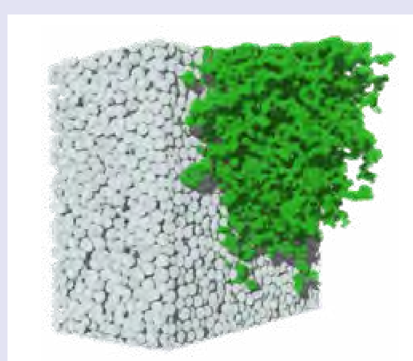
We utilize our in-house developed 3D scanner, based on optical index matching, to investigate the fundamental dynamics of two-phase flow in porous media, from pore-scale, via mesoscale up to macro-scale. Currently, we are pursuing different approaches where the transitions between flow regimes can be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

[1] Auradou H., Måløy K. J., Schmittbuhl, J., Hansen, A., Bideau, D., (1999). Competition between correlated buoyancy and uncorrelated capillary effects during drainage. *Physical Review* E 60, 7224
[2] Meheust, Y., Lævoll, G., Måløy, K. J. , Schmittbuhl, J. (2002) Interface scaling in a two-dimensional porous medium under combined viscous, gravity, and capillary effects. Physical Review E 66, 051603.
[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, and the porous medium is cut in half, with the right side removed for

Production in highlight

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.

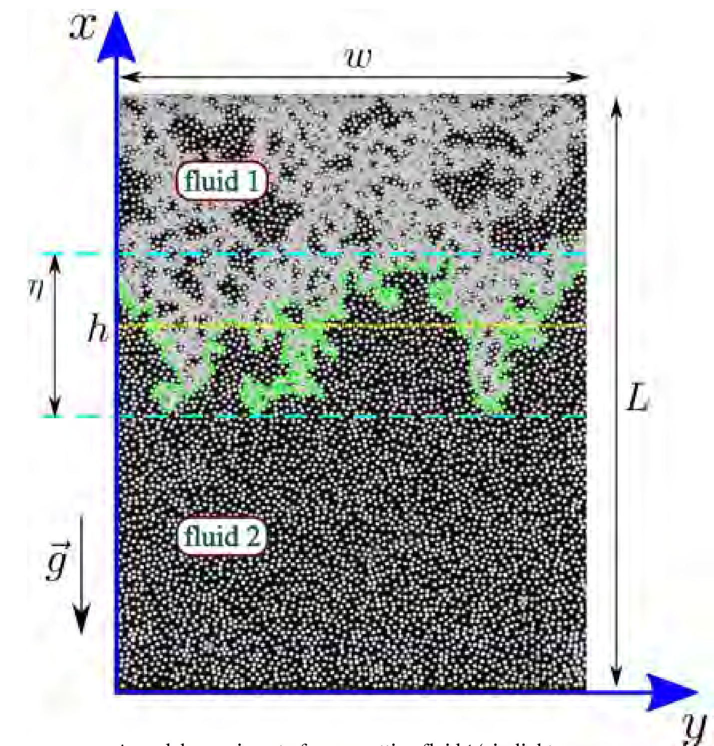
Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Knut Jørgen Måløy[1], Marcel Moura[1], Alex Hansen[2], Eirik Grude Flekkøy[1], and Renaud Toussaint[1,3]

Affiliation
1) PoreLab, The Njord Centre, University of Oslo, Norway
2) PoreLab, Department of Physics, NTNU, Trondheim, Norway
3) CNRS, Institut Terre et Environnement de Strasbourg, University of Strasbourg, Strasbourg, France

Burst dynamics, upscaling and dissipation of slow drainage in porous media

The enormous diversity of scales is one of the most challenging and fascinating features of porous media science. Hydrocarbon reservoirs or water aquifers are in the range of kilometers. Pores are typically ten to a hundred micrometers in diameter or seven orders of magnitude smaller. How can we infer large-scale flow dynamics from small-scale physics? A top-down approach using Darcy's law on a mesoscopic level is commonly used to solve these problems. However, this approach does not take into account local fluctuations, like capillary or viscous fluctuations, which are averaged out. In this work, we choose a bottom-up approach where we emphasize the capillary fluctuations and compare those fluctuations with the characteristic forces which are set up by the external fields on the system which are gravitational or viscous fields. The work is limited to the slow displacement of stabilized drainage fronts. We demonstrate how dissipation at small scales is related to dissipation at larger scales, as well as how we can predict saturation, dissipation, and surface energy at large scales if we know the characteristic length scales set by the characteristic forces involved. Furthermore, our theoretical description explains how the Haines jumps' local activity and dissipation relate to dissipation on larger scales. In a consistent description, the presented theory is compared to both previous and new experiments.



A model experiment of a nonwetting fluid 1 (air, lighter color) invading another wetting fluid 2 (glycerol-water mix, darker color) in a porous model of width w and length L. A syringe pump is connected to the lower side and the model is open to air on the upper side. The model can be tilted with an effective gravitational constant $g=g_0 \sin(\theta)$ along the x-direction of the model, where $g_0= 9.82$ m/s2. The average position of the active front (seen in green) is h and the width of the front is 2η.

Production in highlight

Måløy, K., Moura, M., Hansen, A., Flekkøy, E., Toussaint, R. (2021). Burst Dynamics, Upscaling and Dissipation of Slow Drainage in Porous Media. *Front. Phys*. 9:796019.

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Marcel Moura[1], Joachim Falck Brodin[1], Per Arne Rikvold[1], Eirik Grude Flekkøy[1] and Knut Jørgen Måløy[1]

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

Capillary pumping: the spreading of pollution in porous media

If you look at a raindrop rolling down a car's windshield you will see that it frequently leaves behind a thin water trail. As the drop moves down the glass, the area just behind it does not get immediately dry: a thin water film persists, sometimes even for a long time after the drop passes by. If the glass surface were not so smooth, such films would remain for much longer, and this is precisely what happens inside porous media like natural soils and rocks. When a wet portion of the soil gets dry, say after some hours of sunshine following a storm, thin liquid films remain on the surface of the soil grains. These thin films bring an interesting consequence: they can interconnect different parts of the soil, like a whole set of water bridges forming a large network of water streets and avenues. This analogy may seem a bit far-fetched but it is quite descriptive: just like our streets, the water films act as an invisible transportation network in an invisible water city. Plant roots can use this network to obtain nutrients from far away, but pollutants can also take a high-speed road to spread quickly in the soil (see figure). In this project, we are interested in understanding the dynamics of the transport of polluted water through a network of thin water films in a porous medium. This is analogous to the scenario in which some polluted water is spilt on the ground and starts to seep through the porous space. As natural soils are unfortunately not transparent, we employ artificial porous samples in our study (either made of glass or 3D printed in transparent plastic). We have observed that the residual water content in the sample (how wet or dry the soil is) plays a key role in the pollution spreading dynamics. We have found that for intermediate residual water content, the thin liquid films in the sample, behave like a network of tiny pumps, which act to spread the pollution very quickly. Once this behavior is properly understood, we believe it will allow us to also understand how we can make use of the thin film network for soil remediation measures. The same transport mechanisms that aid the pollution spreading can be tailored to spread a cleaning agent in the soil, to remediate the damage caused by the pollution.

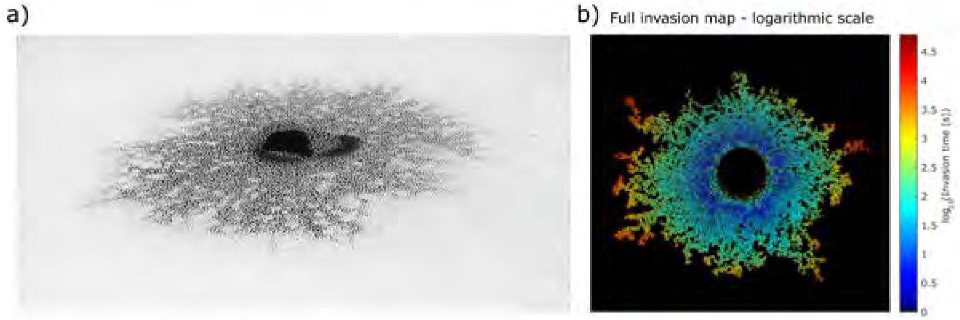


Figure: a) Experiment illustrating how a source of pollution (central dark blob) spreads through a partially wet porous network (here made of glass beads). Water films covering the internal surfaces of the porous medium can act as a fast pathway for the spreading of pollution. b) Spatiotemporal invasion map of a typical experiment. The color code shows the time (in seconds, logarithmic scale) for the pollution to reach a given point in the network.

Production in highlight

Moura, M., Brodin, J., Rikvold, P., Måløy, K. Capillary pumping: the spreading of pollution in a porous medium. In preparation.

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

PoreLab
NTNU-UiO Porous Media Laboratory

Funding
Research Council of Norway (INTPART COLOSSAL #309073), Equinor and the University of Oslo (Akademia-project MODIFLOW)

Participants
François Renard[1], Gaute Linga[1,2], Fabian Barras[1], Knut Jørgen Måløy[2], Marcel Moura[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[2], Clara Sena[4], Atle Jensen[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]

Affiliation
1) The Njord Center, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Geosciences Rennes, University of Rennes, France
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

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

Through a wide international collaboration between geophysicists and physicists in Norway, Brazil, USA and France, we study the couplings between flows, chemical evolution, deformation, and fracturing that cover all the time and length scales of natural geological processes. In this project, which 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 have 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 ground), and georesources (geothermal energy, CO_2 sequestration, solution mining).

This project started in 2021 with the visit of Dr. Pascal Lacroix (University Grenoble Alpes) to Oslo for a six-month period to work on landslides processes. Dr. Lacroix will co-supervise a PhD student from Oslo in the next years. PhD student Jean-Baptiste Jacob (University Grenoble Alpes) has spent one month at Njord to work on fossil earthquakes, and this collaboration will continue in the ERC project BREAK. A writing workshop with early career researchers from Norway and France was held in Blesle in June 2021. During this workshop, a PhD student progressed on an article on how to use machine learning to classify glacier instabilities. Two other articles on nanoparticles were finalized. In July, Njord researchers co-organized the Fifth Summer School on Flow and Transport in Porous and Fractured Media in Cargèse, Corsica. With an attendance of more than 70 persons, including 55 early career researchers, this school was a great success. It will create long-lasting interactions between researchers at the Njord Centre and many participants of the eight partner universities of COLOSSAL.

Finally, the highlight of this year was a one-week field trip organized between the Universities of Oslo and Rennes, where eleven master students from Oslo and eighteen master students from Rennes worked together to unravel the complex subsurface flow processes in an active groundwater aquifer located near Ploemeur, France.

Master students from the master course of Hydrogeology at the University of Oslo spent one week on the field near Ploemeur, France, to study groundwater. Dr. Tanguy Le Borgne (University of Rennes) is teaching them how to measure the chemical and physical properties of groundwater under in situ conditions.

PoreLab
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Production in highlight

Bouchayer, C., Aiken, J. M., Thørgersen, K., Renard, F., Schuler, T. V. Automating the classification of surging glaciers in Svalbard. *Journal of Geophysical Research*, submitted.

Mathiesen, J., Linga, G., Misztal, M., Renard, F., & Borgne, T. L. (2021). Enhanced dispersion in intermittent multiphase flow. *arXiv preprint arXiv:2109.10985.*

Montes-Hernandez, G., Findling, N., Renard, F. (2021). Direct and indirect nucleation of magnetite nanoparticles from solution revealed by time-resolved Raman spectroscopy. *Crystal Growth and Design*, 21, 3500–3510.

Putnis, C. V., Wang, L., Ruiz-Agudo, E., Ruiz-Agudo, C., & Renard, F. (2021). Crystallization via Nonclassical Pathways: Nanoscale Imaging of Mineral Surfaces. In *Crystallization via Nonclassical Pathways Volume 2: Aggregation, Biomineralization, Imaging & Application* (pp. 1-35). American Chemical Society.

Funding
UiO, 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].
Post-doctorate fellow: Kjetil Thøgerson[1,4]
Current PhD students: Vidar Skogvoll[1,4], Coline Bouchayer[2], Torstein Sæter[3]
Graduated PhD students: Ole Rabbel[1,2], Petter Vollestad[3], Xiaojiao Zheng[1,2]

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

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

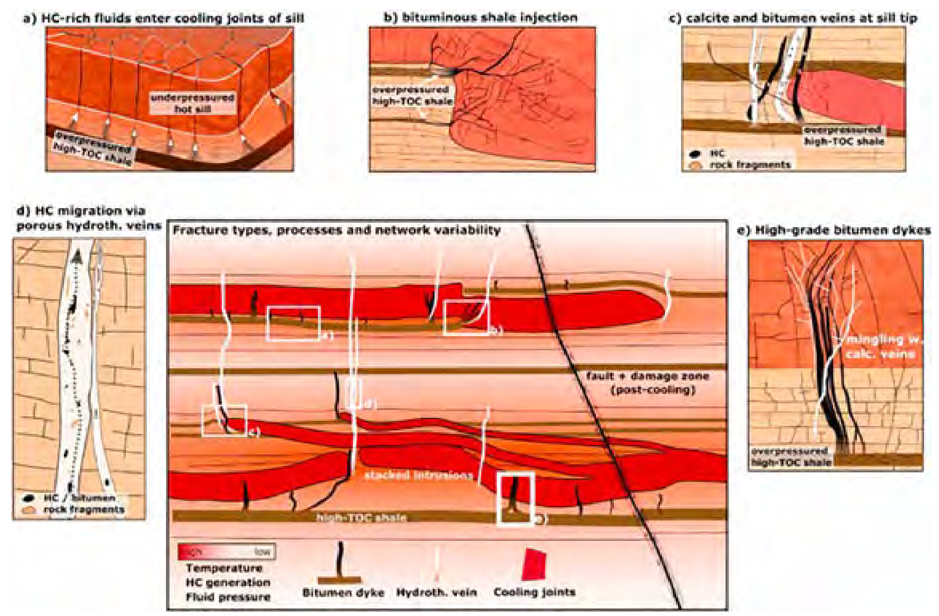


Figure 1. Schematic summary of fracture types, underlying mechanisms, and fracture network variations interpreted from field evidence. From Rabbel et al. (2021).

Project highlight 1: Fracture networks in shale-hosted igneous intrusions

We present a comprehensive field study from the Neuquén Basin, Argentina, using a reservoir-scale outcrop of a sill complex emplaced in organic-rich shale, which constitutes a direct analogue of oil-producing fractured igneous reservoirs. We provide field evidence of various fracturing mechanisms affecting the fracture network, including cooling joints, bituminous dykes, hydrothermal veins, and tectonic faults. Our results indicate that all observed fracture types are involved in hydrocarbon migration and/or storage (Figure 1). Bitumen of very high thermal grade within the intrusions implies migration of hydrocarbons into the sills in a destructive high-temperature environment. Importantly, bitumen dykes and faults locally alter the fracture network, creating zones of strongly increased fracture intensity and connectivity and therefore improved reservoir properties. The results are part of the PhD thesis of Ole Rabbel who defended in 2021.

Project highlight 2: Dislocation dynamics and crystal plasticity

Plastic deformation of crystals originates in the formation of dislocation in the crystal lattice and their migration through the stressed lattice. A fundamental challenge in modelling crystal plasticity is to be able to resolve dislocations on atomic scales and on long timescales. Our approach to solve this challenge is to describe the broken symmetries of a crystal lattice through an order parameter that, by definition, capture information about all topological transformations of the crystal lattice including dislocations. We develop a formalism for extracting the configuration stress from a given state of the crystal order parameter for different crystal symmetries for thin-film and bulk crystals (Skogvoll et al., 2021a). The method is generalized to bulk crystals, and we propose a formalism to determine the dislocation density tensor and its evolution from the configuration of the order parameter.

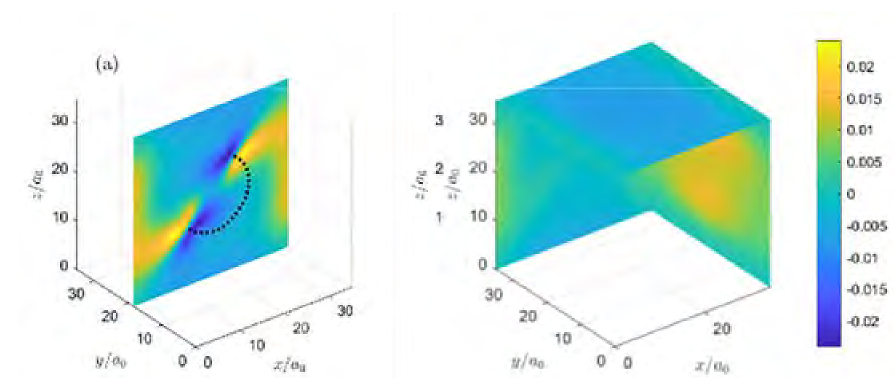


Figure 2: In-plane sections of the configurational stress for the dislocation loop after shrinking to 90% of its initial circumference under (a) unconstrained diffusive dynamics and (b) diffusive dynamics with mechanical equilibrium constraint. Skogvoll et al. (2021b).

Publications in highlight

Skogvoll, V., Skaugen, A., & Angheluta, L. (2021a). Stress in ordered systems: Ginzburg-Landau type density field theory. *Physical Reviews B* 103, 224107.

Skogvoll, Vidar; Angheluta, Luiza; Skaugen, Audun; Salvalaglio, Marco; Vinals, Jorge (2021b). A phase field crystal theory of the kinematics and dynamics of dislocation lines. In review *arXiv*:2110.03476

Skogvoll, V., Skaugen, A., Angheluta, L., & Viñals, J. (2021c). Dislocation nucleation in the phase-field crystal model. *Physical Review B*, 103(1), 014107.

Rabbel, O., Palma, O., Mair, K., Galland, O., Spacapan, J. B., & Senger, K. (2021). Fracture networks in shale-hosted igneous intrusions: Processes, distribution and implications for igneous petroleum systems. *Journal of Structural Geology*, 104403.

Peyaud, V., Bouchayer, C., Gagliardini, O., Vincent, C., Gillet-Chaulet, F., Six, D., & Laarman, O. (2020). Numerical modeling of the dynamics of the Mer de Glace glacier, French Alps: comparison with past observations and forecasting of near-future evolution. *The Cryosphere*, 14(11), 3979-3994.

Outreach

titan.uio.no/Teknisk ukeblad: *«Feltarbeidet er grunnlaget for alt det vi geologer gjør»*, 2021

phys.org *«Mathematicians derive the formulas for boundary layer turbulence 100 years after the phenomenon was first formulated»*, 2021

Funding
The Research Council of Norway: Researcher Project for Young Talents (M4, #325819) and Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Gaute Linga[1,2], Knut Jørgen Måløy[2], Eirik Grude Flekkøy[2], François Renard[1], Luiza Angheluta[1], Tanguy Le Borgne[1,3], August Johansson[4], Francesca Watson[4]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) University of Rennes 1, France
4) SINTEF Digital, Norway

Mixing in multiphase flow through microporous media

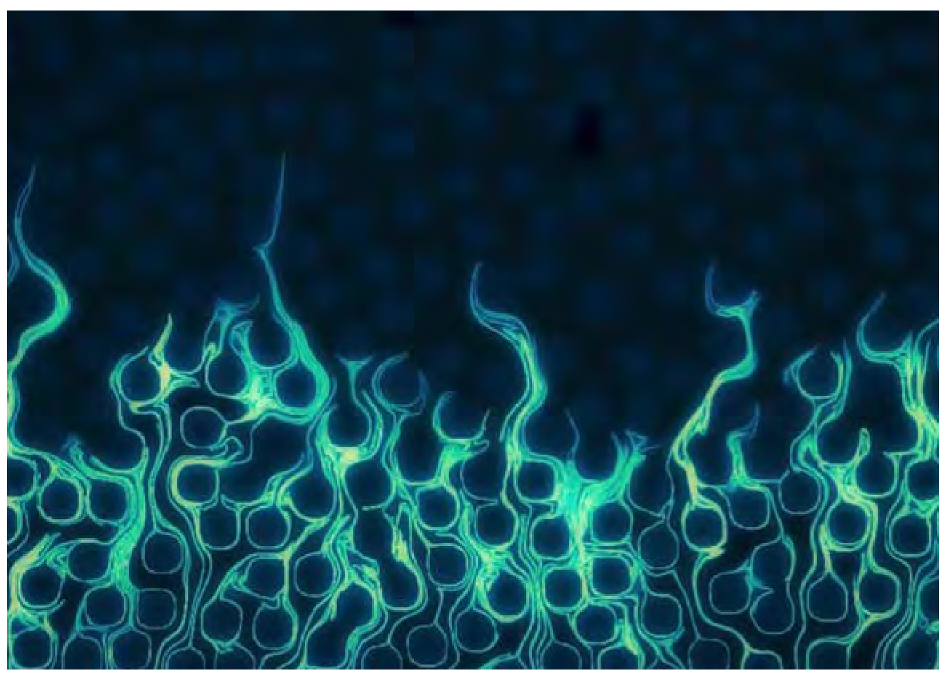
Mixing is the operation by which a system is brought from segregation to uniformity. Solute mixing exerts an important influence on chemical reactions by bringing reactants in contact. It thus controls processes across a wide range of natural and industrial porous systems; from CO2 sequestration in deep aquifers, to drug delivery in the human body. Despite its ubiquity, very 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 goal of this project (abbreviated 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.

The project addresses four main research questions:

- How can we simulate mixing in microscale multiphase flow?
- How can we quantitatively image solute mixing in multiphase flow?
- How do spatial and temporal frequencies interact and influence mixing during multiphase flow in porous media?
- Can novel concepts of mixing in porous media be used to design geo-inspired microfluidic mixers?

M4 takes an interdisciplinary approach combining the theoretical, numerical and experimental strengths of the project partners: The multiphase flow expertise (UiO) will be combined with the expertise on solute mixing (UdR) with a perspective to microfluidics (SINTEF). We develop numerical methods for highly accurate simulation of mixing in multiphase flows, and we will design and execute novel experiments imaging solute mixing in 3D porous media. The numerical and experimental breakthroughs fuel the development of a theoretical framework describing mixing in multiphase flow.

Evidence of chaotic mixing in a simulated two-phase flow through a porous medium consisting of randomly arranged cylindrical obstacles. A strip of solute (light colour) is elongated exponentially in time by a net upward flow. The two fluid phases can be distinguished as the two dark shades filling the space between the obstacles.



Production in highlight

Mathiesen, J., Linga, G., Misztal, M., Renard, F., Le Borgne, T., (2021). Enhanced dispersion in intermittent multiphase flow. *arXiv*:2109.10985

Funding
University of Oslo

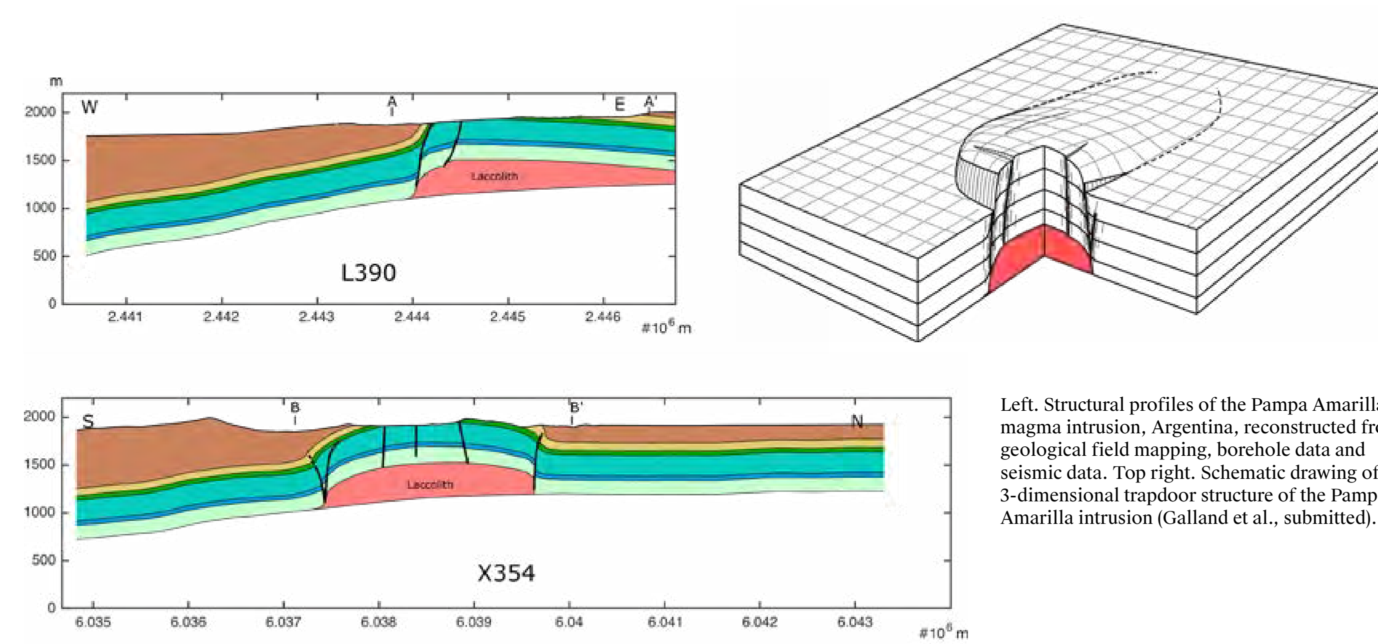
Participants
Olivier Galland[1], Guldstrand, F.[1], Bertelsen, H.[1], Schmiedel, T.[1], Burchardt, S.[2], Sigmundsson, F.[3], Poppe, S.[4]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) Department of Earth Sciences, University of Uppsala, Sweden
3) Institue of Earth Sciences, University of Iceland, Iceland
4) Vrije Universiteit, Belgium

Magma emplacement mechanics in volcanic plumbing systems

The mechanics of magma emplacement and transport in the Earth's crust is on principle a relatively simple system: it corresponds to the coupled viscous flow of a magma and deformation of the rocks it flows through. However, the complexity arises when considering the mechanical properties of the magma and host rock: the magma viscosities span up to 10 orders of magnitude and magma rheology can be strongly non-linear, and conversely, rocks can deform and fail under multitude modes (elastic, plastic, tensile, shear, ductile, flow etc). Our general understanding of such systems relies on simplified systems that account for strong assumptions, but we are far from approaching the natural complexity that governs magma emplacement and the dynamics of volcanic plumbing systems.

The aim of this project is to integrate multi-disciplinary research in order to reveal the complex physics governing magma emplacement. In particular, we integrate geological observations at world-class field case studies, results of laboratory models, numerical models and even theoretical models.



Left. Structural profiles of the Pampa Amarilla magma intrusion, Argentina, reconstructed from geological field mapping, borehole data and seismic data. Top right. Schematic drawing of the 3-dimensional trapdoor structure of the Pampa Amarilla intrusion (Galland et al., submitted).

Production in highlight

Galland, O., de la Cal, H., Mescua, J., Rabbel, O. 3-dimensional trapdoor structure of laccolith-induced doming, Pampa Amarilla laccolith, Mendoza Province, Argentina. Submitted to *Tectonophysics*.

Bertelsen, H. S., Guldstrand, F., Sigmundsson, F., Pedersen, R., Mair, K., & Galland, O. (2021). Beyond elasticity: Are Coulomb properties of the Earth's crust important for volcano geodesy?. *Journal of Volcanology and Geothermal Research*, 410, 107153.

Mattsson, T., Petri, B., Almqvist, B., McCarthy, W., Burchardt, S., Palma, J. O., ... & Galland, O. (2021). Decrypting magnetic fabrics (AMS, AARM, AIRM) through the analysis of mineral shape fabrics and distribution anisotropy. *Journal of Geophysical Research: Solid Earth*, e2021JB021895.

Poppe, S., Holohan, E. P., Rudolf, M., Rosenau, M., Galland, O., Delcamp, A., & Kervyn, M. (2021). Mechanical properties of quartz sand and gypsum powder (plaster) mixtures: Implications for laboratory model analogues for the Earth's upper crust. *Tectonophysics*, 814, 228976.

Schmiedel, T., Burchardt, S., Mattsson, T., Guldstrand, F., Galland, O., Palma, J. O., & Skogby, H. (2021). Emplacement and Segment Geometry of Large, High-Viscosity Magmatic Sheets. *Minerals*, 11(10), 1113.

Funding
Equinor and the University of Oslo (AKADEMIA-project MODIFLOW)

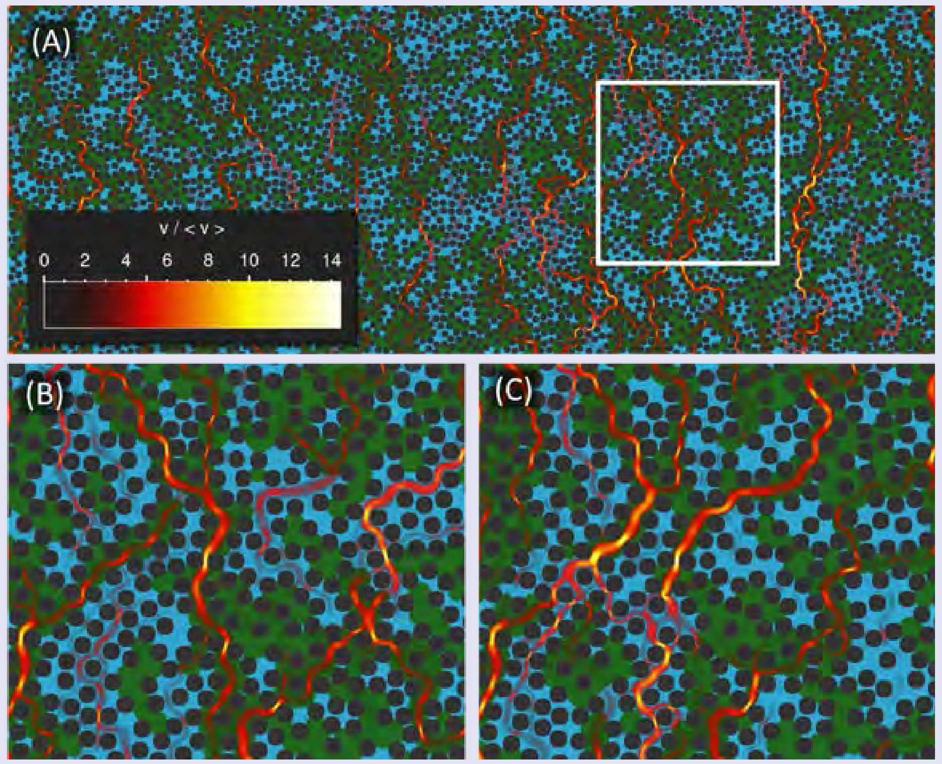
Participants
Gaute Linga[1,2], Fabian Barras[1], François Renard[1], Bjørn Jamtveit[1], Joachim Mathiesen[1,3], Tanguy Le Borgne[1,4]

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

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 the fault and reservoir scales.

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 2D numerical simulations of solute transport in immiscible two-fluid flow.



Modelling of dispersion in multiphase fluid flow in porous media. Two fluids (blue has properties of water, green has properties of oil) flow together in a porous medium (black circles). The yellow to red colours indicate the fluid velocity. A) Full view of the simulation domain. B-C) Snapshots of fluid flow at two different time steps, demonstrating the intermittency of the flow. This intermittency enhances solute dispersion.

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.

Finally, this project also investigates fluid flow at larger scales where anthropogenic injection can reactivate existing crustal faults and induce detrimental seismicity. In this context, a collaboration with researchers from Ecole Polytechnique Fédérale de Lausanne conducting rock friction experiments shed new light on the fluid-induced reactivation of faults and the characteristics of the resulting frictional rupture (slow events versus fast and violent ruptures).

Production in highlight

Mathiesen, J., Linga, G., Misztal, M., Renard, F., & Borgne, T. L. (2021). Enhanced dispersion in intermittent multiphase flow. *arXiv preprint arXiv:*2109.10985.

Funding
The Research Council of Norway (project PoreFlow #301132).

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

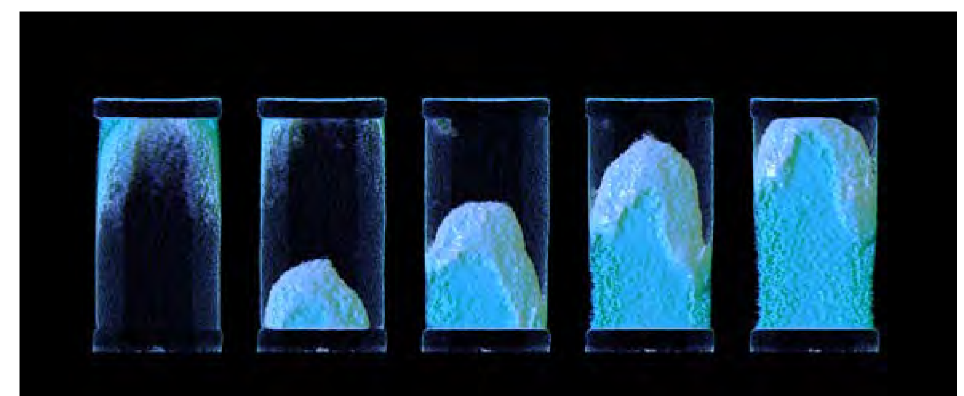
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) Faculty of Civil Engineering and Geosciences, Department of Geoscience and Engineering, TU Delft, Netherlands
3) Univ. Grenoble Alpes, 3SR, F-38000 Grenoble, France
4) Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland
5) Institute of 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 cement in boreholes. In the framework of the projects ARGUS and PoreFlow, 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 2021, we obtained 2 days at ILL and 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.

In the project ARGUS, we investigated the transport of cadmium in porous rocks. Cadmium is a resilient heavy metal that is among the top six pollutants worldwide. We used in-situ neutron imaging of Cd-doped flow experiments in limestone and sandstone samples. These experiments help us to quantify the retention and sorption mechanisms of cadmium in rocks leading to better risk preparedness and hazardous waste treatment.

The PoreFlow project is a collaboration with the group of Dag Breiby at NTNU in Trondheim. 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.



Time-lapse of water injection inside a sandstone core sample imaged with neutron microtomography.

Production in highlight

Renard, F. (2021) Using large instruments to study flow and fractures in rocks. 5th *Cargèse summer school on Flow and Transport in Porous and Fractured Media*, July 20-31 2021, Cargèse, France.

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Ivar S. Haugerud[2,3], Gaute Linga[1,2], Eirik Grude Flekkøy[2]

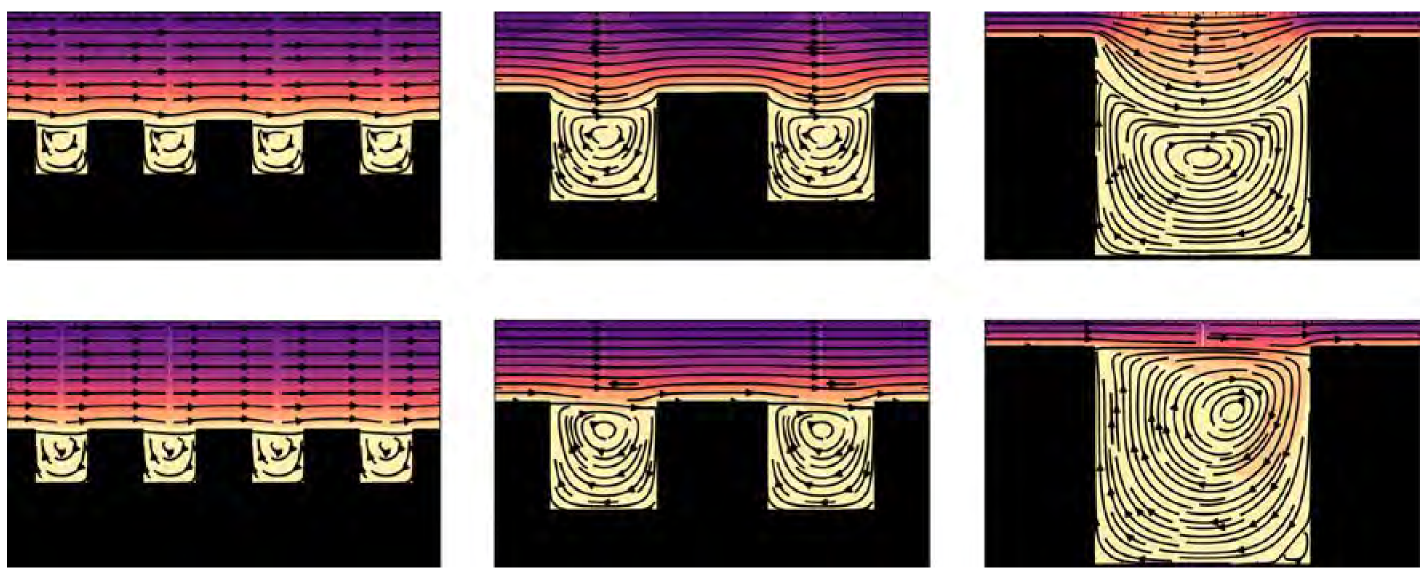
Affiliation
1) The Njord Centre, University of Oslo, Norway
2) PoreLab, The Njord Centre, University of Oslo, Norway
3) Universität Augsburg, Germany

Taylor dispersion in rough channels

Since the original work of Taylor, the notion of an effective diffusion has proven to be extremely useful. His theory and extensions thereof have become the standard for estimating the spreading in systems ranging from transport in blood and groundwater systems, sugar transport in plants, and the still relevant dispersion of airborne droplets for spreading in disease transmission. In Taylor's and Aris' approach the flow field is assumed to be axially invariant, however, most channels and pores in natural and industrial systems are not perfectly flat.

Despite the ubiquity of rough surfaces and high-inertia flows, it is unclear exactly how fluid flow, especially with high inertia, will interplay with the discontinuous boundary roughness to influence the effective diffusion.

In order to understand this, we systematically investigate how a periodic discontinuous rough square boundary, illustrated in the figure, influences the effective diffusion of a passive solute in two-dimensional channel flows. The investigation of this research question is mainly numerical, using the finite element method. The goal is to find and understand the effective diffusion coefficient's dependency on the boundary.



An illustration of the periodic flow field for three different boundary amplitudes. The top row is found for creeping flow, while the bottom row has a higher Reynolds number, producing larger recirculation zones.

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Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

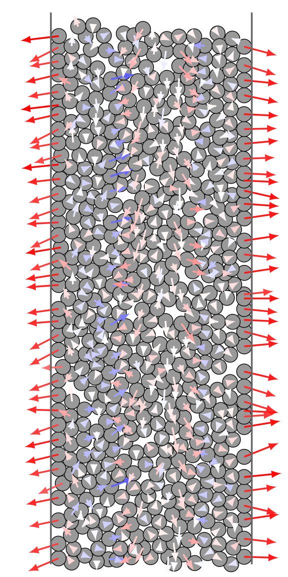
Participants
Louison Thorens[1,2], Knut Jørgen Måløy[1], Mickael Bourgoin[2], Stephane Santucci[2], Eirik Grude Flekkøy[1]

Affiliation
1) PoreLab, The Njord Centre, University of Oslo, Norway
2) University of Lyon, ENS de Lyon, Université Claude Bernard, CNRS, Laboratoire de Physique, France

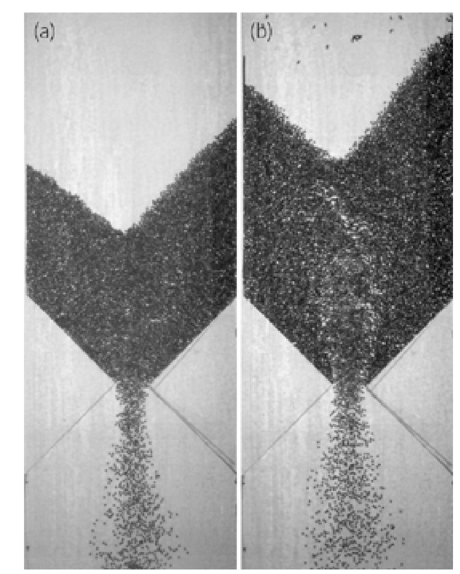
Tunable interactions inside deformable porous media

Interactions between grains are known to affect the shape and the behavior of a granular assembly. We propose to use ferromagnetic grains (typically steel), which acquire a magnetic momentum under the influence of an external magnetic field, leading to grain/grain interactions inside the medium.

First, we highlighted the existence of a novel tunable magnetic Janssen effect in a static grain column (fig. 1) where we can control the pressure exerted on the walls even for a mixture of ferromagnetic and non-ferromagnetic particles [1-2]. Second, based on the static observations of a ferromagnetic granular medium, we propose to look at a classical granular dynamic system: the discharge of a silo. Based on the observations of [3], we study a magnetic hourglass (fig. 2) where we highlight the apparition of a stick-slip behavior during the discharge [4]. Finally, we investigate the bulldozing experiment previously discussed by [5] where a bead/liquid mixture is slowly sucked out of confined geometry. Based on our results on ferromagnetic granular physics, we intend to control the apparition of the bulldozing instability (fig. 3) and its resulting pattern.



Local forces in a magnetic Janssen configuration.



Discharge of a 2D-silo without magnetic field (a), and with a strong magnetic field normal to the plain (b).

Trigger of the bulldozing instability using ferromagnetic interactions.

Production in highlight

Thorens, L., Måløy, K. J., Bourgoin, M., & Santucci, S. (2021). Magnetic Janssen effect. *Nature communications*, 12(1), 1-6.

Thorens, L., Måløy, K. J., Bourgoin, M., & Santucci, S. (2021). Taming the Janssen effect. In *EPJ Web of Conferences* (Vol. 249, p. 08004). *EDP Sciences*.

Lumay, G., & Vandewalle, N. (2008). Controlled flow of smart powders. *Physical Review E*, 78(6), 061302.

Thorens, L., Viallet, M., Måløy, K. J., Bourgoin, M., & Santucci, S. (2021). Discharge of a 2D magnetic silo. In *EPJ Web of Conferences* (Vol. 249, p. 03017). EDP Sciences.

Dumazer, G., Sandnes, B., Ayaz, M., Måløy, K. J., & Flekkøy, E. G. (2016). Frictional fluid dynamics and plug formation in multiphase millifluidic flow. *Physical review letters*, 117(2), 028002.

PoreLab
NTNU-UiO Porous Media Laboratory

Chapter 3 | Part 2

Mechano-Bio-Chemical Processes Across Scales

1. Active Brownian particles moving through disordered environments
2. Collisional Orogeny in the Scandinavian Caledonides
3. Hot geothermal systems around shallow magma bodies
4. Lower Cretaceous magmatism in Svalbard
5. Molecular dynamics simulations of nanoscale geological processes
6. Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity.
7. Structural and Metamorphic Transformation Processes in the Lower Continental Crust and Upper Mantle

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Kristian Stølevik Olsen[1], Luiza Angheluta[2], Eirik Grude Flekkøy[1]

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

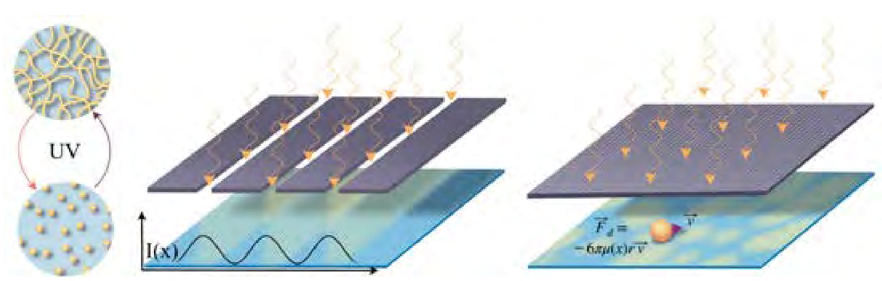
Active Brownian particles moving through disordered environments

Disordered media are ubiquitous in systems where self-propelled particles are present. In biological settings examples include soil-dwelling bacteria that navigate porous media as well as cell migration in the extracellular matrix. Self-propelled motion in the presence of disorder can also be found in synthetic situations, like in active microfluidic devices.

Here we investigate the behavior of active Brownian particles that have an internal energy depot and move through a landscape with a quenched frictional disorder. We consider the cases of very fast internal relaxation processes and the limit of strong disorder. Using a linear stability analysis we identify the characteristic timescale over which the particle relaxes to a constant speed, assuming a slowly varying frictional disorder. While most minimal models for active particles assume a constant self-propulsion speed we have here showed that the speed has an inverse square-root dependence on the local value of the drag coefficient for rapid internal relaxation. Analytical calculations of the mean-square displacement in this fast-relaxation approximation is shown to agree well with numerically integrated energy depot dynamics and predict normal dispersion for bounded drag coefficient and anomalous dispersion for power-law dependence of the drag on spatial coordinates.

In the strongly disordered regime the particle experiences a frictional disorder that changes faster than the typical internal relaxation timescale. In this limit the speed shows a seemingly chaotic behavior which is not trivially predicted from the quenched disorder. In this case the self-propulsion speed can, for practical purposes, be considered a fluctuating quantity. Distributions of self-propulsion speeds are investigated numerically for different parameter choices.

The project sheds light on active motion in disordered media with many potential extensions. For example, the effect of quenched frictional disorder on the collective behavior of active particles remains largely unexplored. Another avenue pf exploration would be to include also rotational drag which may be relevant for realistic motion of finite-size particles in complex media.



Sketch of a setup where light can be used to control and design viscosity patterns in photo-rheological fluids. Such fluids typically have a polymeric suspension where the degree of entanglement in the polymeric network can be altered with UV light. Such setups can be used to optically control active or passive particles by strategically selecting appropriate optical filters, leading to a distribution of light intensities. Small spherical particles moving in such quasi-2D fluid environments experience an inhomogeneous Stokesian drag, as depicted in the rightmost figure.

Production in highlight

Olsen, K. S., Angheluta, L., & Flekkøy, E. G. (2021). Active Brownian particles moving through disordered landscapes. *Soft Matter*, 17(8), 2151-2157.

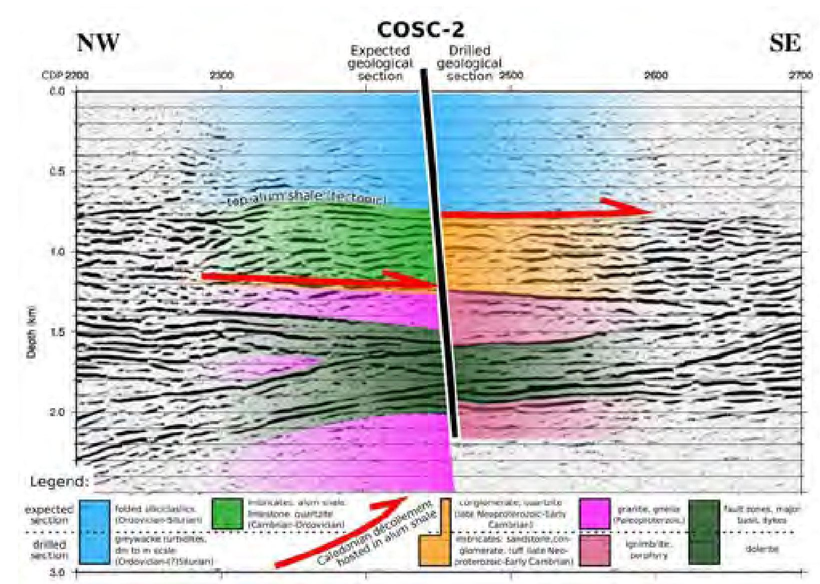
Funding
International Continental Scientific Drilling Program (ICDP)

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, Norway

Collisional Orogeny in the Scandinavian Caledonides

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 2022. The sampling party will take place in March 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., under review).

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

Production in highlights

Lorenz H., et al. (incl. Menegon L.). COSC-2 – drilling the basal décollement and underlying margin of paleocontinent Baltica in the Paleozoic Caledonide orogen of Scandinavia. *Scientific Drilling*. Under review.

Funding
University of Oslo

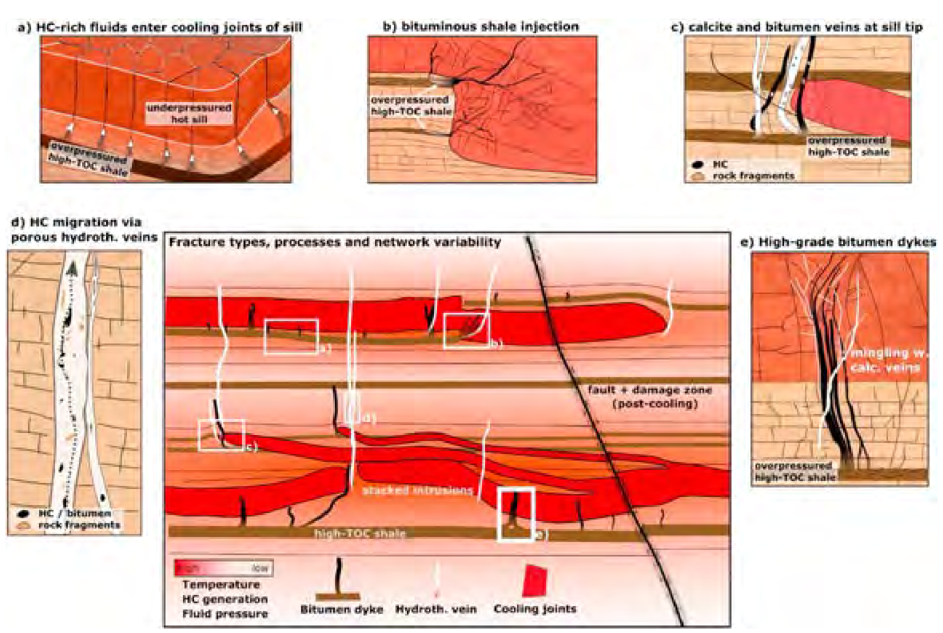
Participants
Olivier Galland[1], Ole Rabbel[1], Karen Mair[1], Dougal Jerram[2]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) CEED, University of Oslo, Norway/DougalEarth, UK

Hot geothermal systems around shallow magma bodies

Magma emplacement in the crust brings an immense amount of heat that can deeply transform the host rock of the magma and mobilize aqueous fluids. The geothermal effects of magma intrusions depend greatly on the chemistry of the magma itself and on the lithology and fluid content of the host rock. The geothermal implications of igneous intrusions include maturation of organic-rich shale to form hydrocarbons, supercritical geothermal systems, metamorphic reactions and ore formations.

The aim of this project is to reveal the mechanical and chemical processes at work in high-temperature geothermal systems. Currently, we are mainly addressing the effects of igneous intrusions on hydrocarbons formation and migration.



Schematic summary of fracture types, underlying mechanisms and fracture network variations interpreted from field evidence presented in this paper. Central image visualizes the large-scale features, including intrusion architecture and its relation to spatial fracture network variations. Insets (a–f) highlight specific fracture types and potential implications for igneous reservoirs. (Rabbel et al., 2021)

Production in highlight

Rabbel, O., Palma, O., Mair, K., Galland, O., Spacapan, J. B., & Senger, K. (2021). Fracture networks in shale-hosted igneous intrusions: Processes, distribution and implications for igneous petroleum systems. *Journal of Structural Geology*, 104403.

Rabbel, O., Galerne, C., Hasenclever, J., Galland, O., Mair, K., Palma, O. Impact of permeability evolution in igneous sills on hydrothermal flow in volcanic sedimentary basins. Earth and *Olanetary Science Letters*, submitted.

Galland, O., Villar, H., Mescua, J., Augland, L. E., Jerram, J., Medialdea, A., Midtkandal, I., Palma, O., Planke, S., Zanella, A. The Volcanic legacy on fluid migration - An exceptional example of bitumen seep around a subvlcanic intrusion, Argentina. In preparation.

Funding
The Research Council of Norway
Arctic Field Grant (#322464)

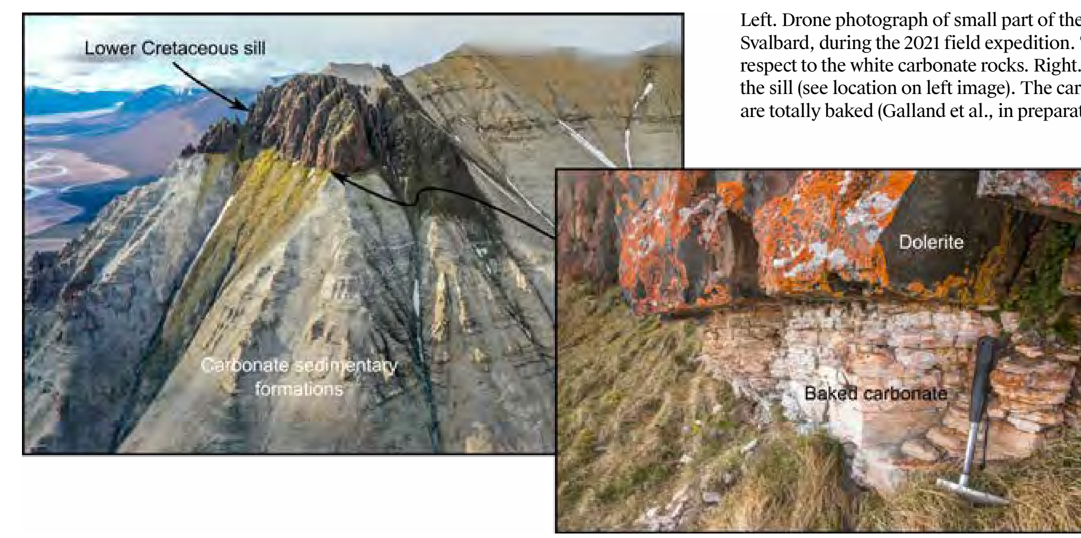
Participants
Olivier Galland[1], Hans Jørgen Kjøll[2], Kim Senger[3]

Affiliation
1) The Njord Centre, University of Oslo, Norway
2) Department of Geosciences, University of Oslo, Norway
3) UNIS, Svalbard

Lower Cretaceous magmatism in Svalbard

Svalbard has been affected by voluminous volcanism during Lower Cretaceous. This magmatic event formed the High Arctic Large Igneous Province (HALIP) and had a major impact on the tectono- stratigraphic evolution of the region. The aim of the project is to conduct field expeditions in Svalbard to obtain an extensive and regionally significant understanding of the distribution, timing and emplacement mechanisms of the Lower Cretaceous magmatism in Svalbard, in particular the plumbing system in the forms of dykes and sills. Of particular interest is whether (1) host rocks of distinct lithologies and mechanical properties affected the emplacement of magma, and conversely (2) contact metamorphism is dependent on the lithology of the host rock. This second point is crucial for quantifying how much greenhouse gases were liberated during the process, and so for assessing whether the HALIP volcanism had global impact on the Earth's climate.

We conducted a large-scale mapping and data collection of the volcanic exposed at the surface as well as a data compilation of subsurface volcanic rocks documented on seismic data and borehole data. In addition, during the last three Summers, we have conducted several field expeditions to perform detailed mapping of spectacularly exposed igneous sills.



Left. Drone photograph of small part of the studied igneous sill in Dicksonland, Svalbard, during the 2021 field expedition. The dark rocks stand out very out with respect to the white carbonate rocks. Right. Field photograph of the bottom contact of the sill (see location on left image). The carbonate in contact with the magmatic rocks are totally baked (Galland et al., in preparation).

Production in highlights

Senger, K., Betlem, P., Birchall, T., Buckley, S.J., Coakley, B., Eide, C.H., Flaig, P.P., Forien, M., Galland, O., Gonzaga, L., Jensen, M., Kurz, T., Lecomte, I., Mair, K. et al. (2021). Using digital outcrops to make the high Arctic more accessible through the Svalbox database. *Journal of Geoscience Education* 69, 123-137.

Senger, K., Galland, O. Early Cretaceous magmatism in central Spitsbergen: stratigraphic and spatial extent. *G3*. Submitted.

Galland, O., Kjøll, H. J., Horota, R., Runge, J., Senger, K. 3-dimensional structure of large mafic sills: the case study of Dicksonland, Central Spitsbergen, Svalbard. In preparation.

Funding
University of Oslo and EU Horizon 2020 MSCA CoFund (CompSci)

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

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

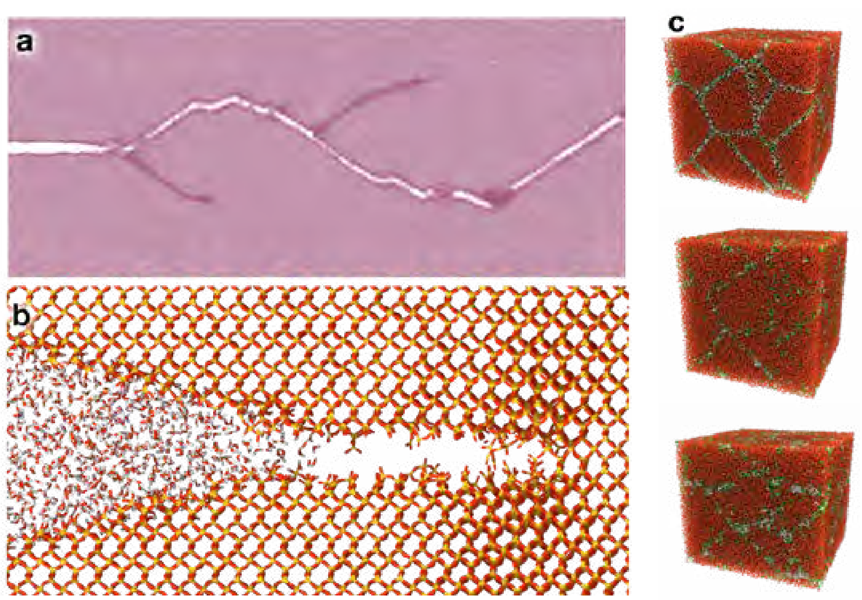
Molecular dynamics simulations of nanoscale geological processes

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 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. 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 indicating that the grain size dependence is different at lower stresses, and we are investigating the mechanisms behind this difference.



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., Hafreager, A., Jamtveit, B., Malthe-Sørenssen, A., & Renard, F. (2021). Molecular dynamics study of confined water in the periclase-brucite system under conditions of reaction-induced fracturing. *Geochimica et Cosmochimica Acta*, 294, 13-27.

Sveinsson, H. A., Ning, F., Cao, P., Fang, B., & Malthe-Sørenssen, A. (2021). Grain-Size-Governed Shear Failure Mechanism of Polycrystalline Methane Hydrates. *The Journal of Physical Chemistry C*, 125(18), 10034-10042.

Funding
The Research Council of Norway Researcher Grant with Mobility (#286733)

Participants
Joanna Dziadkowiec[1,2], Anja Røyne[1], Dag Kristian Dysthe[1], Hsiu-Wei Cheng[2], 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, electrochemical reactions, friction and reactivity.

Solid-solid interfaces are usually the weakest regions within granular rocks and materials. Nanoscale spaces conserved between contacting grains are often the only remaining pathways for fluid migration. These percolating fluids can progressively weaken the initially cohesive granular contacts. In this project, we explore mineral contacts and seek robust treatments that can improve intergranular adhesion.

Our nanoscale approach is based on the surface forces apparatus (SFA) and atomic force microscope (AFM). Both experimental techniques can measure nanometer to micrometer-ranged surface forces acting between two solid surfaces. By measuring adhesive and repulsive forces, we can infer how strong are mineral contacts while varying the composition of aqueous solutions in contact with the surfaces or by adding mineral consolidants that provide adhesion.

We show that nanoscale adhesive forces acting between mineral surfaces are ion-specific. They depend not only on the properties of the surfaces and solution ionic strength but also on the ion-specific hydration properties of dissolved ions [1]. However, most often adhesion between surfaces cannot be significantly enhanced by adjusting solution composition. Here, we can obtain stronger effects when using consolidants such as silica nanoparticles. Such additives are injected in a colloidal form into a porous space of granular rock, and glue mineral grains together. We show that this effect strongly depends on silica nanoparticle size [2]. Last, we use SFA to explore cohesion in cementitious materials. Here, the hydrating calcium silicate can induce strong adhesion between grains. Our results indicate that the adhesive properties can be largely attributed to the soft, gel-like nature of the precipitating calcium silicate hydrate nanoplatelets [3].

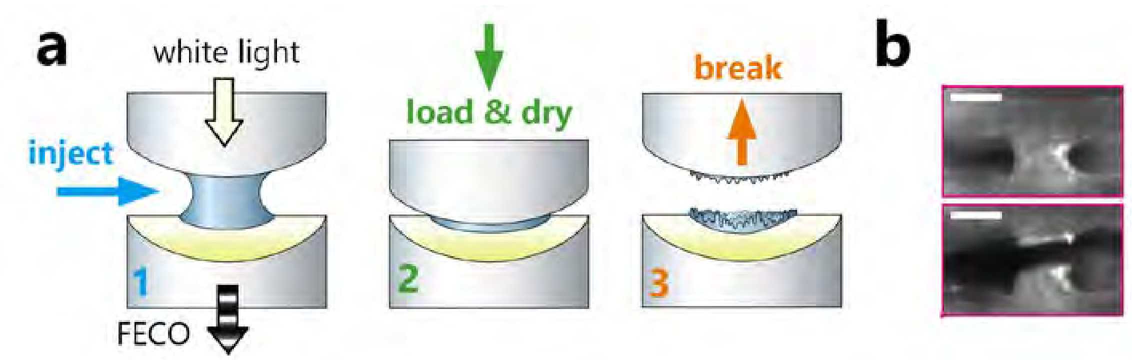


Figure 1. a) SFA setup adapted to study mechanical strength of colloidal silica nanoconsolidants; b) snapshots of a tensile strength SFA test, showing an intact and a broken cured silica bridge.

Production in highlights

Dziadkowiec, J., Ban, M., Javadi, S., Jamtveit, B., & Røyne, A. (2021). Ca2+ Ions Decrease Adhesion between Two (104) Calcite Surfaces as Probed by Atomic Force Microscopy. *ACS Earth and Space Chemistry*, 5(10), 2827-2838.

Dziadkowiec, J., Cheng, H.-W., Ludwig, M., Ban, M., Tausendpfund, T. P., von Klitzing, R., Mezger M., Valtiner, M. (2021). Cohesion gain induced by nanosilica consolidants for monumental stone restoration. Under review.

Liberto, T., Nenning, A., Bellotto, M., Dalconi, C., Dworschak, D., Kalchgruber, L., Robisson, A., Valtiner M., Dziadkowiec, J. (2021). Resolving early stage cohesion in cementitious systems due to calcium silicate hydration. Under preparation.

Funding
European Research Council Advanced Grant (DIME), UK Natural Environment Research Council

Participants
Bjørn Jamtveit[1], Claire Aupart[1], Lucy Campbell[2], Kristina Dunkel[1], Sarah Incel[1], Arianne Petley-Ragan[1], Xin Zhong[1], Håkon Austrheim[1], Benoit Cordonnier[1], Luca Menegon[1], François Renard[1], and numerous international collaborators.

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

Structural and Metamorphic Transformation Processes in the Lower Continental Crust and Upper Mantle

When continents collide the evolution of the mountain chain that forms during the associated Orogeny (=mountain-building event) is to a first order affected by the density and rheology of the lower crust. Prior to the collision, the lower crust will in most cases be characterized by dry and strong rocks. However, during the progress of the collision, the properties of the lower crust may change as a result of strutural and metamorphic transformation processes. Many of these are strongly affected by the presence or absence of fluids, and may lead both to densification and weakening. Dry rocks are non-porous and generally more or less impermeable to fluids. Introduction of fluids to such rocks is often associated with fracturing driven by earthquakes. Sometimes, earthquakes also happen without the introduction of fluids. The goal of this project is to understand the coupling of earthquakes, fluid migration, metamorphic reactions and structural transformation processes in the lower crust. To do this we carry out field-studies both in Norway (Bergen Arcs and Lofoten) and abroad (Western Alps).

The structural transformations that the lower crust experiences during earthquake cycles are preserved in the geological record in the form of pristine pseudotachylytes (solidified quenched frictional melt produced during coseismic slip, Figure 1) and mylonitised pseudotachylytes, which form by solid-state viscous creep during the postsesimic and interseismic periods. The generation of earthquakes (and, thus, of pseudotachylytes) in the lower crust is an intensely debated issue, as it requires mechanisms capable of developing, at least transiently, very high differential stresses.

Our studies of wall rock microstrutures demonstrate that earthquakes in the lower crust form by dynamic rupture, i.e. brittle deformation. This is in contrast to most models of lower crustal deformation, which assume that the lower crust is weak and only deforms in ductile manners. Brittle deformation at lower crustal depths require very high stresses and may be linked to stress pulses generated by large earthquakes at shallower levels in the crust. Our field work in Lofoten has also proposed a new model for the generation of transient high stresses. In this model, the source for the transient high stresses is local (deep), and is the result of localised stress amplification in dry and strong materials generated at the contacts with weak ductile shear zones (Figure 2). An alternative proposal to brittle rupture for the generation of deep pseudotachylytes has been thermo-mechanical runaway, where thermal feedback in highly localised ductile shear zones leads to rapid slip and melting. However, our work has highlighted that unambiguous microstructural evidence for this process is still missing.

Seismic slip rates on faults, however, require a co-seismic weakening mechanism. Using novel Raman spectroscopic methods, we have demonstrated that frictional melts that form during lower crustal earthquakes can develop very high pressure (overpressure) and hence reduce the frictional strength of the earthquake faults.

In a releated project, we study how earthquakes may allow seawater into the mantle part of oceanic lithosphere and cause serpentinization and major changes in its petrophysical properties. This is partly based on studies of drill cores obtained through the Oman Continental Drilling Project.

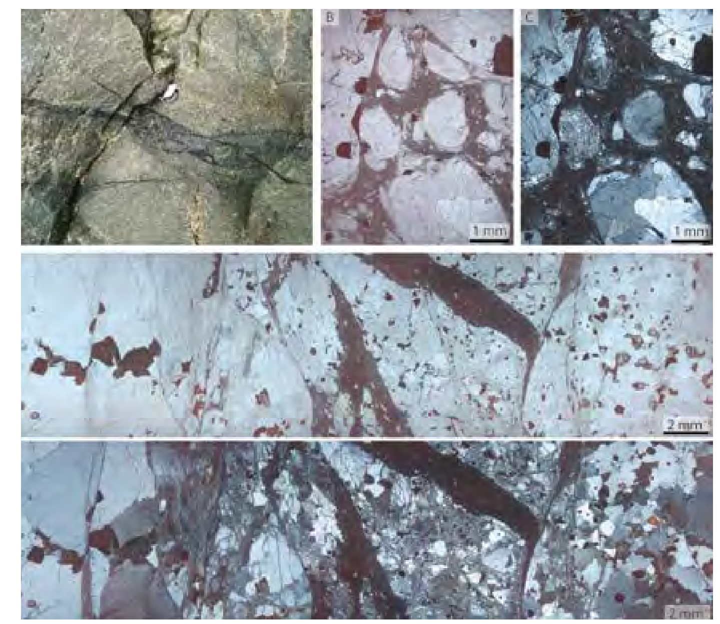


Figure 1. Dry Pseudotachylyte in amphibole-bearing paragneiss. Optical micrographs in plane polarized (a) and cross polarized (b) light showing a pseudotachylyte that juxtaposes pyroxene and amphibole-rich (bottom) and poor (top) host rock. There is no alteration zone around the pseudotachylyte. c) Backscatter electron image of the pseudotachylyte cutting pyroxene grains that exhibit alteration rims of amphibole. The pseudotachylyte contains a fine-grained mixture of plagioclase and pyroxene, some larger, slightly strained plagioclase clasts, and dendritic garnet with euhedral overgrowths. d) Optical micrograph (plane polarized light) of a pseudotachylyte containing numerous clasts of plagioclase (white), pyroxene (pale green) and amphibole (greenish brown).

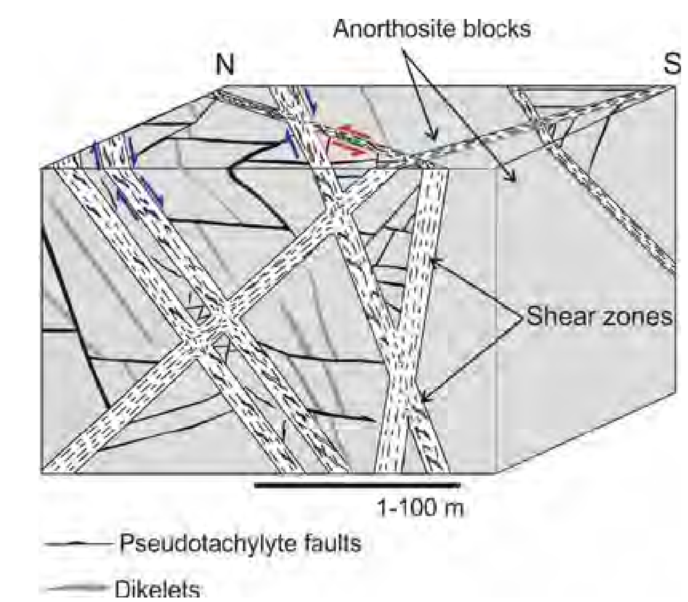


Figure 2. Block diagram showing the conceptual model for pseudotachylyte generation during lower crustal earthquakes by local stress amplification in volumes of dry and strong lower crustal rocks (anorthosites, in grey) bounded by weak ductile shear zones (in white with black dashes). The model is based on field observations from Nusfjord, Lofoten.

Production in highlight

Menegon, L., Campbell, L.R., Mancktelow, N.S., Camacho, A., Papa, S., Toffol, G., Pennacchioni, G., 2021. The earthquake cycle in the dry lower continental crust: insights from two deeply exhumed terranes (Musgrave Ranges, Australia and Lofoten, Norway). *Philosophical Transactions of the Royal Society A*, (invited contribution).

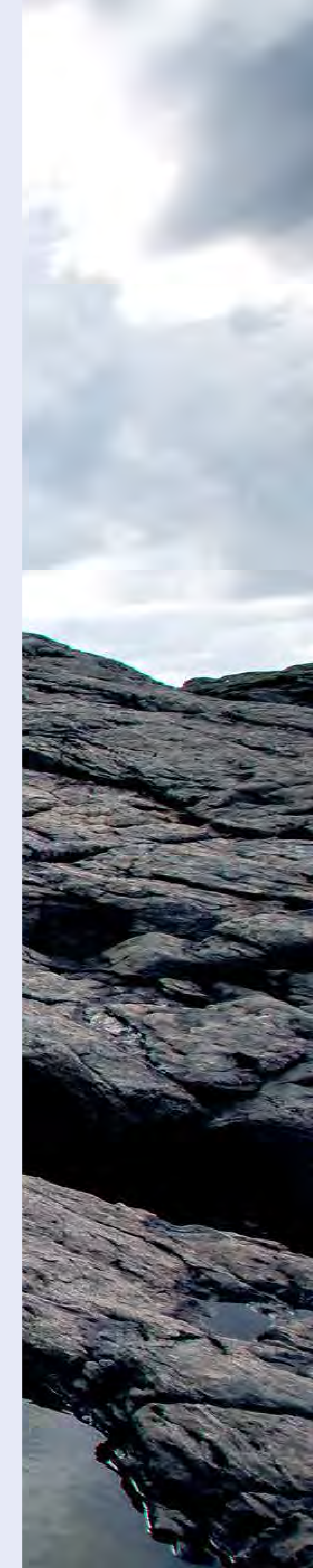
Dunkel, K. G., Morales, L. F. G. & Jamtveit, B. (2021). Pristine microstructures in pseudotachylytes formed in dry lower crust, Lofoten, Norway. "Understanding earthquakes using the geological record", *Philosophical Transactions of the Royal Society A* special issue (Invited contribution) 379, 20190423.

Campbell, L.R., Menegon, L. High stress deformation and short-term thermal pulse preserved in exhumed lower crustal seismogenic faults (Lofoten, Norway). *Journal of Geophysical Research-Solid Earth*, under review.

Chapter 3 | Part 3

Fracture, Friction and Creep

1. Birth, life and death of a frictional rupture
2. Brittle-viscous deformation cycles at the base of the seismogenic crust
3. Break-through rocks
4. Emergent networks: Predicting strain localization and fracture network development
5. Fracture and heat dissipation, from material science to neuroscience
6. History-dependent friction
7. Maturation and fracturing of organic-rich shale during primary migration



Funding
The Research Council of Norway (History Dependent Friction, #287084), The Swiss National Science Foundation

Participants
Fabian Barras[1], Kjetil Thøgersen[1], Einat Aharonov[1, 2], François Renard[1]

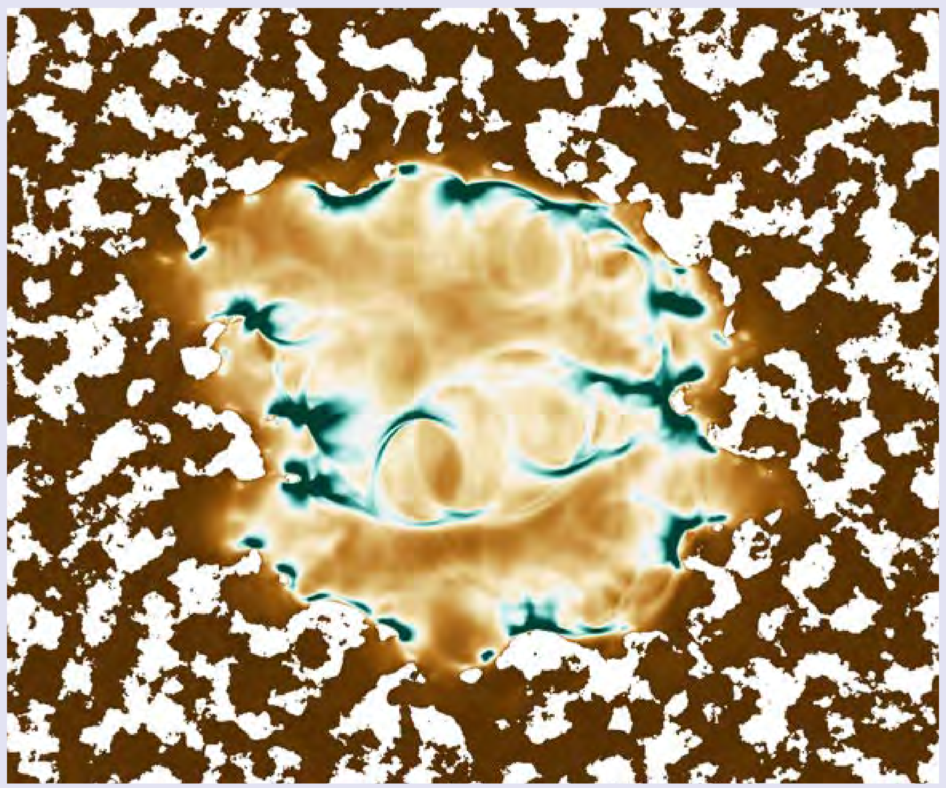
Affiliation
1) The Njord Center, University of Oslo, Norway
2) Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel

Birth, life and death of a frictional rupture

Frictional rupture, the process by which sliding starts between two contacting solids, is at the origin of different processes arising in engineering compounds (e.g. squealing of brake pads) and geological systems (e.g. earthquakes, glacier surges). The challenge of predicting these processes stems from the interplay of system-size rupture propagation with the microscopic and nanoscopic scales where friction originates from the roughness of surfaces and their molecular interactions. The objective of this project is three-fold and consists in the parallel investigation of the birth (nucleation), the life (propagation) and the death (arrest) of frictional rupture.

Two solids come into contact only through the peaks of their rough surfaces. Figure 1 shows a computational simulation of frictional rupture nucleation at the microcontact scale. Shear failure arises either by the ductile deformation of the contacting asperities or through the brittle failure of their apexes. Through numerical simulations, we showed how these two end-member failure scenarios lead to very different values of the static coefficient of friction at the macroscopic scale. Once these microscopic slip fronts have coalesced into a continuous rupture patch, the propagation dynamics becomes similar to the one of a tensile crack fracturing a brittle material. At this intermediate scale, we used the analogy to fracture mechanics to study the energy balance governing rupture propagation in a collaboration with researchers from Ecole Polytechnique Fédérale de Lausanne conducting experiments of frictional ruptures between two blocks of acrylic glass.

Last, we demonstrated how frictional ruptures sufficiently large to interact with the system boundaries allow stable pulse-like propagation solution, a widely-observed rupture mode for earthquakes. Using this postulate of large rupture size, we proposed a one-dimensional equation of motion for pulse-like rupture propagating along crustal faults. Combined to a generic description of friction at the interface, this minimal model allows for describing the parameters governing the arrest of frictional rupture and explaining some universal features of earthquake ruptures observed in nature.



Birthplace of a frictional rupture: Slip fronts (in blue) invade the sparse network of microcontacts (in white) forming the junctions between two contacting surfaces. Shades of brown depict the relative slip velocity between the two surfaces.

Publications in highlights

Thøgersen, K., Aharonov, E., Barras, F., & Renard, F. (2021). Minimal model for the onset of slip pulses in frictional rupture. *Physical Review E*, 103(5), 052802.

Barras, F., Aghababaei, R., & Molinari, J. F. (2021). Onset of sliding across scales: How the contact topography impacts frictional strength. *Physical Review Materials*, 5(2), 023605.

Paglialunga, F., Passelègue, F., Brantut, N., Barras, F., Lebihain, M. & Violay, M. (2021). On the scale dependence in the dynamics of frictional rupture: constant fracture energy versus size-dependent breakdown work. Under review.

Roch, T., Barras, F., Geubelle, P. H., & Molinari, J. F. (2022). cRacklet: a spectral boundary integral method library for interfacial rupture simulation. Journal of Open Source Software, 7(69), 3724.

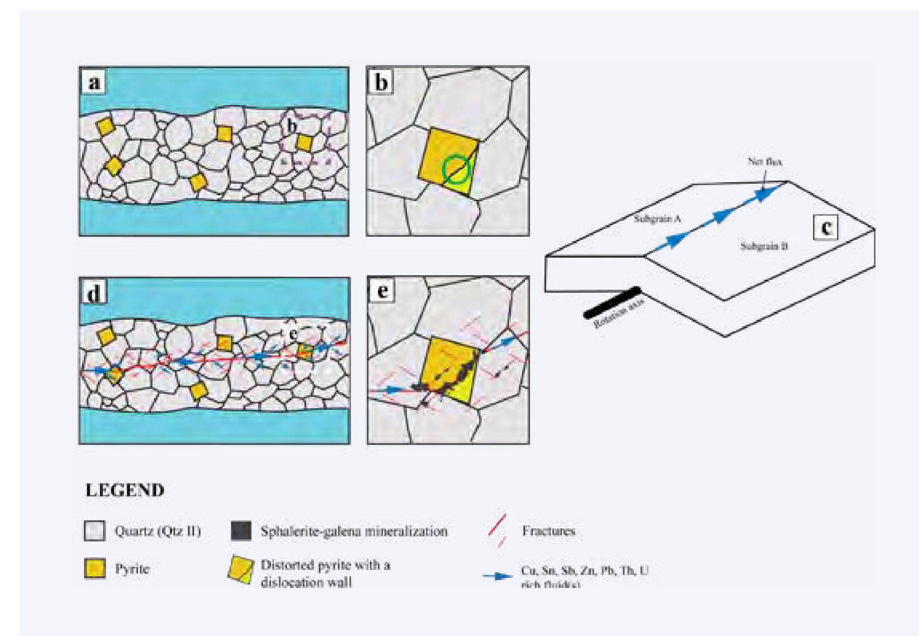
Funding
Posiva Oy (Finland), University of Plymouth (UK), University of Bologna (Italy), University of Oslo

Participants
Luca Menegon[1], Giulio Viola[2], Mark Anderson[3], Paolo Garofalo[2], Jussi Mattila[4], Francesca Prando[3], Barbara Marchesini[2], Åke Fagereng[5]

Affiliation
1) The Njord Center, University of Oslo, Norway
2) University of Bologna, Bologna, Italy
3) University of Plymouth, Plymouth, UK
4) Rock Mechanics Consulting Finland Oy, Vantaa, Finland
5) Cardiff University, Cardiff, UK

Brittle-viscous deformation cycles at the base of the seismogenic crust

Most of continental earthquakes nucleate at the *brittle-viscous transition*, where the strength of crustal rocks is at its maximum. Crustal deformation near the *brittle-viscous transition* involves the competition between fracturing and viscous flow, and a prominent role of variations in fluid pressure is often invoked to explain the mechanics of fault zones at depth. This project uses a network of fault zones that were active across the brittle-viscous transition at 10-15 km of depth and that are now exhumed in south-western Finland. The study area is located in Onkalo, the site of a deep geological repository for high-grade nuclear waste.



Conceptual model of the feedback between grain-scale deformation of pyrite, fluid infiltration and trace element distribution. From Marchesini et al. (2022).

By combining fluid-inclusion studies with trace element distribution in sulphides, and with electron backscatter diffraction (EBSD) analysis of crystal lattice distortion, we found out that: (i) transient fluid overpressure triggered a switch to brittle and seismic fault behavior in the deep, 'ductile' crust, and (ii) Sb, Ag and Sn are the most effective tracers of the intragranular deformation of suplhides accommodated by cracking and plastic lattice distortion. In deformed sulphide aggregates at the brittle-viscous transition, these elements migrate more easily than the other tracers. We are currently investigating the distribution and interconnection of porosity in the fault rocks using Hg-porosimetry combined with x-ray microtomography.

Furthermore, a complementary case-study to Onkalo has focused on the generation of hydraulic gradients by local pressure variations within shear zones. Such gradients are capable of expelling fluids from the shear zone to the host rock, and to trigger brittle deformation in an otherwise viscous deformation regime.

Production in highlights

Marchesini B., Menegon L., Schwarz G., Neff C., Keresztes Schmidt P., Garofalo P.S., Hattendorf B., Günther D., Mattila J., Viola G. (2022). Structural pathways for migration of radionuclides through brittle sulphide-bearing faults: a study from the Olkiluoto deep nuclear waste repository. Journal of *Structural Geology* 154, 104473.

Menegon, L., Fagereng, Å. (2021). Tectonic pressure variations during viscous creep drive fluid flow and brittle failure at the base of the seismogenic zone. *Geology*, 49, p. 1255–1259.

Funding
The European Research Council, Advanced Grant (project BREAK, ERC #101019628)

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

Affiliation
1) The Njord 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. In this project, we will build several experiments that rely on dynamic synchrotron X-ray imaging and ultrasonic monitoring to unravel hidden earthquake physics processes. The project relies on a joint collaboration between the Njord Centre at the University of Oslo and the European Synchrotron Radiation Facility (ESRF). We will design and conduct a suite of experiments to image the slow and fast processes that occur before and during laboratory earthquakes under *in situ* conditions and directly inside the samples.

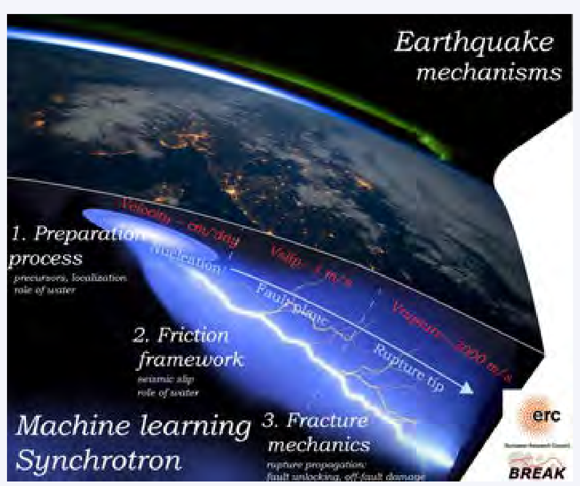
The two main challenges are:

1. Develop a new rock deformation apparatus 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 2021, 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.



The three main components of the project BREAK will allow unraveling of the slow and fast deformation processes that occur before and during laboratory earthquakes.

Production in highlights

Kandula, N., McBeck, J., Cordonnier, B., Weiss, J., Dysthe, D. K., Renard, F. (2021). Synchrotron 4D X-ray imaging reveals strain localization at the onset of system-size failure in porous reservoir rocks. *Pure and Applied Geophysics*, 1-26.

McBeck, J., Cordonnier, B., Renard, F. (2021). The influence of spatial resolution and noise on fracture network properties calculated from X-ray microtomography data. *International Journal of Rock Mechanics and Mining Sciences*, 147, 104922.

Renard, F. (2021). Reaction-induced fracturing: when chemistry breaks rocks. *Journal of Geophysical Research*, 126.

Van Stappen, J. F., McBeck, J. A., Cordonnier, B., Pijnenburg, R.P.J., Renard, F., Spiers, C.J., Hangx, S.J.T. 4D synchrotron X-ray imaging of grain scale deformation mechanisms in a seismogenic gas reservoir sandstone during axial compaction. *Rock Mechanics and Rock Engineering*, in review.

Funding
The Research Council of Norway Researcher Project for Young Talents (Emergent Networks, #300435) and U.S. Department of Energy

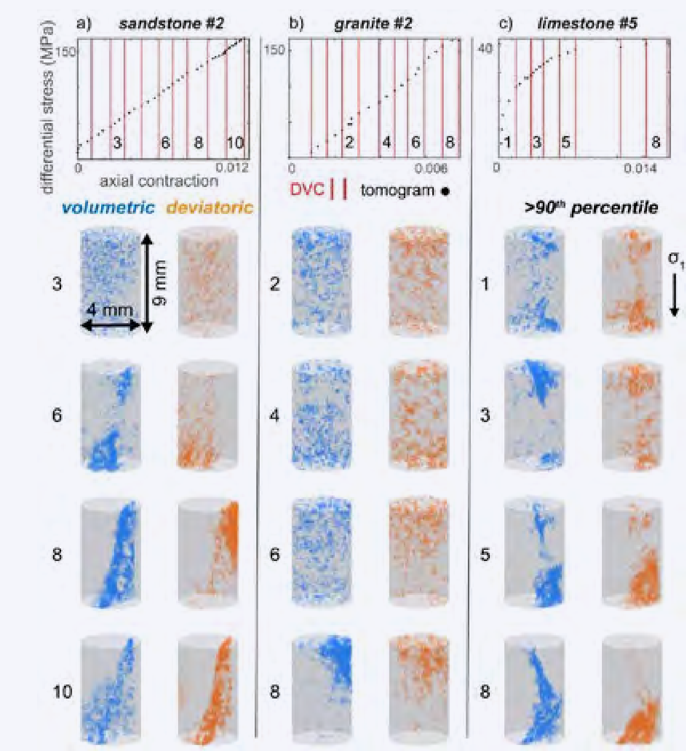
Participants
Jess McBeck[1], François Renard[1], Yehuda Ben-Zion[2], Xiaoyu (Bruce) Zhou[2], John Aiken[1], Joachim Mathiesen[3], Stig-Nicolai Foyn[1], Gabriel Cabrera[1], Chastity Aiken[4]

Affiliation
1) The Njord Center, University of Oslo, Norway
2) University of Southern California and the Southern California Earthquake Center, USA
3) University of Copenhagen, Denmark
4) IFREMER, Plouzane, France

Emergent networks: Predicting strain localization and fracture network development

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.



Strain localization in three types of rocks captured with X-ray synchrotron tomography during triaxial compression. Example snapshots of local incremental strain fields in three experiments: a) sandstone #2, b) granite #2, and c) limestone #5. The first row shows the differential stress-axial strain evolutions for each experiment, including the conditions when we acquired a tomogram (black dots) and the tomogram pairs we used in the DVC analysis (red lines). The numbers in the plots correspond to the numbered cores shown below. The cores show the location of the absolute values of the volumetric (blue) and deviatoric (orange) local incremental strain values that are above the 90th percentile of the population of these respective strain components.

Production in highlights

McBeck, J. A., Zhu, W., & Renard, F. (2021). The competition between fracture nucleation, propagation, and coalescence in dry and water-saturated crystalline rock. *Solid Earth*, 12(2), 375-387.

McBeck, J., Ben-Zion, Y., & Renard, F. (2021). Volumetric and shear strain localization throughout triaxial compression experiments on rocks. *Tectonophysics*, 229181.

McBeck, J. A., Ben-Zion, Y., & Renard, F. (2021). How the force and fracture architectures develop within and around healed fault zones during biaxial loading toward macroscopic failure. *Journal of Structural Geology*, 147, 104329.

McBeck, J., Ben-Zion, Y., & Renard, F. (2021). Fracture Network Localization Preceding Catastrophic Failure in Triaxial Compression Experiments on Rocks. *Frontiers in Earth Science*, 9.

McBeck, J., Aiken, J. M., Cordonnier, B., & Renard, F. (2021) Predicting Fracture Network Development in Crystalline Rocks. *Pure and Applied Geophysics*.

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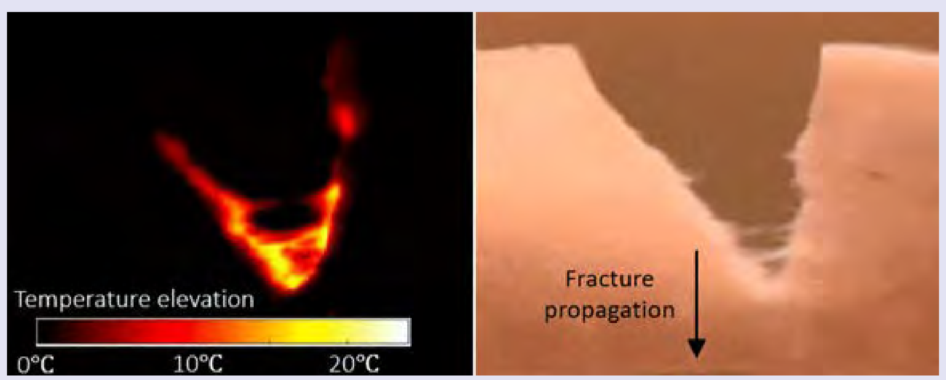
The CNRS (Centre National de la Recherche Scientifique), INSU ALEAS program
The International Research Project France-Norway D-FFRACT
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)
The Lavrentyev Institute of Hydrodynamics, Grant No 14.W03.31.0002

Participants
Tom Vincent-Dospital[1], Renaud Toussaint[1,2], Alain Cochard[2], Stéphane Santucci[3,4], Eirik G. Flekkøy[1] and Knut Jørgen Måløy[1]

Affiliation
[1] Porelab, The Njord Center, University of Oslo, Norway
[2] ITES, University of Strasbourg, France
[3] ENS de Lyon, University Claude Bernard, France
[4] Lavrentyev Institute of Hydrodynamics, Russia

Fracture and heat dissipation, from material science to neuroscience

When fractures propagate in a material, the mechanical energy previously stored in the material deformation is dissipated. A part of this dissipation happens locally, around the fracture tip, in the form of heating. The associated temperature rise allows for large microscopic fluctuations, which allows to pass activation energy barriers and break individual molecules along the crack front. This leads to further fracture advance, reinforcing the release of heat, which is a positive feedback loop. For conditions where this reinforcement is sufficiently strong, it can lead to dramatic jumps in the rupture speed, as the material is thermally weakened.



Infrared (left) and optical (right) pictures of a porcine cutaneous tissue being tear. The heat dissipated during the rupture is enough to trigger the skin thermo-sensitive channels.

Based on these elements, we developed a model coupling mechanics, statistical physics and chemistry. We showed that these elementary ingredients reproduce well the mechanical behaviour of fracture in acrylic glass (PMMA), as well as the one of peeled tapes (i.e. the rupture of polymeric glue), and, more generally, of many brittle materials (Vincent-Dospital et al., 2021a). This also explains features such as fractoluminescence during fast rupture, that is, the emission of visible light from extremely high temperatures – hotter than 1000 °C – in the close vicinity of running crack tips. This model also renders a transition between a brittle and a ductile fracture mode, as observed in the Earth crust, and explains this transition as a critical point (Vincent-Dospital et al., 2020).

We furthermore showed that the heat released around running fractures can also play a role in bio-tissues, and in particular in skin. Indeed, the cutaneous tissue contains various neuronal protein transmitters that may be activated by the transient temperature anomalies around occurring damages. We thus proposed a novel – thermal – process for the generation of mechanical pain and the detection of life-threatening injuries. We demonstrated the relevance of such pain hypothesis both with theoretical studies and with tearing experiments of porcine skin in front of an infrared camera (see illustration) (Vincent-Dospital, 2021b and 2021c).

Finally, in rupture cases where heating should remain negligible (e.g., for cracks that are slow enough), thermal effects are still of high importance in the propagation of fractures. We could indeed explain, with numerical simulations of thermally activated ruptures in disordered interfaces, the morphology of experimental creeping fronts in PMMA, the distribution of local velocities along these fronts, and the avalanche distribution in their dynamics (Vincent-Dospital et al. 2021d).

Publications in highlights

Vincent-Dospital T., Toussaint R., Cochard A., Flekkøy, E. G. and Måløy, K. J. (2021a). Thermal dissipation as both the strength and weakness of matter. A material failure prediction by monitoring creep. *Soft Matter*, 17, 4143-4150.

Vincent-Dospital, T., Toussaint, R. (2021b). Thermo-mechanical pain: the signaling role of heat dissipation in biological tissues. *New Journal of Physics*, 23:023028.

Vincent-Dospital T., Toussaint, R., Måløy, K. J. (2021c). Heat Emitting Damage in Skin: A Thermal Pathway for Mechanical Algesia. *Frontiers in Neuroscience*, 15:780623.

Vincent-Dospital, T., Cochard, A., Santucci, S., Måløy, K. J., Toussaint R. (2021d). Thermally activated intermittent dynamics of creeping crack fronts along disordered interfaces. *Scientific Reports*, 11:20418.

PoreLab
NTNU-UiO Porous Media Laboratory

Funding
The Research Council of Norway, (History-dependent friction, #287084) and EU Horizon 2020 MSCA CoFund (CompSci)

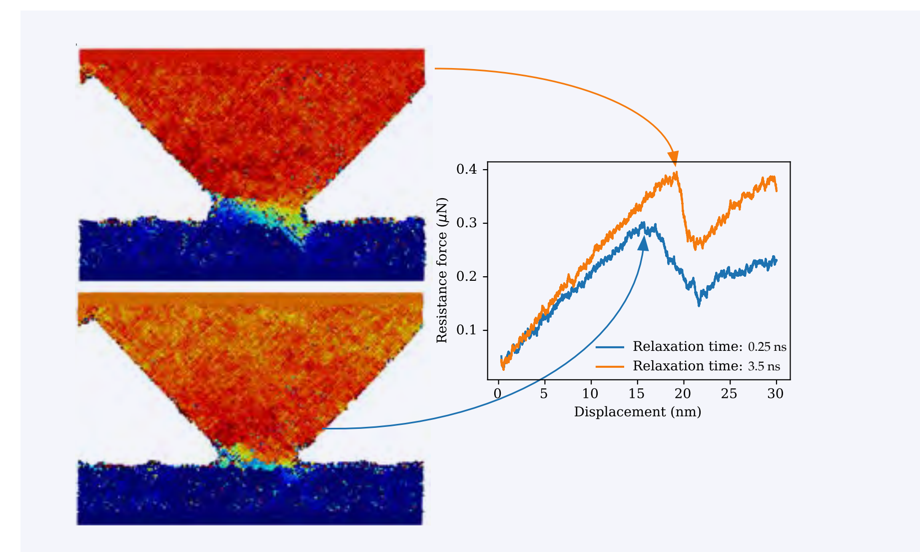
Participants
Henrik Andersen Sveinsson[1], Even Marius Nordhagen[1], Julien Scheibert[2], François Renard[1], Evangelos Korkolis1, Anders Malthe-Sørensen[1]

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 reattachment. In this project we will address how to reformulate the laws of friction to include the history of the contact – a history-dependent law of friction. We will determine under what circumstances history-dependent friction is important, develop a theory for history-dependent friction, test and apply this theory on atomic-, meso- and macroscopic scales and apply it to key problems in glaciology and geoscience.

On the atomic scale, we have developed a model for a silicon carbide asperity under conditions where ageing 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. We are currently extending this model to look at the collective behavior on a regular grid of such multiple frictional contacts. 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.

Production in highlights

Thogersen, K., Aharonov, E., Barras, F., & Renard, F. (2021). Minimal model for the onset of slip pulses in frictional rupture. *Physical Review E*, 103(5-1), 052802.

Funding
The Research Council of Norway (PROMETHEUS, #267775)

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

Affiliation
1) The Njord Center, University of Oslo, Norway
2) Department of Geosciences & NGI, University of Oslo, Norway
3) University of Nancy, France
4) University Grenoble Alpes, France
5) British Geological Survey, UK

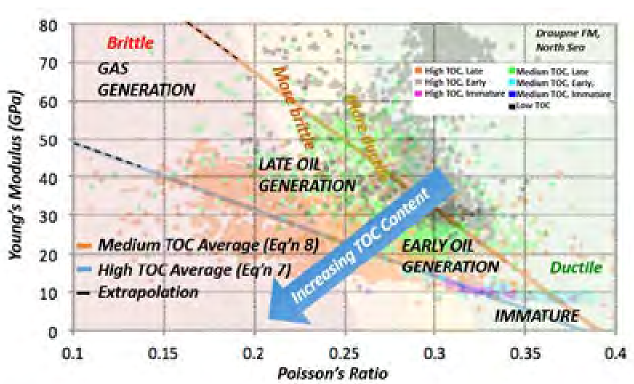
Maturation and fracturing of organic-rich shale during primary migration

How hydrocarbons are expelled from source rocks during burial controls how much oil and gas could migrate toward reservoir rocks.

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 the propagation of hydraulic fractures.

We follow three complementary approaches. First, we develop a baseline understanding of the relationship between organic content and maturation as it relates to the geomechanical components of the rock. Second, we perform 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 perform analogue modelling of the fracturing process within an anisotropic medium focused on understanding the size, shape, density, and orientation of fractures in relation to the anisotropy.

We have submitted three articles. One article presents a new rock physics template that quantifies how kerogen maturation modify the geomechanical properties of shales at the basin scale (see figure below). The second article is a study of kerogen lenses where a novel multiscale synchrotron microtomography imaging technique is used. In the third article, we have implemented a new machine learning technique for shale classification.



Organic maturation product (OMP) rock physics template: This template explores how maturation and TOC impact shale brittleness and ductility in the Draupne Formation, the central North Sea (Johnson et al., 2022, in review).

Production in highlights

Johnson, J., R., Hansen, J., A., Renard, F., Mondol, N. H. (2021). Mapping the maturity of organic-rich shale with combined geochemical and geophysical data, Draupne Formation, Norwegian Continental Shelf. *Marine and Petroleum Geology*, in review.

Johnson, J. R., Kobchenko, M., Mondol, N. H., and Renard, F. (2021). Multiscale synchrotron microtomography imaging of kerogen lenses in organic-rich shales from the Norwegian Continental Shelf. *International Journal of Coal Geology*, in review.

Xue, C., McBeck, J., Qiu, L., Zhong, J., Wu, J., Renard, F. (2021). Application of machine learning for shale lithofacies prediction on borehole scale and its controls on the pore structure in Shanxi and Taiyuan shales, Ordos Basin, China. *Rock Mechanics and Rock Engineering*, in review.

Chapter 3 | Part 4

Pattern Formation and Dynamical Systems

1. Flows in Networks
2. Oumuamua- distinguishing between models via infrared observations
3. Super-diffusive melting in frozen rocks or soils
4. The transition from viscous fingers to compact displacement during unstable drainage in porous media

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644), and the U.S. National Science Foundation (#DMR-1104829)

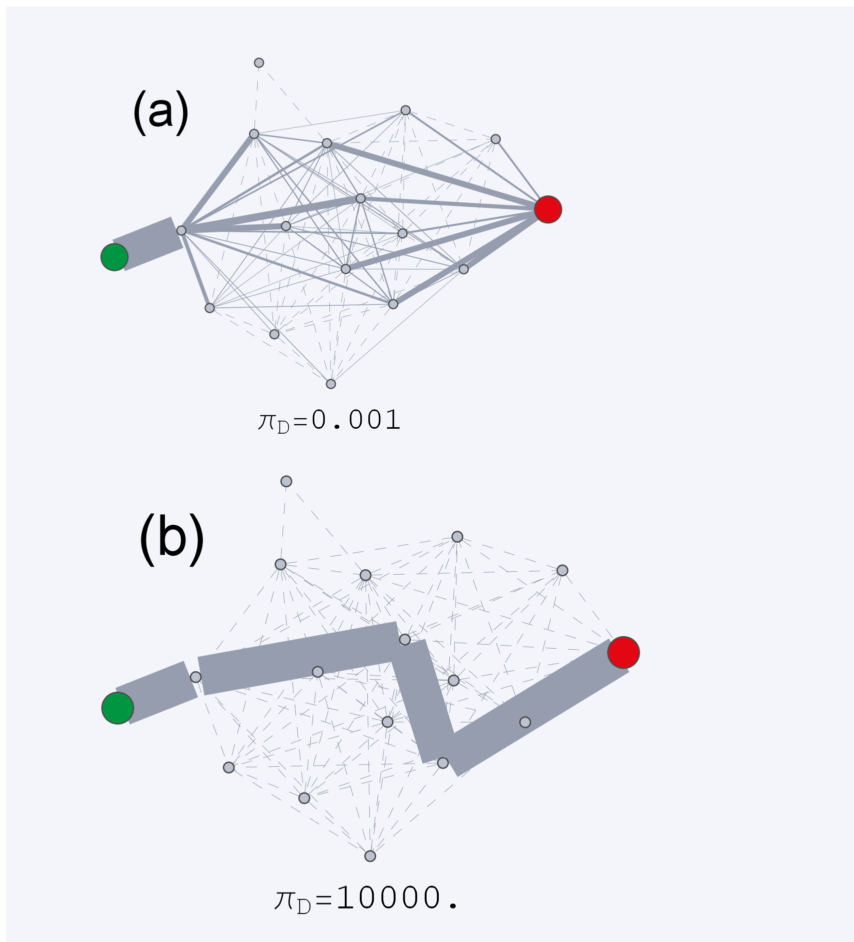
Participants
P. A. Rikvold[1,2], A. J. Gurfinkel[2]

Affiliation
1) PoreLab, The Njord Center, University of Oslo, Norway
2) Department of Physics, Florida State University, Tallahassee, FL, USA

Flows in Networks

The network-theoretical description of complex systems as *nodes* connected by *edges* has multiple applications in science, technology, and social science, including flows in porous media. Among the most important concepts in network theory are *centralities*, which quantify the importance of particular nodes or edges. Our objective is to develop tunable node centralities based on the behavior of potential-driven flows or, equivalently, random walks. These centralities can be characterized either by their *grasp*: the ability of flows between pairs of nodes to follow non-optimal (non-geodesic) paths, or their *reach*: the distance away from a source node that a flow can be detected.

We use a combination of absorbing random walks and algebraic solutions of currents in electrical circuits, in which random "walkers" have a tunable probability π_D to "die" on their way. *Grasp* is quantified by flows between pairs of nodes. With low π_D, the walkers spread over the whole network like an electrical current (wide grasp), while with high π_D, only those proceeding along the shortest paths survive (narrow grasp). To quantify *reach*, we choose a single node as a source. With low π_D, the flow persists over large graph distances (long reach), while a large π_D limits it to short paths (short reach) [2]. We propose several, grasp- and reach-parametrized centralities and corresponding statistical measures in the form of grasp- and reach distributions.



Extremes of grasp illustrated on a social network of kangaroos. Line thickness indicates flow magnitude. Dashed edges carry negligible flow. (a) Large grasp, corresponding to low death rate, π_D. (b) Small grasp, corresponding to high π_D. From [2].

Production in highlights

Gurfinkel, A. J., & Rikvold, P. A. (2020). Absorbing random interpolating between centrality measures on complex networks. *Physical Review E*, 101(1), 012302.].

Gurfinkel, A. J., & Rikvold, P. A. (2021). Adjustable reach in a network centrality based on current flows. *Physical Review E*, 103(5), 052308.

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

Participants
Eirik Grude Flekkøy[1]
Joachim Brodin[1]

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

Oumuamua- distinguishing between models via infrared observations

Since the first known interstellar object 1I/2017 U1 ('Oumuamua) was discovered in October 2017, much effort has gone into explaining its formation and unusual behavior.

This behavior is characterized by a lack of cometary activity as well as a non-gravitational acceleration. A key problem has been to explain this acceleration, which for comets is caused by out-gassing. Lacking any trace of such out-gassing a possible explanation is that it is governed by the radiation pressure from the sun- in which case the mass of the object would have to be extremely small. We recently suggested that 'Oumuamua originated as a cosmic 'dust-bunny', a cometary fractal aggregate (CFA) that was formed in a cometary tail. Given the inferred size of 'Oumuamua a fractal dimension around 2.3 would explain the extra-gravitational acceleration from the radiation pressure.

Others have proposed it to be a sublimating substance covered by a rocky crust that was formed by heating during a close encounter with a nearby star.

Another suggestion is that it is a chunk of frozen N2 ejected from a Pluto-like surface or a piece of pure H_2 ice. Finally, the possibility that it is a light sail developed by an alien civilization has been advocated. Since 'Omuamua itself is no longer observable, deciding between these models must await the next passage of a similar object. We show that the combination of optical and infrared observations offers such a distinction possibility if the passage of the next object is as close to the earth as was 'Oumuamua. In order to study the thermal properties of a fractal that is subject to radiative heating, we introduced a geometric particle model with the prescribed fractal dimension. This model is shown in the figures.

Optical dayside- and infrared night side (to the right) radiation from the geometric CFA model of 'Oumuamua using an 8 million particle model with the prescribed fractal dimension. The dayside images correspond to different orientations of the model relative to the sun, while the infrared image is a back side view of the night side.

Production in highlights

Flekkøy, E. G. & Brodin, J. F. Discerning between different 'Oumuamua models by optical and infrared observations. Accepted in *The Astrophysical Journal Letters*.

Flekkøy, E. G., Luu, J. & Toussaint, R. (2019). The interstellar object 'Oumuamua as a fractal dust aggregate. *The Astrophysical Journal Letters*, 885(2), L41.

Luu, J., Flekkøy, E. G., & Toussaint, R. (2020). 'Oumuamua as a Cometary Fractal Aggregate: The "Dust Bunny" Model. *The Astrophysical Journal Letters*, 900(2), L22.

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

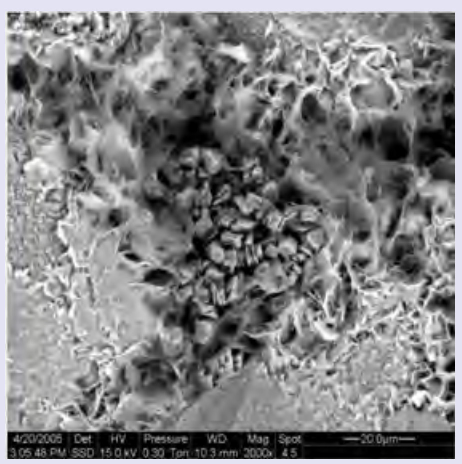
Participants
Eirik Grude Flekkøy[1], Alex Hansen[2], Erika Eiser[2]

Affiliation
[1] PoreLab, The Njord Centre, University of Oslo, Norway
[2] Institute of Physics, PoreLab, NTNU, Trondheim, Norway

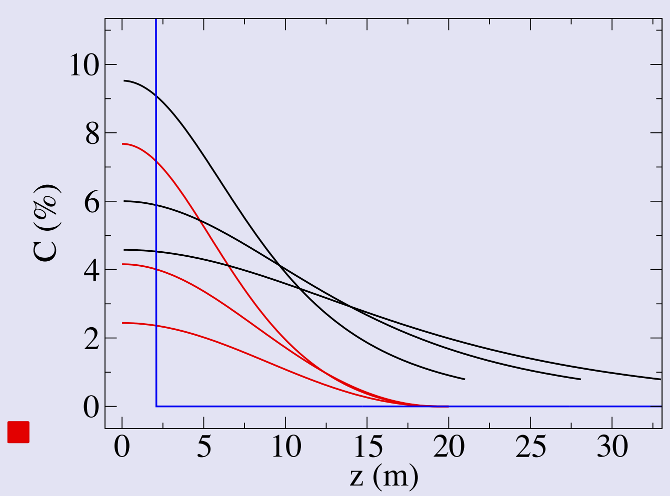
Super-diffusive melting in frozen rocks or soils

The melting of water in frozen soils or rocks may be strongly affected by freezing point depression. This thermodynamic effect, which causes melting at sub-zero temperatures may be important in frost-heave and melting of tundras.

Water that freezes in porous media will still leave pockets of liquid water in pores that are sufficiently small. This is due to the Gibbs-Thomson effect and causes a residual concentration of liquid water that may be several 10's of degrees below the bulk freezing temperature. As heat passes through such a system some of the ice melts, but the heat bypasses all the pores which are not at the melting point determined by their size. Consequently, the melting front spreads out and causes water to melt at much larger depths than it would without the freezing point depression effect. When described analytically this process may be shown to give rise to super-diffusive behavior. In some cases, it may even result in hyper-ballistic spreading of the liquid concentration. Experimental studies are on the way to observing this effect by optical means.



Nanopores that may contain frozen water.



Concentration of liquid water with depth. The blue curve shows the case with no freezing point depression, the colored curves the case where pores freeze/melt at different temperatures depending on the pore size.

Production in highlights

Flekkøy, E. G., Hansen, A., & Baldelli, B. (2021). Hyperballistic superdiffusion and explosive solutions to the non-linear diffusion equation. *Frontiers in Physics*, 9, 41.

PoreLab
NTNU-UiO Porous Media Laboratory

Funding
The Research Council of Norway Centre of Excellence (Porous Media Laboratory, #262644)

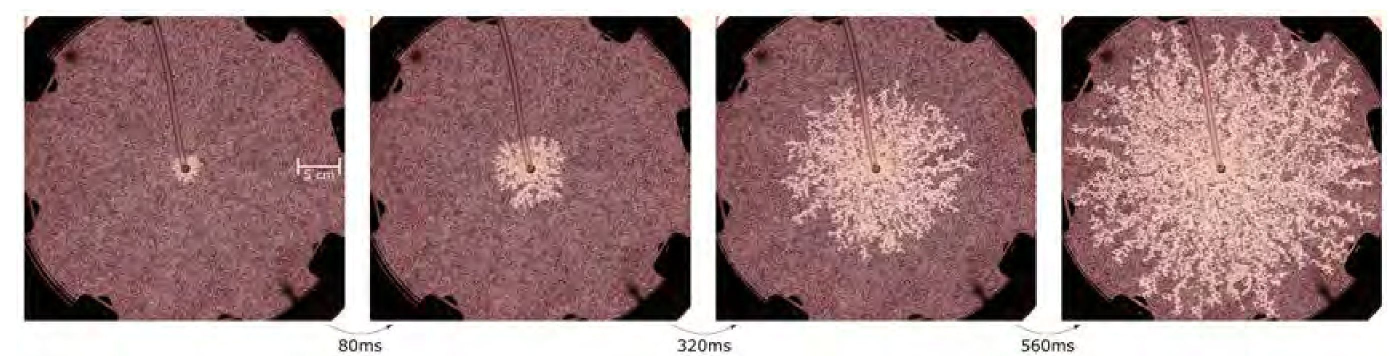
Participants
Fredrik Kvalheim Eriksen[1], Marcel Moura[1], Mihailo Jankov[1], Antoine Turquet[1,2], Knut Jørgen Måløy[1], Eirik Grude Flekkøy[1]

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 viscous fluid displaces a fluid with much higher viscosity at high injection rates in a porous medium. However when the low viscosity invading fluid has a finite significant viscosity, even if it is much lower than the displaced fluid's viscosity, a compact region appears in the internal part of the displacement structure. 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 invasion 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 between the invading and defending fluids. 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 more or less 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.

Production in highlights

Eriksen, F., Moura, M., Jankov, M., Turquet, A., Måløy, K. (2021). The transition from viscous fingers to compact displacement during unstable drainage in porous media. Accepted in *Phys. Rev. Fluids*.

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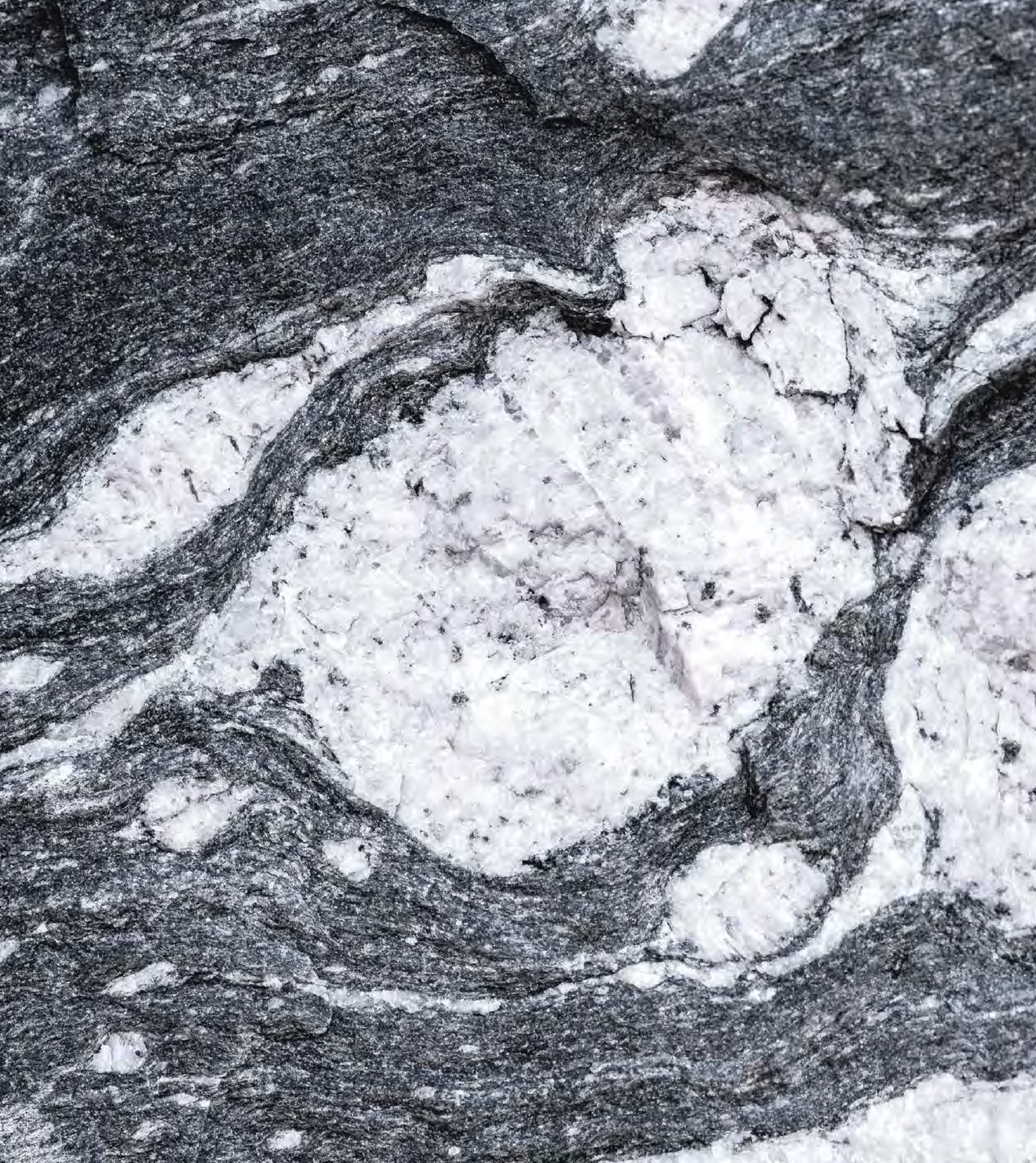

04

Appendices

List of staff

Senior Academic Staff

Last name	First name	E-mail	Function
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 Grete	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	Researcher
Schmid	Daniel Walter	daniel.schmid@geo.uio.no	Adjunct professor (20%)
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 Olga Maryse	claire.aupart@outlook.fr	Researcher
Barras	Fabian	fabian.barras@mn.uio.no	Postdoctoral Fellow
Combriat	Thomas Daniel	t.m.d.combriat@fys.uio.no	Postdoctoral Fellow
Cordonnier	Benoit	Benoit.cordonnier@geo.uio.no	Researcher
Dziadkowiec	Joanna	joanna.dziadkowiec@fys.uio.no	Postdoctoral Fellow
Eriksen	Fredrik Kvalheim	f.k.eriksen@fys.uio.no	Postdoctoral Fellow
Kobchenko	Maya	maya.kobchenko@fys.uio.no	Researcher
Korkolis	Evangelos	evangelos.korkolis@mn.uio.no	Postdoctoral Fellow
Linga	Gaute	gaute.linga@mn.uio.no	Postdoctoral Fellow
McBeck	Jessica	j.a.mcbeck@geo.uio.no	Researcher
Moura	Marcel	marcel.moura@fys.uio.no	Researcher
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
Vincent-Dospital	Tom	tom.vincent-dospital@fys.uio.no	Postdoctoral Fellow
Zertani	Sascha Heinrich Pablo	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 Lili Mathy	c.l.m.bouchayer@geo.uio.no	Doctoral Research Fellow
Brodin	Joachim Falck	j.f.brodin@fys.uio.no	Doctoral Research Fellow
Camposano	Anthony Val	a.v.camposano@fys.uio.no	Doctoral Research Fellow
Guren	Marthe Grønlie	m.g.guren@geo.uio.no	Doctoral Research Fellow
Jain	Harish Pruthviraj	harishpj@fys.uio.no	Doctoral Research Fellow
Johnson	James Ronald	j.r.johnson@geo.uio.no	Doctoral Research Fellow
Kandula	Neelima	neelima.kandula@geo.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 Stølevik	k.s.olsen@fys.uio.no	Doctoral Research Fellow
Rabbel	Ole	ole.rabbel@geo.uio.no	Doctoral Research Fellow
Razbani	Mohammad Amin	m.a.razbani@fys.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
Skogvoll	Vidar	vidarsko@mn.uio.no	Doctoral Research Fellow
Thorens	Louison	louison.thorens@fys.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
Drobac	Bojana	bojanadr@student.geo.uio.no	Adm. support
Rosenqvist	Marija Plahter	m.p.rosenqvist@mn.uio.no	Adm. support

Visiting guests from abroad in 2021

Last name	First name	E-mail	Visiting from
Eilersen	Andreas Thomas	andreaseilersen@nbi.ku.dk	Denmark
Khobaib	Khobaib	khobaib88@hotmail.com	India
Jacob	Jean-Baptiste	jean-baptiste.jacob@univ-grenoble-alpes.fr	France
Lacroix	Pascal	pascal.lacroix@univ-grenoble-alpes.fr	France
Rozynek	Zbigniew	zbigniew.rozynek@gmail.com	Poland
Xue	Chunqi	b18010007@s.upc.edu.cn	China

Master students

Last name	First name	E-mail	Supervisor(s)
Blum	Cletus	cletusb@student.geo.uio.no	Amanda Johansen DiBiagio, Hans Petter Jostad, Karen Mair, Håkon Heyerdahl
Body	Nellie Sofie	nelliesb@student.geo.uio.no	Olivier Galland
Bratsberg	Eldrid	eldribr@student.geo.uio.no	Olivier Galland
Buvik	Tord Alexander	tordab@student.geo.uio.no	Bahman Bohloli, Halvard Smith, François Renard
Cabrera	Gabriel Sigurd	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
Drobac	Bojana	bojanadr@student.geo.uio.no	François Renard, Kevin Tuttle
Due	Thor Gustav With	tgdue@student.geo.uio.no	Luke Griffiths, François Renard
Falkeid	Silje Merete Kristiansen	smfalkei@student.geo.uio.no	Luca Piciullo, Anders Solheim, Karen Mair
Foyn	Stig-Nicolai	s.n.foyn@fys.uio.no	Jessica McBeck, François Renard
Fredriksson	Sofia Maria	sofiamfr@student.geo.uio.no	François Renard, Gina Mikarlsen, Kim Rudolph-Lund
Haugerud	Ivar Svalheim	i.s.haugerud@fys.uio.no	Eirik Flekkøy, Knut Jørgen Måløy
Kings	Jonathan	jonathan.kings@fys.uio.no	Eirik Flekkøy
Liplass	Ingrid Ishaug	ingridil@student.geo.uio.no	Zhongqiang Liu, François Renard, Elin Skurtveit, Ørjan Nerland
Meakins	Max William John	mwmeakin@student.geo.uio.no	Bjørn Jamtveit, Sverre Planke, John Millett, Hans Jørgen Kjøll
Moen	Emily	e.q.z.moen@fys.uio.no	Luiza Angheluta-Bauer
Payabyab	Ronald Mathew	rmpayaby@student.geo.uio.no	François Renard, Desiree Silvana Treichler
Reiakvam	Are	arereia@hotmail.com	Hendrik Sturm, Elin Skurtveit, Karen Mair
Reutz	Elisabeth Hoffstad	elisahre@student.geo.uio.no	Olivier Galland
Reykdal	Helene	helenrey@student.geo.uio.no	Axel Bernd Müller, Bjørn Jamtveit
Rosenqvist	Marija Plahter	marijaro@student.geo.uio.no	Bjørn Jamtveit, Sverre Planke, John Millet, Hans Jørgen Kjøll, Daniel Schmid
Scheller	Elizabeth	elizas@student.geo.uio.no	Luca Menegon, Kristina Dunkel, François Renard, Bjørn Jamtveit
Seabra Maronni	Natália	natalise@student.geo.uio.no	Bjørn Jamtveit, Kristina Dunkel
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

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 Falck	Experimental studies on flow in porous media in 3D	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura
Camposano, Anthony Val	Machine-learning-based molecular modelling of nanoscale geological processes	Anders Malthe-Sørenssen, Henrik Andersen Sveinsson
Guren, Marthe Grønlie	Imaging and modelling nanoscale dynamics of mineral-mineral and mineral-fluid interfaces during mechano-chemical transformations	François Renard, Henrik Andersen Sveinsson, Anders Malthe-Sørenssen
Johnson, James Ronald	Microfractures in organic shales and their transport properties	Nazmul Mondol, François Renard
Jain, Harish Pruthviraj	Collective emergent behaviour of active cellular systems	Luiza Angelutha-Bauer, Anders Malthe-Sørenssen
Najafi, Fahimeh	Frictional properties of surface structures generated by machine-learning	Anders Malthe-Sørenssen, Henrik Andersen Sveinsson
Nordhagen, Even Marius	History-dependent effects in atomic-scale friction	Anders Malthe-Sørenssen, Henrik Sveins-son, Kjetil Thøgersen, François Renard
Razbani, Mohammad Amid	Numerical modelling of mineral-microbe interactions	Anders Malthe-Sørenssen, Anja Røyne, Espen Jettestuen
Rønning, Jonas	Turbulence in Bose-Einstein condensates and active matter	Luiza Angheluta, Eirik Grude Flekkøy
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
Michalchuk, Stephen	Mechanisms and significance of transient brittle deformation in the ductile crust	Luca Menegon, François Renard, Kristina Dunkel

Finished PhDs in 2021

Candidate	Title/Topic	Supervisor(s)
Kandula, Neelima	Dynamic synchrotron imaging of brittle failure in crustal rocks	François Renard, Dag Kristian Dysthe, Jerome Weiss
Olsen, Kristian Stølevik	Active and passive Brownian particles in complex environments	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura
Rabbel, Ole	Fracturing of igneous intrusions emplaced in organic-rich shale: Implications for hydrothermal flow, petroleum sys-tems and exploration in volcanic basins	Olivier Galland, Karen Mair
Thorens, Louison	Unstable drainage of frictional fluids and magnetic control of the mechanical behavior of confined granular media	Knut Jørgen Måløy, Mickaël Bourgoin, Eirik Grude Flekkøy, Stéphane Santucci

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-Vincent	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
Eriksen, Fredrik Kvalheim	Deformation and flow in porous media	Knut Jørgen Måløy
Kobchenko, Maya	Maturation of kerogen in organic-rich shales	François Renard
Korkolis, Evangelos	History-dependent friction	Anders Malthe-Sørenssen, François Renard
Linga, Gaute	Numerical modelling of the complexity of fluid flow in de-forming porous media	François Renard, Eirik Grude Flekkøy
McBeck, Jessica Ann	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
Thøgersen, Kjetil	Friction controls on glacier motion	Thomas Vikhamar Schuler, Anders Malthe-Sørenssen, Andreas Kääb
Zertani, Sascha	The cyclic interplay of seismic and aseismic deformation in the lower continental crust	Luca Menegon, Bjørn Jamtveit

Guest talks, workshops and seminars

Date	Speaker and name of talk
January 22nd	Carl Fredrik Berg, NTNU. "Wettability and efficiency of quasi-static displacements"
January 29th	Pascal Lacroix, ISTerre. “Life and death of slow-moving landslides”
February 5th	Marie Violay, École Polytechnique Fédérale de Lausanne. “Mechanical behavior of fluid-induced earthquakes”
February 12th	Seth Saltiel, Lamont-Doherty Earth Observatory. “How can subglacial seismicity constrain bed conditions and mechanics?: experimental exploration of ice slip on soft beds”
February 19th	Suzanne Hangx, Utrecht University. “The importance of understanding fluid-rock interactions for geo-energy storage and production: learnings from CO_2 storage”
February 26th	Åke Fagereng, Cardiff University. “Effects of heterogeneity on fault slip behavior”
March 5th	Anne Pluymaker, U Delft. “Fluid limestone interactions: a roc mechanics approach”
March 12th	Ramin Aghababaei, Aarhus University. “Micromechanics of surface asperities fracture during sliding contact”
March 19th	Jonathan Bamber, University of Bristol. “A Bayesian Hierarchical Modelling approach to solve for seal level, global mass movement and solid earth deformation simultaneously”
April 9th	Elsa Bayart, ENS Lyon. "Solid friction: heterogeneities and rupture arrest"
April 16th	Neal Iverson, Iowa State University. “A slip law for glaciers”
April 23rd	Irene Manzella, University of Plymouth. “Volcanoes, landslides and tsunamis: a numerical study of the 2019 Stromboli events”
April 30th	Stefanos Papanikolaou, National Center for Nuclear Research, Poland. “From statistical features to mechanical yielding in digital image correlation and surface strain maps”
May 7th	Jay Fineberg, The Hebrew University of Jerusalem. “How Friction Starts: Nucleation fronts initiate frictional motion”
June 3rd	EarthFlows June Meeting. Organizer: Luiza Angheluta-Bauer
August 3rd	Renaud Touissant, Université de Strasburg/University of Oslo. “Induced seismicity under Strasbourg: Possible mechanisms”
August 27th	Eric Larose, Université Grenoble Alpes. “Environmental seismology: an emerging tool for probing slopes stability, rockfalls, and the evolution of the permafrost”
September 3rd	Luke Zoet, University of Wisconsin-Madison. “Investigating subglacial processes through seismicity and experimentation”
September 10th	Chris MacMinn, University of Oxford. “Fluid-fluid phase separation in a soft porous medium”
September 23rd-24th	Breaking the Crust-seminar, 70 international participants at the Norwegian Academy of Sciences (organizers: Bjørn Jamtveit, François Renard)

Date	Speaker and name of talk
October 1st	Mathijs Janssen, University of Oslo. “Electrolyte relaxation near electrified surfaces – from flat planes to nanoporous supercapacitors”
October 8th	Julien Scheibert, École Centrale Lyon. ”Towards the design of contact interfaces with a specified friction law”
October 22nd	Martijn van den Ende, Université Côte d’Azur. “Earthquakes, fibre-optic cables, and a zebra: intelligent solutions for tomorrow’s seismology”
October 29th	Anna Rogowitz, University of Vienna. “Transforming a gabbro into an eclogite without fracturing – A tale of opening and closing fluid pathways”
November 5th	Jordi Bolibar, Utrecht University. “Towards interpretable, physics-informed machine learning models for glacier evolution”
November 12th	Camilla Cattania, Massachusetts Institute of Technology. “How do earthquakes begin? Numerical and theoretical insights into the nucleation processes of small and large earthquakes”
December 3rd	Richard Walker, Leicester University. “The rock record of igneous sheet intrusions: the preservation of magma emplacement processes”
January – November	*Porous Media Tea Time Talks. Biweekly event with talks from early career researchers*. 17 events in 2021. Organizer: Marcel Moura (University of Oslo), Maja Rücker (Imperial College London, UK), Kamaljit Singh (Heriot-Watt University, UK), Tom Bultreys (Ghent University, Belgium), Mohammad Nooraiepour (University of Oslo) and Catherine Spurin (Imperial College London, UK)

Production list 2021

Published in 2021

1. **Aiken, J. M.** & Lewandowski, H. J.M. (2021). *Data sharing model for physics education research using the 70 000 response Colorado Learning Attitudes about Science Survey for Experimental Physics dataset*. Phys. Rev. Phys. Educ. Res. 17, 020144.

2. **Aupart, C.**, Morales, L., Godard, M., & **Jamtveit, B.** (2021). *Seismic faults triggered early stage serpentinization of peridotites from the Samail Ophiolite, Oman*. Earth and Planetary Science Letters, 574, 117137.

3. **Austrheim, H.**, Corfu, F., & Renggli, C. J. (2021). *From peridotite to fuchsite bearing quartzite via carbonation and weathering: with implications for the Pb budget of continental crust*. Contributions to Mineralogy and Petrology, 176(11), 1-14.

4. **Barras, F.**, Aghababaei, R., & Molinari, J. F. (2021). *Onset of sliding across scales: How the contact topography impacts frictional strength*. Physical Review Materials, 5(2), 023605.

5. Bertelsen, H. S., Guldstrand, F., Sigmundsson, F., Pedersen, R., **Mair, K.**, & **Galland, O.** (2021). *Beyond elasticity: Are Coulomb properties of the Earth's crust important for volcano geodesy?* Journal of Volcanology and Geothermal Research, 410, 107153.

6. Birnir, B., **Angheluta, L.**, Kaminsky, J., & Chen, X. (2021). *Spectral link of the Generalized Townsend-Perry constants in turbulent boundary layers*. Physical Review Research, 3(4), 043054.

7. Busek, M., Nøvik, S., Aizenshtadt, A., Amirola-Martinez, M., **Combriat, T.**, Grünzner, S., & Krauss, S. (2021). *Thermoplastic Elastomer (TPE)–Poly (Methyl Methacrylate)(PMMA) Hybrid Devices for Active Pumping PDMS-Free Organ-on-a-Chip Systems*. Biosensors, 11(5), 162.

8. de Ruiter, L., Gunnæs, A. E., **Dysthe, D. K.**, & **Austrheim, H.** (2021). *Quartz dissolution associated with magnesium silicate hydrate cement precipitation*. Solid Earth, 12(2), 389-404.

9. **Dunkel, K. G.**, Morales, L. F., & **Jamtveit, B.** (2021). *Pristine microstructures in pseudotachylytes formed in dry lower crust, Lofoten, Norway*. Philosophical Transactions of the Royal Society A, 379(2193), 20190423.

10. **Dunkel, K. G.**, Zhong, X., Arnestad, P. F., Valen, L. V., & **Jamtveit, B.** (2021). *High transient stress in the lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten Archipelago, northern Norway*. Geology, 49(2), 135-139.

11. **Dziadkowiec, J.**, Ban, M., Javadi, S., **Jamtveit, B.**, & **Røyne, A.** (2021). *Ca_2+ Ions Decrease Adhesion between Two (104) Calcite Surfaces as Probed by Atomic Force Microscopy.* ACS Earth and Space Chemistry, 5(10), 2827-2838.

12. Engvik, A. K., Gautneb, H., Baranwal, V. C., Rønning, J. S., Knežević Solberg, J., Liu, Y., & **Austrheim, H.** (2021). *The control of shea-zone development and electric conductivity by graphite in granulite: An example from the Proterozoic Lofoten-Vesterålen Complex of northern Norway*. Terra Nova, 33(5), 529-539.

13. **Flekkøy, E. G.**, Hansen, A., & **Baldelli, B.** (2021). *Hyperballistic superdiffusion and explosive solutions to the non-linear diffusion equation*. Frontiers in Physics, 9, 41.

14. **Guren, M. G.**, **Sveinsson, H. A.**, Hafreager, A., **Jamtveit, B.**, **Malthe-Sørenssen, A.**, & **Renard, F.** (2021). *Molecular dynamics study of confined water in the periclase-brucite system under conditions of reaction-induced fracturing*. Geochimica et Cosmochimica Acta, 294, 13-27.

15. Gurfinkel, A. J., & **Rikvold, P. A.** (2021). *Adjustable reach in a network centrality based on current flows*. Physical Review E, 103(5), 052308.

16. **Jamtveit, B.**, **Dunkel, K. G.**, Petley-Ragan, A., **Austrheim, H.**, Corfu, F., & Schmid, D. W. (2021). *Rapid fluid-driven transformation of lower continental crust associated with thrust-induced shear heating*. Lithos, 396, 106216.

17. Jennings, C. S., Rossman, J. S., Hourihan, B. A., Marshall, R. J., Forgan, R. S., Blight, B. A., **Olsen, K.S.** ... & Börner, H. G. (2021). *Where physics meets chemistry meets biology for fundamental soft matter research*. Soft Matter, 17, 2034.

18. **Kandula, N.**, **McBeck, J.**, **Cordonnier, B.**, **Weiss, J.**, **Dysthe, D. K.**, & **Renard, F.** (2021). *Synchrotron 4D X-Ray Imaging Reveals Strain Localization at the Onset of System-Size Failure in Porous Reservoir Rocks*. Pure and Applied Geophysics, 1-26.

19. **Khobaib, K.**, Hornowski, T. & **Rozynek, Z.** (2021). *Particle-covered droplet and a particle shell under compressive electric stress*. Phys Rev E 103, 062605.

20. **Khobaib, K.**, Mikkelsen, A., **Vincent-Dospital, T.**, & **Rozynek, Z.** (2021). *Electric-field-induced deformation, yielding, and crumpling of jammed particle shells formed on non-spherical Pickering droplets*. Soft Matter, 17(19), 5006-5017.

21. Klaessens, D., Reisberg, L., Jousselin, D., Godard, M., & **Aupart, C.** (2021). *Osmium isotope evidence for rapid melt migration towards the Moho in the Oman ophiolite*. Earth and Planetary Science Letters, 572, 117111.

22. Koehn, D., Piazolo, S., Beaudoin, N. E., Kelka, U., Spruženiece, L., Putnis, C. V., & **Toussaint, R.** (2021). *Relative rates of fluid advection, elemental diffusion and replacement govern reaction front patterns*. Earth and Planetary Science Letters, 565, 116950.

23. Levy dit Vehel V., Hatano T., Vanel L., **Måløy K. J.**, & Osvanny R. (2021). *Dilation as a precursor in a continuous fault*. EPJ, 249, 15006

24. **Malthe-Sørenssen, A.** (2021). *The onset of a slip*. Nature Physics, 17(9), 983-985.

25. Marchesini, B., **Menegon, L.**, Schwarz, G., Neff, C., Keresztes Schmidt, P., Garofalo, P.S., Hattendorf, B., Günther, D., Mattila, J., Viola, G. (2022). *Structural pathways for migration of radionuclides through brittle sulphide-bearing faults: a study from the Olkiluoto deep nuclear waste repository*. Journal of Structural Geology 154, 104473.

26. Mattsson, T., Petri, B., Almqvist, B., McCarthy, W., Burchardt, S., Palma, J. O., ... & **Galland, O.** (2021). *Decrypting magnetic fabrics (AMS, AARM, AIRM) through the analysis of mineral shape fabrics and distribution anisotropy*. Journal of Geophysical Research: Solid Earth, e2021JB021895.

27. **McBeck, J. A.**, Ben-Zion, Y., & **Renard, F.** (2021). *How the force and fracture architectures develop within and around healed fault zones during biaxial loading toward macroscopic failure*. Journal of Structural Geology, 147, 104329.

28. **McBeck, J. A.**, **Cordonnier, B.**, & **Renard, F.** (2021). *The influence of spatial resolution and noise on fracture network properties calculated from X-ray microtomography data*. International Journal of Rock Mechanics and Mining Sciences, 147, 104922.

29. **McBeck, J. A.**, Zhu, W., & **Renard, F.** (2021). *The competition between fracture nucleation, propagation, and coalescence in dry and water-saturated crystalline rock*. Solid Earth, 12(2), 375-387.

30. **McBeck, J.**, **Aiken, J. M.**, **Cordonnier, B.**, Ben-Zion, Y. & **Renard, F.** (2021). *Predicting fracture network development in crystalline rocks*. Pure and Applied Geophysics, 1-25.

31. **McBeck, J.**, Ben-Zion, Y., & **Renard, F.** (2021). *Fracture Network Localization Preceding Catastrophic Failure in Triaxial Compression Experiments on Rocks*. Frontiers in Earth Science, 9.

32. **McBeck, J.**, Ben-Zion, Y., Zhou, X., & **Renard, F.** (2021). *The influence of preexisting host rock damage on fault network localization*. Journal of Structural Geology, 104471.

33. **McBeck, J.**, **Mair, K.**, & **Renard, F.** (2021). *Decrypting healed fault zones: how gouge production reduces the influence of fault roughness*. Geophysical Journal International, 225(2), 759-774.

34. Meghraoui, M., **Toussaint, R.**, & Aksoy, M. E. (2021). *The slip deficit on the North Anatolian Fault (Turkey) in the Marmara Sea: insights from paleoseismicity, seismicity and geodetic data*. Mediterranean Geoscience Reviews, 3(1), 45-56.

35. **Menegon, L.**, & Fagereng, Å. (2021). *Tectonic pressure gradients during viscous creep drive fluid flow and brittle failure at the base of the seismogenic zone*. Geology, 49(10), 1255-1259.

36. **Menegon, L.**, Campbell, L., Mancktelow, N., Camacho, A., Wex, S., Papa, S., ... & Pennacchioni, G. (2021). *The earthquake cycle in the dry lower continental crust: insights from two deeply exhumed terranes (Musgrave Ranges, Australia and Lofoten, Norway)*. Philosophical Transactions of the Royal Society A, 379(2193), 20190416.

37. Montes-Hernandez, G., Findling, N., & **Renard, F.** (2021). *Direct and Indirect Nucleation of Magnetite Nanoparticles from Solution Revealed by Time-Resolved Raman Spectroscopy*. Crystal Growth & Design, 21, 6, 3500-3510.

38. Morgan, M. L., James, D. W., Monloubou, M., **Olsen, K. S.**, & Sandnes, B. (2021). *Subdiffusion model for granular discharge in a submerged silo*. Physical Review E, 104(4), 044908.

39. **Måløy, K. J.**, **Moura, M.**, Hansen, A., **Flekkøy, E. & Toussaint, R.** (2021) *Burst dynamics, up-scaling and dissipation of slow drainage in porous media*. Front. Phys. 9, 796019

40. **Olsen, K. S.** (2021). *Diffusion of active particles with angular velocity reversal*. Physical Review E, 103(5), 052608.

41. **Olsen, K. S.**, **Angheluta, L.**, & **Flekkøy, E. G.** (2021). Active Brownian particles moving through disordered landscapes. Soft Matter, 17(8), 2151-2157.

42. Pellegrino, L., **Menegon, L.**, Zanchetta, S., Langenhorst, F., Pollok, K., Tumiati, S., Malaspina, N. (2021). *Mantle weakening by reaction-induced strain localization at high-pressure conditions: an example from the garnet pyroxenites of Ulten Zone (Eastern Alps, N Italy)*. Journal of Geophysical Research: Solid Earth, 126.

43. Petley-Ragan, A. J., Plümper, O., Ildefonse, B., & **Jamtveit, B.** (2021). *Nanoscale earthquake records preserved in plagioclase microfractures from the lower continental crust*. Solid Earth, 12(4), 959-969.

44. Poppe, S., Holohan, E. P., Rudolf, M., Rosenau, M., **Galland, O.**, Delcamp, A., & Kervyn, M. (2021). *Mechanical properties of quartz sand and gypsum powder (plaster) mixtures: Implications for laboratory model analogues for the Earth's upper crust*. Tectonophysics, 814, 228976.

45. Putnis, A., Moore, J., Prent, A. M., Beinlich, A., & **Austrheim, H.** (2021). *Preservation of granulite in a partially eclogitized terrane: Metastable phenomena or local pressure variations?*. Lithos, 400, 106413.

46. Putnis, C. V., Wang, L., Ruiz-Agudo, E., Ruiz-Agudo, C., & **Renard, F.** (2021). *Crystallization via Nonclassical Pathways: Nanoscale Imaging of Mineral Surfaces. In Crystallization via Nonclassical Pathways Volume 2: Aggregation, Biomineralization, Imaging & Application* (pp. 1-35). American Chemical Society.

47. **Rabbel, O.**, Palma, O., **Mair, K.**, **Galland, O.**, Spacapan, J. B., & Senger, K. (2021). *Fracture networks in shale-hosted igneous intrusions: Processes, distribution and implications for igneous petroleum systems*. Journal of Structural Geology, 104403.

48. **Renard, F.** (2021). *Reaction-Induced Fracturing: When Chemistry Breaks Rocks*. Journal of Geophysical Research: Solid Earth, 126(2).

49. Rogowska, M., Hansen, P. A., Sønsteby, H. H., **Dziadkowiec, J.**, Valen, H., & Nilsen, O. (2021). *Molecular layer deposition of photoactive metal-naphthalene hybrid thin films*. Dalton Transactions, 50(37), 12896-12905.

50. **Rozynek, Z.**, Banaszak, J., Mikkelsen, A., **Khobaib, K.** & Magdziarz, A. (2021) *Electrorotation of particle-coated droplets: from fundamentals to applications*. Soft Matter 17, 4413–4425.

51. Schmiedel, T., Burchardt, S., Mattsson, T., Guldstrand, F., **Galland, O.**, Palma, J. O., & Skogby, H. (2021). *Emplacement and Segment Geometry of Large, High-Viscosity Magmatic Sheets*. Minerals, 11(10), 1113.

52. Senger, K., Betlem, P., Birchall, T., Buckley, S. J., Coakley, B., Eide, C. H., **Galland, O.** ... & Smyrak-Sikora, A. (2021). *Using digital outcrops to make the high Arctic more accessible through the Svalbox database*. Journal of Geoscience Education, 69(2), 123-137.

53. **Shafabakhsh, P.**, Ataie-Ashtiani, B., Simmons, C. T., Younes, A., & Fahs, M. (2021). *Convective-reactive transport of dissolved CO_2 in fractured-geological formations*. International Journal of Greenhouse Gas Control, 109, 103365.

54. **Sinha, S.**, Roy, S., & Hansen, A. (2021). *Crack localization and the interplay between stress enhancement and thermal noise*. Physica A: Statistical Mechanics and its Applications, 569, 125782.

55. **Skogvoll, V.**, Skaugen, A., **Angheluta, L.**, & Viñals, J. (2021). *Dislocation nucleation in the phase-field crystal model*. Physical Review B, 103(1), 014107.

56. **Sveinsson, H. A.**, Ning, F., Cao, P., Fang, B., & **Malthe-Sørenssen, A.** (2021). *Grain-Size-Governed Shear Failure Mechanism of Polycrystalline Methane Hydrates*. The Journal of Physical Chemistry C, 125(18), 10034-10042.

57. **Thorens L., Måløy K.J.**, Bourgoin M. & Santucci S. (2021). Taming the Janssen effect. EPJ, 249, 08004

58. **Thorens L.**, Viallet M., **Måløy K.J.**, Bourgoin M. & Santucci S. (2021). *Discharge of a 2D magnetic silo*. EPJ, 249, 03017

59. **Thorens, L.**, **Måløy, K. J.**, Bourgoin, M., & Santucci, S. (2021). *Magnetic Janssen effect*. Nature communications, 12(1), 1-6.

60. **Thøgersen, K.**, **Aharonov, E.**, **Barras, F.**, & **Renard, F.** (2021). *Minimal model for the onset of slip pulses in frictional rupture*. Physical Review E, 103(5), 052802.

61. **Vincent-Dospital, T.**, & **Toussaint, R.** (2021). *Thermo-mechanical pain: the signaling role of heat dissipation in biological tissues*. New Journal of Physics, 23(2), 023028.

62. **Vincent-Dospital, T.**, Cochard, A., Santucci, S., **Måløy, K. J.**, & **Toussaint, R.** (2021). Thermally activated intermittent dynamics of creeping crack fronts along disordered interfaces. Scientific reports, 11(1), 1-16.

63. **Vincent-Dospital, T.**, Steyer, A., **Renard, F.** & **Toussaint, R.** (2021). *Frictional anisotropy of 3D-printed fault surfaces*. Frontiers in Earth Sciences, 9, 4.

64. **Vincent-Dospital, T.**, **Toussaint, R.** & **Måløy, K. J.** (2021). *Heat Emitting Damage in Skin: A Thermal Pathway for Mechanical Algesia*. Front. Neurosci. 15:780623.

65. **Vincent-Dospital, T.**, **Toussaint, R.**, Cochard, A., **Flekkøy, E. G.**, & **Måløy, K. J.** (2021). *Thermal dissipation as both the strength and weakness of matter. A material failure prediction by monitoring creep*. Soft Matter, 17(15), 4143-4150.

66. Zehner, J., **Røyne, A.**, & Sikorski, P. (2021). *A sample cell for the study of enzyme-induced carbonate precipitation at the grain-scale and its implications for biocementation*. Scientific Reports, 11(1), 1-10.

67. Zehner, J., **Røyne, A.**, & Sikorski, P. (2021). *Calcite seed-assisted microbial induced carbonate precipitation (MICP)*. Plos one, 16(2), e0240763.

68. Zhong, X., Dabrowski, M., & **Jamtveit, B.** (2021). *Analytical solution for residual stress and strain preserved in anisotropic inclusion entrapped in an isotropic host*. Solid Earth, 12(4), 817-833.

69. Zhong, X., **Petley-Ragan, A. J.**, Incel, S. H., Dabrowski, M., Andersen, N. H., & **Jamtveit, B.** (2021). Lower crustal earthquake associated with highly pressurized frictional melts. Nature Geoscience, 1-7.

To be published in 2022 or in process for publishing

1. **Austrheim, H.**, Engvik, A. K., Ganerød, M., **Dunkel, K. G.**, Velo, M. R. *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, under review.

2. Aslan, G., de Michele, M., Raucoules, D., **Renard, F.** & Cakir, Z. *Dynamics of a giant slow landslide along the coast of the Aral Sea, Central Asia*. Frontiers in Earth Sciences, in review.

3. **Bouchayer, C.**, **Aiken, J.M.**, **Thøgersen, K.**, **Renard, F.** & Schuler, T.V. *Automating the classification of surging glacier in Svalbard*. JGR: Solid Earth - Special issue in Machine learning, submitted.

4. 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*. Journal of Geophysical Research: Solid Earth, submitted.

5. Bouchon, M., Socquet, A., Marsan, D., Guillot, S., Durand, V., Gardonio, B., Campillo, M., Perfettini, H., Schmittbuhl, J., **Renard, F.** & Boullier, A. M. *Observation of rapid long-range seismic bursts in the Japan Trench subduction leading to the nucleation of the Tohoku earthquake*. Submitted.

6. Cabrita D.I.G., Faleiros F.M., Ribeiro B.V., **Menegon, L.**, Cawood P.A., Campanha G.A.C. *Deformation, thermochronology and tectonic significance of the crustal-scale Cubatão Shear Zone, Ribeira Belt, Brazil*. Tectonophysics, under review.

7. Campbell, L.R. & **Menegon, L.** *High stress deformation and short-term thermal pulse preserved in exhumed lower crustal seismogenic faults (Lofoten, Norway)*. Journal of Geophysical Research-Solid Earth, under review.

8. Ceccato, A., **Menegon, L.**, Hansen, L.N. *The effect of intracrystalline H2O content on low-temperature plasticity in quartz: insights from nanoindentation*. Geophysical Research Letters, under review

9. Cheng, H. W., **Dziadkowiec, J.**, Wieser, V., Imre, A. M., & Valtiner, M. (2021). *Real-time visualization of metastable charge regulation pathways in molecularly confined slit geometries*. arXiv preprint arXiv:2104.01157.

10. **Dziadkowiec, J.**, Cheng, H.-W., Ludwig, M., Ban, M., Tausendpfund, T. P., von Klitzing, R., Mezger M. & Valtiner, M. *Cohesion gain induced by nanosilica consolidants for monumental stone restoration*. Under review.

11. **Eriksen, F. K.**, **Moura, M.**, **Jankov, M.**, Turquet, A. L. & **Måløy, K. J.** *The transition from viscous fingers to compact displacement during unstable drainage in porous media*. Physical Review Fluids, accepted.

12. Feder, J., **Flekkøy, E. G.** & Hansen, A. (2022). Physics of flow in porous media. Cambridge Univeristy press, in press.

13. **Flekkøy, E. G.** & **Brodin, J. F.** *Discerning between different 'Oumuamua models by optical and infrared observations*. Preprint.

14. **Galland, O.**, de la Cal, H., Mescua, J. & **Rabbel, O.** *3-dimensional trapdoor structure of laccolith-induced doming and implications for laccolith emplacement, Pampa Amarilla laccolith, Mendoza Province, Argentina*. Tectonophysics, submitted.

15. Guldstrand, F., Souche, A., Bertelsen, H.S., Zanella, A. & **Galland, O.** *Emplacement of laboratory igneous sheets and fingers influenced by the Mohr-Coulomb properties of the host*. Geochemistry, Geophysics, Geosystems, under review.

16. **Haugerud, I.**, **Linga G.** & **Flekkøy, E. G.** *Solute dispersion in channels with periodic discontinuous wall roughness*. JFM, under review

17. Hernandez, J.A., Mohn, C.E., **Guren, M.G.**, Baron, M.A. & Trønnes, R.G. *Ab initio molecular dynamics simulations of davemaoite (CaSiO3) melting*. Geophysical Research Letters, submitted

18. **Johnson, J. R.**, **Kobchenko, M.**, Mondol, N. H., & **Renard, F.** *Multiscale synchrotron microtomography imaging of kerogen lenses in organic-rich shales from the Norwegian Continental Shelf*. International Journal of Coal Geology, submitted.

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

20. **Khobaib K.**, **Rozynek Z.** & Hornowski T. *Mechanical properties of particle-covered droplets probed by non-uniform electric field*. Journal of Molecular Liquids, submitted.

21. Lescoutre, R., Almqvist, B., Koyi, H., Berthet, T., Hedin, P., **Galland, O.**, Brahimi, S., Lorenz, H., Juhlin, C. (2022) *Large-scale flat-lying mafic intrusions in the Baltican crust and their influence on basement deformation during Caledonian orogeny*. GSA Bulletin, in press.

22. Liberto, T., Nenning, A., Bellotto, M., Dalconi, C., Dworschak, D., Kalchgruber, L., Robisson, A., Valtiner M., **Dziadkowiec, J.** *Resolving early stage cohesion in cementitious systems due to calcium silicate hydration*. Under preparation.

23. **Linga, G.**, **Angheluta, L.** & **Mathiesen, J.** *Onset of turbulence in channel flows with scale-invariant roughness*. PRResearch, under review.

24. Lorenz, H., **Menegon, L.** et al. *COSC-2 – drilling the basal décollement and underlying margin of paleocontinent Baltica in the Paleozoic Caledonide orogen of Scandinavia*. Scientific Drilling, under review

25. **Mathiesen, J.**, **Linga, G.**, **Renard, F.** & **Le Borgne, T.** *Enhanced dispersion in intermittent multiphase flow*. Physical Review Letters, submitted.

26. **McBeck, J.**, **Aiken, J.**, **Cordonnier, B.** & **Renard, F.** *The influence of segmentation method on fracture network properties calculated from X-ray microtomography data*. International Journal of Rock Mechanics and Mining Science, submitted.

27. **McBeck, J.**, Ben-Zion, Y. & **Renard, F.** *Predicting fault reactivation and macroscopic failure in discrete element method simulations of restraining and releasing step overs*. Earth and Planetary Science Letters, submitted

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

29. **McBeck, J.**, Ben-Zion, Y., Zhou, X. & **Renard, F.** *Off-fault deformation preceding slip along healed faults in restraining and releasing step overs: Insights from discrete element method models*. Journal of Geophysical Research: Solid Earth, submitted.

30. Paglialunga, F., Passelègue, F., Brantut, N., **Barras, F.**, Lebihain, M. & Violay, M. *On the scale dependence in the dynamics of frictional rupture: constant fracture energy versus size-dependent breakdown work*. EPSL, under review.

31. Palma, J.O., Burchardt, S., **Galland, O.**, **Schmiedel, T.**, Guerriero, L., Ruiz, R., Jerram, D., **Mair, K.** & Leanza, H.A. *Stratigraphy of the Chachahuén caldera, a back arc volcano in an intraplate setting*. Journal of South American Earth Sciences, under review.

32. Rincón, M., Marquez, A., Herrera, R., **Galland, O.**, Sanchez-Oro, J., Concha, D. & Montemayor, A.S. *Monitoring volcanic and tectonic sandbox analogue models using the Kinect v2 sensor*. Earth and Space Science, under review.

33. Roch, T., **Barras, F.**, Geubelle, P.H. & Molinari, J. F. *cRacklet: a spectral boundary integral method library for interfacial rupture simulation*. JOSS, under review.

34. Senger, K. & **Galland, O.** *Early Cretaceous magmatism in central Spitsbergen: stratigraphic and spatial extent*. Geochemistry, Geophysics, Geosystems, under review.

35. **Thøgersen, K.**, Gilbert, A., **Bouchayer, C.** & Schuler, T.V. *Glacier surges controlled by the close interplay between subglacial friction and drainage*. JGR: Earth processes, under review.

36. Van Stappen, J. F., **McBeck, J. A.**, **Cordonnier, B.**, Pijnenburg, R.P.J., **Renard, F.**, Spiers, C.J. & Hangx, S.J.T. *4D synchrotron X-ray imaging of grain scale deformation mechanisms in a seismogenic gas reservoir sandstone during axial compaction*. Rock Mechanics and Rock Engineering, in review.

37. **Xue, C.**, **McBeck, J.**, Qiu, L., Zhong, J., Wu, J. & **Renard, F.** *Application of machine learning for shale lithofacies prediction on borehole scale and its controls on the pore structure in Shanxi and Taiyuan shales, Ordos Basin, China*. Rock Mechanics and Rock Engineering, in review

Invited talks

1. **Barras, F.**, *There is a crack in everything*. Breaking the Crust Seminar, September 24.
2. **Dunkel, K. G.**, *Microstructural records of lower crustal earthquakes*. TaG-NuG (Tectonics and Geodynamics – Neotectonics and Natural Hazards) Lunch Seminar, RWTH Aachen, March 2021.
3. **Dunkel, K. G.**, *Reaction-induced deformation in the (upper) crust*, Breaking the Crust Seminar, Oslo, September 2021.
4. **Galland, O.** *Breaking through the crust – Mechanics of magma propagation*. Breaking the Crust seminar, September
5. **Galland, O.** *Multi-scale structures associated with igneous intrusions and implications for fluid migrations – An integrated field, seismic and modelling study*. Simposio de Magmatismo y Sistemas Petroleros, IAPG, April 8
6. **Guren, M. G.** *Molecular dynamics simulations of fracture instabilities in quartz*. EarthFlows Seminar, June
7. **Guren, M. G.** *Molecular modelling of dry and wet interfaces during mech-ano-chemical transformations*. University of Texas at Austin – Friday Seminar, September
8. **Guren, M. G.** *Molecular modelling of dry and wet interfaces*. Breaking the Crust Seminar, September
9. **McBeck, J.** *Precursory off-fault deformation to slip along healed faults in restraining and releasing step overs*. Southern California Earthquake Center Annual Meeting, September
10. **McBeck, J.** *Precursory off-fault deformation: Insights from discrete element method models*. Breaking the Crust Seminar, September
11. **McBeck, J.** *Predicting fracture network characteristics using machine learning*. EGU General Assembly, April
12. **McBeck, J.** *Predicting the timing of catastrophic failure*. DeTect Seminar, February
13. **McBeck, J.** *Using fracture characteristics and strain fields to predict the timing of failure*. Tectonic/FEAR Seminar, March
14. **McBeck, J.**, *Lazy localization? Deciphering the link between work optimization and spatial localization throughout fault network development*. Earthflows Seminar, May
15. **Menegon, L.** *How to stress the lower crust*. Breaking the Crust Seminar, Oslo, September
16. **Menegon, L.** *Strength evolution of the lower crust: a journey through the Wilson Cycle*. Rifts and Rifted Margins Online Seminars, October 18
17. **Moura, M.**, Eriksen, F., Turquet, A., Flekkøy, E., Toussaint, R., Jankov, M. & Måløy, K. J. *Complexity: "More is Different" also in porous media flows*. 5th Summer School on Flow and Transport in Porous and Fractured Media, Cargèse, France. July 26.
18. **Moura, M.** *Formação de padrões, sistemas complexos e mecânica de fluidos em meios porosos: mais é diferente*. Federal Rural University of Pernambuco, Brazil. November 11.
19. **Renard, F** *How correct are we when calculating fracture properties from X-ray microtomography data?* 14th Euroconference on Rock Physics and Rock Mechanics, Edinburgh and zoom, August 30-September 3
20. **Renard, F** *Strain localization generated by the force of crystallization*- CrysPoM VII: 7th International Workshop on Crystallization in Porous Media, Pau, France. June 7-9
21. Silva, D. & **Rikvold, P. A.** *Multicritical Bifurcation and Weak First-order Transition in a Three-dimensional, Three-state Lattice-gas Model. 88th Meeting of the Southeastern Section of the American Physical Society*. Tallahassee, FL, USA. November 18.

Other talks

1. **Barras, F.**, **Linga, G.**, **Renard, F.**, *Coupling Navier-Stokes and elastodynamics at the tip of a fluid-driven dynamic fracture*. Engineering Mechanics Institute (EMI) Conference, Columbia University, New York City, USA, May 25-28.
2. **Bouchayer, C.**, **Aiken, J.**, **Thøgersen, K.**, **Renard, F.** & Schuler, T. *Surging potential and probabilistic map of surging for Svalbard glaciers*. AGU Fall Meeting, New Orleans, USA. December 12-18
3. **Bouchayer, C.**, **Aiken, J.**, **Thøgersen, K.**, **Renard, F.** & Schuler, T. *Surging potential and probabilistic map of surging for Svalbard*. IGS Nordic Branch meeting, Oslo. November
4. **Dziadkowiec, J.** & **Røyne, A.** *Do soluble organic acids bind to basal mica surfaces?* Nordic Clay Meeting, 3rd Symposium Clays & Ceramics 2021, February 8-9.
5. **Guren, M. G.**, Noiriel, C. & **Renard, F.** Linking microscale and macroscale dissolution rates in carbonates using x-ray microtomography data and numerical modelling. Goldschmidt conference, July 4-6
6. **Mathiesen, J.**, **Linga, G.**, **Renard, F** & **Le Borgne, T.** Enhanced dispersion in intermittent multiphase flow. AGU Fall Meeting, New Orleans, USA. December 12-18
7. **McBeck, J.**, Ben-Zion, Y. & **Renard, F.** *Fracture network localization preceding catastrophic failure*. AGU Fall Meeting, New Orleans, USA. December 12-18
8. **Moura, M.**, Måløy, K. J., Flekkøy, E. & Toussaint, R. *Coffee is for drinking, tea is for porous media science: intermittent burst dynamics in slow drainage experiments in porous media*. 13th Annual Meeting of the International Society for Porous Media, November.
9. **Renard, F.** *Using large instruments to study flow and fractures in rocks*. 5th Cargèse summer school on Flow and Transport in Porous and Fractured Media,Cargèse, France. July 20-31
10. **Thøgersen, K.**, **Barras, F.**, Aharonov, E. & **Renard, F.** *How do earthquakes stop? Insights from a minimal model for frictional rupture*. AGU Fall meeting, New Orleans, USA. December 12-18

Posters and PICOs

1. **Aiken, J. M.**, **Cordonnier, B.**, Meakins, M., Rosenqvist, M. & Jamtveit, B. *Automating CT scan segmentation for CO2 sequestration applications*. AGU meeting.
2. **Barras, F.**, Aghababaei, R. & Molinari, J.-F. *Bridging the failure of surface asperities to the macroscopic rupture energy during the onset of frictional sliding*. EGU2021: European Geosciences Union General Assembly 2021, (pp. EGU21-14445)
3. Bertelsen, H.S., Guldstrand, F., Sigmundsson, F., Pedersen, R., **Mair, K.** & **Galland, O.** *Beyond elasticity: Are Coulomb properties of the Earth's crust important for volcano geodesy?* European Geosciences Union General Assembly 2021, (EGU21-13325)
4. **Bouchayer C.**, **Aiken J.M.**, **Thøgersen K.**, **Renard F.** & Schuler T.V. *Why do glaciers surge? understanding the controlling parameters using machine learning*. Svalbard Science Conference.
5. **Dziadkowiec, J.** *Nucleation in confinement – experiments in surface forces apparatus*. CECAM Psi-k Research Conference: New Horizons in Nucleation: a playground for classical and ab initio simulation methods.

6. **Dziadkowiec, J.**, Ban, M., Javadi, S., **Jamtveit, B.**, **Røyne, A.** *Ion-specific adhesion between brittle calcite surfaces*. Virtual Adhesion Science Gathering 2021.

7. **Dziadkowiec, J.**, Zareeipolgardani, B., Cheng, H-W., **Dysthe, D.K.**, **Røyne, A.**, Valtiner, M. *Forces between reactive surfaces*. EGU2021: European Geosciences Union General Assembly 2021.

8. **Galland, O.**, Schmiedel, T., Bertelsen, H.S., Guldstrand, F., Haug, T. & Souche, A. *Are dykes just filled hydraulic fractures? – Inelastic deformation and emplacement mechanisms of igneous tabular intrusions*. European Geosciences Union General Assembly 2021, (EGU21-14654)

9. **Guren, M. G.**, **Sveinsson, H. A.**, Hafreager, A., **Jamtveit, B.**, **Malthe-Sørenssen, A.**, & **Renard, F.** *Molecular dynamics study of confined water in the periclase-brucite system under conditions of reaction-induced fracturing*. EGU General Assembly Conference Abstracts (pp. EGU21-10766).

10. Kirilova, M., Toy, V., Sauer, K., **Renard, F.**, Gessner, K., Wirth, R., ... & Morrison, S. *Porosity evolution within the active Alpine Fault zone, New Zealand. Implications for fault zone rheology*. EGU General Assembly Conference Abstracts (pp. EGU21-9399).

11. **Kobchenko, M.**, Pluymakers, A., **Cordonnier, B.**, Mondol, N., & **Renard, F.** *Time-lapse synchrotron X-ray imaging of deformation modes in organic-rich Green River Shale heated under confinement*. EGU General Assembly Conference Abstracts (pp. EGU21-5585).

12. **Korkolis, E.**, Gimbert, F., Weiss, J., & **Renard, F.** *Irregular stick-slip and the role of cohesion in an ice friction experiment.* EGU General Assembly Conference Abstracts (pp. EGU21-7436).

13. Lecoustre, R., Almqvist, B., Koyi, H., **Galland, O.**, Hedin, P., Brahimi, S., Lorenz, H., Juhlin, C. *Large-scale flat-lying mafic intrusions in the granitic Baltica crust of central Sweden and implications for basement deformation during Caledonian orogeny*. EGU2021: European Geosciences Union General Assembly 2021, May 19-30 (PICO EGU21-6121)

14. **McBeck, J.**, **Aiken, J. M.**, **Cordonnier, B.**, Ben-Zion, Y., & **Renard, F.** *Predicting fracture network development in crystalline rocks*. EGU General Assembly Conference Abstracts (pp. EGU21-2965).

15. **Renard, F.**, **McBeck, J.**, & **Cordonnier, B.** *Damage coalescence controls slow and fast faulting: Insights from dynamic X-ray microtomography experiments*. EGU General Assembly Conference Abstracts (pp. EGU21-1577).

In media

1. **Angheluta, L.** *Mathematicians derive the formulas for boundary layer turbulence 100 years after the phenomenon was first formulated*. Phys Org, November 16th. [News]

2. **Cordonnier, B.** *Environment and mining.* ESRF, June. [Web]

3. **Cordonnier, B.** *Shale rock multi-scale imaging by X-ray micro- and nano-tomography.* ESRF, May. [News]

4. **Galland, O.** *Avkjølt lava på La Palma har skapt en ny halvøy: – Det kan bli et fint turistområde*. Aftenposten, October 2nd. [News]

5. **Galland, O.** *Kan se vulkanutbruddet fra verandaen*. Aftenposten Junior Skole, October 7th. [News]

6. **Galland, O.** *Kommer lavaen til sjøen, blir det farlig*. La Palma-utbruddet kan vare i tre måneder. Aftenposten, September 26th. [News]

7. **Galland, O.** *Skritt for skritt legger han grunnlaget for at geologer kan dra på virtuelt feltarbeid*. Titan, July 5th. [News]

8. **Galland, O.** *Til Kanariøyene i vinter? Disse reglene gjelder nå*. VG, November 21st. [News]

9. **Galland, O.** *Vulkanutbruddet på La Palma: Hvor farlig er det, hvor lenge vil det vare, og hva skjer hvis du går nær flytende lava?* Forskning.no, 25th September. [News]

10. **Jamtveit, B.** *Alumni Spotlight: Bjørn Jamtveit*. CAS, November. [News]

11. **Jamtveit, B.** *Mingeling art and science opens minds*. Physics Today, April 21st. [News]

12. **Jamtveit, B.** *Ny metode avslører hemmelighetene til veldig dype jordskjelv*. Titan, August 11th. [News]

13. **Menegon, L.**, **Zertani, S.**, **Michalchuk, S.** & **Galland, O.** *Feltarbeidet er grunnlaget for alt det vi geologer gjør.* Titan, September, 24th. [News]

14. **Moura, M.** *Slik lager du bedre kaffe med litt fysikk og litt botanikk*. Titan, July 19th. [News]

15. Remi, S., **Dziadkowiec, J.** & **Røyne, A.** *Measuring Large Scale Interactions Between Surfaces with nm Precision to Better Understand Geological Formations*. [Web]

16. **Renard, F.** *I Lofoten kan du se over 400 millioner år gamle jordskjelv i veikanten*. Titan, June 21st. [News]

17. **Renard, F.** *I verkstedet til Ellen Karin Mæhlum blir vitenskap til kunst*. Titan, October [News]

18. **Renard, F.** *La nucléation de la magnétite analysé grâce à la spectroscopie Raman*. CNRS, June. [Web]

19. **Renard, F.** *Noen av verdens best bevarte merker av fossile jordskjelv kan du finne i Lofoten*. Lofotenposten, July 3rd. [News]

20. **Renard, F.** *Unikt funn i Lofoten – avdekket 420 millioner år gammelt jordskjelv*. NRK, June 23rd. [News]

21. **Sveinsson, H.**, Linnebo, Ø. & Haug, D. T. *Hvilken nytte kan historikere, filosofer og språkforskere ha av algoritmer?* Titan, November 16th. [News]

22. **Vincent-Dospital T.** *Fysikkeksperimentet startet hos slakteren og endte som kunnskap om nervesystemet*. Titan, November 29th. [News]

Outreach

1. **Aiken, J.** *A new data set for physics education research*. Towards Data Science, December 22nd. [Blog]

2. **Dysthe, D.** *Hvordan virker ultralyd på mennesker*. Realfagsbiblioteket, November 10th. [Talk and video]

3. **Dysthe, D.** *LagLivLab: Student-mekking på bio-skaperverksted*. Youtube, September 9th. [Video]

4. **Galland, O.** *Volcanism*. French School (4th grade), 3rd December [Talk]

5. **Galland, O.** *Volcanism*. French School (5th grade), 5th November [Talk]

6. **Menegon, L.** *GEO-Wednesday: Hunting for fossil earthquakes in the Norwegian rocks*. Realfagsbiblioteket, May 12th. [Talk and video]

7. **Menegon, L.** *Waiting for #pint22: Hunting for fossil earthquakes in Norway*. Brygg, October 21st. [Talk and video]

8. **PoreLab.** *Everything flows - the question is how.* Outside Oslo City Hall, June 6th-19th. [Outdoor Art Exhibition]

9. **Skogvoll, V.** *8 måter å brekke ting på*. Realfagsbiblioteket, May 3rd. [Talk and video]

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

Project portfolio

Active projects in 2021

Project leader	Project title	Host	Funding Source	Project Start Date	Project End Date	Total Funding (NOK in 1000)
Angheluta, Luiza & Renard, François	EarthFlows 2	The Njord Centre	UiO	01.01.2019	31.12.2023	9 440
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
Galland, Olivier	Structure and emplacement mechanisms of the large sill complexes of central Isfjorden	The Njord Centre	RCN	01.05.2021	31.12.2021	80
Jamtveit, Bjørn	Disequilibirum metamorphism of stressed litosphere	Dept. of Geosciences	EU, ERC	01.09.2015	28.02.2022	21 000
Linga, Gaute	Mixing in Multiphase flows through Microporous Media	The Njord Centre	RCN	01.12.2021	30.11.2025	8 000
Malthe-Sørenssen, Anders	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	7 583
Moura, Marcel	FlowConn: Connectivity enchancement due to thin liquid films in porous media flows	The Njord Centre	RCN	01.09.2021	31.08.2025	8 000
Måløy, Knut Jørgen	Porous Media Laboratory	Dept. of Physics	RCN	01.07.2017	30.06.2027	66 400*
Renard, François	Microfractures in black shales and their transport properties	Dept. of Geosciences	RCN	01.04.2017	30.09.2021	11 201
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 (partner: The Njord Centre)	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*